University of Reading

Investigating human-environmental interactions in the Zagros region during the Late Pleniglacial, Lateglacial, and Holocene period

PhD

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This thesis is dedicated to my parents Malik Abid Rabbani & Uzma Khalid,

and my husband Mussawar Ahmad

Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Maria Rabbani

Abstract

This thesis investigates the environmental history of the Zagros region across the Late Pleniglacial, Lateglacial and Holocene (~17,700-2200 yrs BP), which corresponds to the Epipalaeolithic, Neolithic, Chalcolithic, Bronze, and Iron Age archaeological periods, in order to characterise and explain the changes in the vegetation cover and critically evaluate their interrelationships with anthropogenic activity and climate change.

This research also aims to address the limitations of some of the previous palaeoenvironmental studies, which are characterised by the use of low-resolution records, chronological uncertainties and low geographic variability. A multi-proxy approach is adopted therefore to reconstruct the environmental history of Hashilan wetland (Eastern Zagros) and Lake Ganau (Western Zagros). Two high-resolution palaeoenvironmental records were produced using sedimentological, pollen, non-pollen palynomorph, microcharcoal, macrocharcoal, and geochemical analyses (ITRAX), which enabled the reconstruction of the vegetation, climate, and fire history. This study has produced meaningful data on the exploration of a range of themes, including to the long-standing debate on the 'Early Holocene Precipitation Paradox', the 'Broad Spectrum Revolution' and the 'delayed *Quercus* woodland expansion'. The results provide additional evidence for complexity in terms of the regional variability of climate change during the Pleistocene and Holocene and highlight differences in environmental and climatic conditions between the eastern and western Zagros.

This research has, consequently, not only improved our understanding regarding aspects of climate change, vegetation succession, and human-environmental interactions in the Zagros region, but has also provided the first high-resolution pollen record for the western Zagros region for the Late Pleniglacial and Lateglacial interval. Furthermore, it helps to place climatic and vegetational changes as well as human responses in the Zagros region within the wider region and context, while appreciating local differences across Southwest Asia.

بسم الله الرحمن الرحيم

In the Name of Allah, the Most Gracious, Ever Merciful

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1 Introduction

Among the most pressing challenges our world is facing today is that of global climate change and environmental degradation, including but not limited to global warming, natural resource depletion, and destruction of ecosystems, which are caused by a complex interplay between both natural and human-induced factors (Hajek and Knapp 2022; IPCC 2022; Mirzabaev *et al.* 2022). The study of human-environmental interrelationships enables us to better understand the nature of environmental change and what impact it had on human societies in the past and how these societies adapted to, and impacted upon, the changing environment and climate around them. A better understanding of past human-environmental interactions may enable us to find solutions to our contemporary climatic and environmental problems including recognition of the importance of ecosystems in sustaining human communities (Monbiot 2022) and the need to protect them from degradation.

From an archaeological perspective, the Eastern Fertile Crescent, which includes the Zagros region, is characterised by a great range of notable episodes of socio-political, economic, and cultural changes across the long chronological sequence under study, covering a wide range of themes including the transition from hunter-gatherer lifestyle to sedentary farmers to the emergence of city-states and empires to cite a few (Matthews and Nashili Fazeli 2022). Earlier archaeological studies have often drawn correlations between the decline and/or collapse of ancient societies and climate change, including the downfall of the Mesopotamian Akkadian Empire and the Indus civilisation of South Asia (Weiss *et al.* 1993; Petrie *et al.* 2017). This view can be, however, simplistic and requires high-resolution archaeological and palaeoenvironmental records with robust age-depth models to identify any correlations. Furthermore, the idea that 'correlation implies causation' also appears to ignore to some extent certain important aspects related to adaptability and resilience of humans to environmental and climate change. This idea (of climate determinism), in fact, seems to have been born out of methodological approaches that are characterised by the use of incomplete archaeological datasets, inadequate dating, and/or low-resolution palaeoenvironmental records.

To better understand and improve our understanding of past human-environmental interactions, especially the impact of climate change on vegetation succession and human communities, this PhD provides new palaeoenvironmental data that is based on the study of sediment samples from Hashilan wetland (Iran) and Lake Ganau (Iraq), which are located in the Zagros region of the Eastern Fertile Crescent. Moreover, this study does not focus on a particular period but rather covers a long, extended chronological sequence starting from the Late Pleniglacial to the Lateglacial and into the Holocene, covering approximately 17,700 yrs BP to 2200 yrs BP. Obtaining sediment cores from Hashilan wetland and Lake Ganau has enabled us to reconstruct the vegetation and climatic history of two key sites that are located at different altitudes and in different parts of the Zagros region: eastern/highland vs western/lowland Zagros. Furthermore, both study sites are located favourably in close proximity to archaeological sites, allowing us to study and understand the potential impact human activities had on their surrounding environment and vice versa, as well as the response of human communities to climate and environmental change.

Unlike other regions of Southwest Asia, the central Zagros area including the hilly flanks of western Iran and eastern Iraq have received, since the 1970s, modest archaeological and palaeoenvironmental attention, creating a general disparity in our understanding of the archaeology and the palaeoenvironment of this region. Previous palaeoenvironmental studies, particularly those carried out at the sites of Lake Zeribar and Lake Mirabad of the Zagros region in the 1960s and 1970s, have provided long lake sediment sequences, which have informed us regarding the palaeoenvironmental conditions of the Zagros region (Van Zeist and Bottema 1977). Despite their significance, the earlier work suffers from serious chronological uncertainties, which will be discussed in more detail later in this thesis (Chapter 2 and 3).

In recent years, we have witnessed a surge in new research and studies that have appeared, allowing us to fill gaps in our knowledge (e.g. Matthews *et al.* 2013a; Matthews *et al.* 2020b; Djamali *et al.* 2016; Saeidi Ghavi Andam *et al.* 2021). The recent palaeoenvironmental studies, however, that have been carried out in the Zagros region, which will be discussed in Chapters 2 and 3, focus only on the Middle and Late Holocene phases, and thus provide only a partial picture, limiting our understanding of human-environmental interactions for the earlier time intervals. At present, we have only the Lake Zeribar record at our disposal that covers the last 40,000 years. Furthermore, the spatial coverage of palaeoenvironmental records for the Zagros region is low, with little palaeoenvironmental data available for the western Zagros region, which is however slowly improving (Flohr *et al.* 2017; Sinha *et al.* 2019b; Asouti *et al.* 2020). This long-standing imbalance has not enabled us to investigate and appreciate the local variations that might be detected in this complex and diverse region of Southwest Asia. There is, therefore, an urgent need to adopt multi-proxy, palaeoenvironmental investigative approaches that should be of high-resolution with a robust age-depth model. This would enable us to address the range of issues mentioned above in terms of the chronology and the determination of the regional significance of climatic and environmental changes and their potential impact on human societies in the past (Sharifi *et al.* 2015).

To tackle the above mentioned lacunae in research, the aim for this PhD is to reconstruct the environmental history of the Zagros region during the Late Pleniglacial, Late Glacial and Holocene period (17,700 - 2200 cal. yrs BP), which corresponds to the Epipalaeolithic, Neolithic, Chalcolithic, Bronze and Iron Age archaeological periods. This has been conducted in order to identify, characterise and explain environmental changes and investigate their interrelationships with anthropogenic activity and climate change.

1.1 Research aims and objectives

This research will address the following research questions:

1. To what extent may anthropogenic activity have been responsible for any changes in vegetation composition and succession at Hashilan wetland and Lake Ganau?
2. How resilient were human communities and ecosystems to climate change?
3. To what extent did the environment of Hashilan wetland and Lake Ganau influence and impact human lifestyle, including broadening of the human diet?

To achieve the aims of this study, the following objectives were addressed:

1. To evaluate the impact of human activities on the landscape and environment, especially periods of cultivation and/or animal husbandry through integration of palaeoenvironmental and archaeological records. This objective will enable us to improve understanding of the role farming communities had in driving patterns of vegetation and broader environmental change.
2. To assess the impact of climate change on vegetation succession and the agricultural system, and the resilience, or otherwise, of human communities and ecosystems to climate change.

1.2 Thesis outline

This thesis is divided into ten chapters, which are constructed as follows: Chapter 1 presents the research project and outlines the research aims, research questions and objectives. Chapter 2-4 provide a summary and critical review of the climate history, vegetation history and archaeology of the Zagros and wider region with a focus on themes of human-environmental interactions for each cultural period. Chapter 4 concludes with a summary clearly identifying the gaps in current research. Chapter 5 introduces the study sites and the geographical setting of the region. In Chapter 6, the research methodology is outlined, which is divided into fieldwork and laboratory methods. Chapter 7 outlines the results of Hashilan wetland and Chapter 8 outlines the results of Lake Ganau. In Chapter 9 the results of Hashilan wetland and Lake Ganau are discussed in relation to the aim and research questions of this PhD. Chapter 10 summarises the key findings of this research, evaluating their contribution to wider knowledge and future research questions that have been generated as a consequence of this research. The appendix includes all of the raw data from the analyses.

All radiocarbon ages in this thesis are calibrated year before present (cal. yrs BP).

2 Research context: climate history

To better understand and investigate human-environmental inter-relationships during the Pleniglacial, Lateglacial and Holocene periods, it is important to examine the climatic records available for Southwest Asia. Prior to examining the records for Southwest Asia and the Zagros region in particular, the general global trend observed in the Greenland ice cores and the marine sediments of the North Atlantic is outlined below to act as a climate framework. This is followed by a closer examination of Anatolian records to identify whether the wider region reflects climatic changes identified in the Greenland ice records.

2.1 Overview of climate

The Greenland ice records provide an outstanding record of past global climate changes, due to their very high stratigraphic and temporal resolution and precise dating, clearly indicating the presence of alternating stadial and interstadial periods (Table 2-1) (Rasmussen *et al.* 2014). The last glacial period was punctuated by temperature oscillations called Dansgaard-Oeschger cycles, rapid warm (interstadial) and cold (stadial) oscillations, that have been identified in the Greenland ice cores. Within the Dansgaard-Oeschger cycles, six Heinrich events have been identified in the North Atlantic marine sediments, which are characterised by a large discharge of icebergs into the North Atlantic and are defined in the sediment cores by the existence of layers of ice-rafted debris. The Heinrich events occurred at times of stadial periods and were terminated by prominent warm Interstadials (Bond *et al.* 1993; Bond and Lotti 1995). According to Rasmussen *et al.* (2014), although Heinrich events have been identified during several of the longer stadials, they do not necessarily have the same extent in time as the stadials in which they occur.

Table 2-1: Brief overview of different climatic intervals and terminology used in the literature, relevant for this research

INTIMATE event stratigraphy (Greenland ice records)	INTIMATE event dates cal. yrs BP (Greenland ice records)	Chronostratigraphy	Climatostratigraphy	Heinrich event
GS-2.1a	17,480	Pleniglacial	Oldest Dryas	1
GI-1e	14,692	Lateglacial Interstadial	Bølling-Allerød	-
GI-1d	14,075			
GI-1c3	13,954			
GI-1c2	13,660			
GI-1c1	13,600			
GI-1b GI-1a	13,311 13,099			
GS-1	12,896 -11,703	Lateglacial Stadial	Younger Dryas	0

Cold and dry conditions were prevailing during Greenland Stadial 2 (GS-2) which is characterised by the presence of Heinrich event 1. The onset of the Lateglacial Interstadial (GI-1) at 14,700 yrs BP was characterised by warmer conditions that lasted until ~12,900 yrs BP. These warmer conditions transitioned abruptly to a return to cold glacial like climate, known as Lateglacial Stadial (GS-1). The stadial event lasted until 11,700 yrs BP, leading to the onset of the Holocene epoch. The Holocene, which can be divided into Early Holocene (11,700-8200 yrs BP), Middle Holocene (8200-4200 yrs BP); and Late Holocene period (4200 yrs BP onwards), experienced a return to warmer and wetter conditions (Walker *et al.* 2012).

Recent evidence, however, indicates that the Holocene climate was highly variable with episodes of climatic fluctuations, although weaker in amplitude than the ones identified in the last glacial period (Bond *et al.* 1997; Mayewski *et al.* 2004; Rasmussen *et al.* 2007; Rasmussen *et al.* 2014). The Greenland ice core records also indicate the presence of three cold and dry climatic fluctuations during the Early Holocene; the 11.4 ka event; the 9.3 ka event; and the 8.2 ka event (Rasmussen *et al.* 2014).

The 11.4 ka event has been characterised as a gradual cooling event that lasted 100-120 years which was followed by an abrupt warming of 4 ± 1.5 °C (Rasmussen *et al.* 2007; Kobashi *et al.* 2008). Climatic conditions remained warm after the 11.4 ka event until ~9350 yrs BP. Labelled as the 9.3 ka event, this cold and dry event only lasted until 9240 yrs BP. It had a similar oxygen isotope amplitude as the 8.2 ka event but was shorter in duration (Rasmussen *et al.* 2007: 1911). The 8.2 ka event began with a general cooling and drying that lasted between ~8300-8140 yrs BP. According to Kobashi *et al.* (2007), temperature dropped abruptly by 3.3 ± 1.1 °C and within 20 years the coldest period was reached.

Besides these three abrupt cooling events identified in the Greenland ice records, so-called Bond cycles that occurred every ~1500 years leading to century-scale cold relapses, and significant rapid climate change (RCC) events have been identified. RCC events occurred during the time periods 9000–8000, 6000–5000, 4200–3800, 3500–2500, 1200–1000, and 600–150 yrs BP, in which dry and cool climatic conditions prevailed (Mayewski *et al.* 2004). Palaeoclimatic studies focusing on these time intervals revealed the presence of dry climatic events within them such as the 5.2 ka (Bar-Matthews and Ayalon 2011; Zanchetta *et al.* 2014), 4.2 ka (Cullen et al. 2000; Sharifi et al. 2015) and 2.8 ka (Sinha *et al.* 2019b) events, with evidence for significant impacts on human societies which will be discussed in the Chapter 4. As can be seen the Holocene, thus, is characterised by high climate variability.

Having established a basic global climate framework, we now proceed to examine palaeoclimatic records for the Anatolian region which will provide a broader regional view to compare and contrast the Southwest Asian records (Iran and Iraq) to but also will help to establish whether there is a good climatic agreement between these regions.

2.2 Climate history of Anatolia

The climatic changes observed in the Greenland ice cores have been detected in climatic records of Turkey (Figure 2-1). According to Çağatay *et al.* (2014), the fact that the Lake Van climate record agrees with the Greenland ice core records, the Sofular cave record (Turkey) (Fleitmann *et al.* 2009) and Soreq cave record (Levant) (Bar-Matthews *et al.* 1999), indicates the existence of teleconnections with the North Atlantic system. The isotope records of Lake Van and Eski Acıgöl (Turkey) show the presence of a stadial period (GS-2) that lasted until ~14,700 yrs BP and 14,500 yrs BP, respectively, followed by a warm Lateglacial Interstadial (GI-1) (Çağatay *et al.* 2014; Jones *et al.* 2007). A dry Lateglacial Stadial (GS-1) has been identified in the isotope records of Lake Van (~12,800 yrs BP)(Çağatay *et al.* 2014), Eski Acıgöl (~12,500 yrs BP) (Jones *et al.* 2007) and Nar Lake (Dean *et al.* 2015), followed by a wet Early Holocene. It has been argued, based on pollen data for this region, that even though the Early Holocene was wetter it experienced effective moisture deficiency lasting until approximately the Middle Holocene which in turn affected *Quercus* woodland expansion (Roberts *et al.* 2001), as discussed in the vegetation history section. Lake level study of Lake Van, based on geochemical and mineralogical proxies agrees with the isotopic data, indicating a major regression between ~16,000 and 15,000 yrs BP, followed by an increase during GI-1, decline during GS-1 and an increase again in lake level during the Early Holocene (Çağatay *et al.* 2014: 112).

Figure 2-1: Location of palaeoenvironmental records mentioned in this chapter (author's own - base map: Google maps)

Despite the identification of stadial and interstadial periods at Eski Acıgöl and Nar Lake, their timing slightly varies from the Greenland ice records' stadial and interstadial periods, which could be due to large uncertainties in the U-series dating. This is also applicable to the beginning of the Early Holocene which at Nar Lake and Lake Van occurred at 11,800 yrs BP and 11,500 yrs BP, respectively. These variations in the timing of the onset of the Holocene highlight the importance of well constrained chronologies that allow precise comparisons across sites enabling the emergence of a bigger picture. Despite the slight variations in timings, there is generally a good Lateglacial climatic agreement between the Greenland ice records and climatic records from Turkey.

In terms of the Holocene period, the 9.3 and 8.2 ka cooling events have been identified in the Nar Lake record, indicating dry conditions. Due to uncertainties in the U-Th dating, however, it is difficult to identify whether the 9.3 and 8.2 ka events occurred synchronously at Nar Lake and the Greenland ice records. Furthermore, the duration of the two events at Lake Nar was longer in contrast to the Greenland events, at ~300 yrs each. This suggests that there were additional controls on Eastern Mediterranean hydroclimate (Dean *et al.* 2015).. Based on the varve years, dryness was identified at ~9460-9150 yrs BP (~2340 varve years after onset of the Holocene) and between ~8500-8200 yrs BP

(~3400 varve years after onset of the Holocene) (Dean *et al.* 2015: 169-170). A precise chronology is essential for the identification of such climatic events, especially when it comes to the onset and termination of an event, as can be seen from the above example of Nar Lake.

Studies from this region indicate a wetter Early Holocene transitioning into a drier Late Holocene period which experienced wet–dry oscillations (Roberts *et al.* 2001; Çağatay *et al.* 2014). At Nar Lake a shift to a drier climatic condition has been noted at the Middle Holocene-Late Holocene transition between 4200-1500 yrs BP, labelled as the Middle Holocene Transition (Dean *et al.* 2015). At Lake Iznik arid conditions along with a drop in lake levels have been noted between 4400-4200 yrs BP (Ülgen *et al.* 2012), while at Tecer Lake, a dry event started at ~4200 yrs BP lasting approximately 450 years (Kuzucuoğlu *et al.* 2011). These dry events overlap with the 4.2 ka event and according to Roberts *et al.* (2011) the timing varied according to the degree of sensitivity of the impacted areas to a decrease in precipitation.

As can be seen, sites in Anatolia show similarities and differences between each other but also with the Greenland ice records, timing and amplitude wise. To make better and robust inferences about past regional-scale climatic and environmental changes, a high spatial coverage is required (Finné *et al.* 2011). Furthermore, multi-proxy approaches are essential when investigating regional-scale changes and site-specific local changes. For instance, although there is a good correlation between the Eski Acıgöl and Nar lake records, there are also differences between them, depending on the proxy examined in terms of timing and amplitude of change (Roberts *et al.* 2016). A disagreement in the amplitude and timing across sites could be due to dating uncertainties or sensitivity of the proxy used. It also, however, could indicate a site-specific signal if the same proxies of two sites show poor correspondence (Roberts *et al.* 2016: 358). Other factors that need to be taken into consideration when interpreting poor correspondence of the same proxies across sites include the location of the site, its surrounding and the lake's physical properties (Roberts *et al.* 2016: 360).

In summary, by briefly discussing some Anatolian records it becomes apparent that in order to identify and examine changes in past climate and environment it is crucial to have high-resolution multi-proxy records that have robust chronologies. This enables precise correlations to be made between records, thereby improving our understanding of the complex processes and systems at play. Additionally, improving the spatial coverage of sites studied within a region not only helps to improve our understanding of the past climate and environment but also highlights site-specific local changes. Having provided a brief broader regional picture of the palaeoclimate will allow us to compare and highlight any shortcomings of palaeorecords from Iran and Iraq.

2.3 Climate history of Southwest Asia (Iran and Iraq)

Having established a climatic framework using the Greenland ice and Anatolian records, this section aims to provide a brief overview of the atmospheric circulation systems affecting the Zagros region, followed by highlighting the limitations of palaeoenvironmental records from Southwest Asia, and provide an overview of the climate history for Southwest Asia, which will allow the identification of any differences among the records of the various regions.

2.3.1 **Factors impacting climatic conditions**

Understanding the atmospheric circulation systems is necessary to comprehend the climatic conditions a sub-region might be experiencing. The climate of Southwest Asia is controlled by a number of different atmospheric circulation systems including the Indian Ocean Summer Monsoon (IOSM), mid-latitude Westerlies, Siberian Anticyclone and the position of the Inter Tropical Convergence Zone (ITCZ) (Figure 2-2). Further, the topography needs to be taken into consideration as it can impact on the timing and amount of precipitation an area can experience. For instance, the west side of the Zagros mountains is an area which experiences orographically induced precipitation (Evans *et al.* 2004), and thus climatic conditions in the western Zagros likely would differ from Lake Zeribar's conditions in the eastern Zagros (Bosomworth *et al.* 2020, p.38). This becomes an issue, especially if the palaeoenvironmental records from eastern Zagros are used to explain changes in the archaeological record of western Zagros, as it simplifies and ignores the complexity of the topography and the associated characteristics (i.e. climate) of the Zagros region.

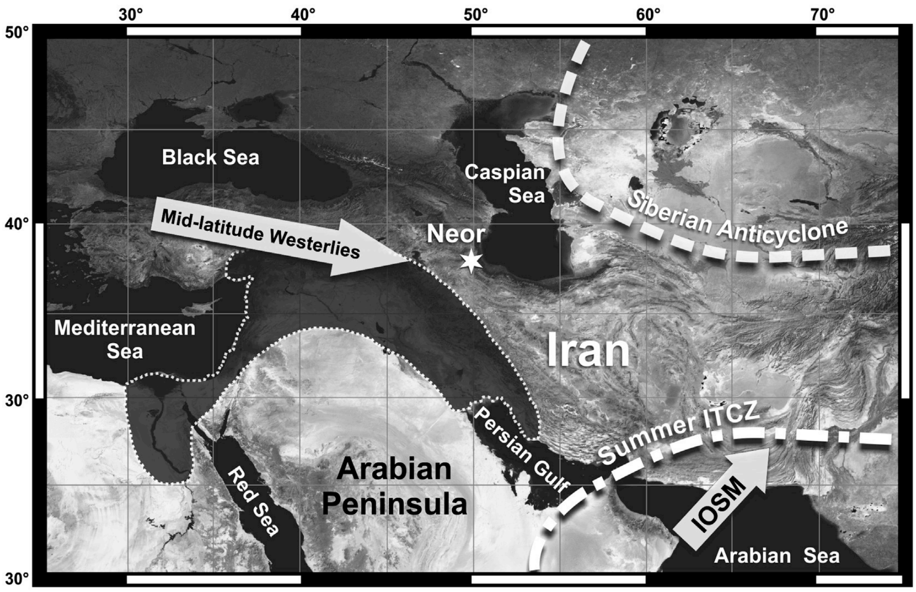

Figure 2-2: Schematic position of the atmospheric circulation systems that affect Southwest Asian climate (Sharifi et al. 2015: 217)

2.3.2 Chronological and resolution issues

Early investigation in the Zagros region focussed primarily on pollen and isotope analysis of calcareous lake sediments to infer palaeoclimatic conditions. Lake Zeribar (Van Zeist and Bottema 1977; Stevens *et al.* 2001), Lake Mirabad (Van Zeist and Bottema 1977; Stevens *et al.* 2006) and Lake Urmia (Djamali *et al.* 2008; Stevens *et al.* 2012) were among the first sediment cores to be investigated and used to reconstruct climatic conditions.

Although Lake Zeribar's isotope and pollen record is one of the most widely utilised records and dates back to 48,000 yrs BP, it suffers from chronology issues that are discussed in detail in the vegetation history ('see chronology issues'). Briefly, one of the difficulties associated with building a reliable, robust age-depth model for this region is the scarcity of dateable material preserved in the sediment cores such as waterlogged plant material or macroscopic charcoal. As a result, bulk sediment is widely used for radiocarbon dating which, due to the underlying limestone geology, can be subject to errors related to hard-water effects yielding an older radiocarbon date (Griffiths *et al.* 2001). For instance, Griffiths *et al.* (2001) radiocarbon dated three charcoal samples from Lake Mirabad that yielded younger dates than the previous two radiocarbon dates based on bulk sediment samples (Stuiver 1969; Van Zeist and Bottema 1977), suggesting contamination of the bulk sediment samples with old carbon from the surrounding limestone or migration of humic acid.

Furthermore, the radiocarbon dates have large age uncertainties which makes precise correlations with the archaeological evidence difficult, thus rendering human-environmental relationships hard to articulate. For instance, some of the radiocarbon dates for Lake Zeribar have age uncertainties of up to several hundred years (Van Zeist and Bottema 1977). This also hinders comparing precise timings of climate events in the palaeoenvironmental records.

Besides the possible uncertainty in the dating of the cores that used bulk sediment, another issue is the coarse resolution of some of these records, which presents a problem in identifying possible short-term trends (Stevens *et al.* 2001; Stevens *et al.* 2006). The isotope record of Lake Mirabad is based on 27 samples for the last 9300 years, while for the last 20,000 years only 45 samples were taken to construct Lake Zeribar's isotope record. To make more than general correlations between palaeoenvironmental and archaeological data both the temporal resolution and spatial scale of both data sets need to be of high-resolution (Walsh *et al.* 2017: 403). Records with different resolution are difficult to compare as a trend in the high-resolution record might not be visible in the low-resolution record. Lastly, the age-depth models of some of the palaeoenvironmental records have been produced using a small numbers of radiocarbon dates, e.g. only three radiocarbon dates are available for the Lake Mirabad record spanning the last 9300 years (Stevens *et al.* 2006). All of the above issues related to chronology and resolution impact our understanding of human-environmental relationships. Robust age-depth models are thus needed with precise radiocarbon dates to improve our understanding of the past.

2.3.3 Upper Pleniglacial (38,000-15,000 yrs BP)

Before discussing the oxygen isotope record of Lake Zeribar, it is important to mention that the climatic factors controlling the oxygen isotope values differ during the glacial and interglacial periods. Changes in oxygen isotope values in the Lake Zeribar record reflect variations in effective moisture (precipitation minus evapotranspiration) during the Pleniglacial and Lateglacial, while changes during the Holocene are argued to reflect a shift in the relative contribution of winter/spring precipitation and winter-only precipitation (Stevens *et al.* 2008: 301). Based on this explanation, increasing oxygen isotope values (average= -0.5%. and max.= 2.5‰) in the Lake Zeribar record suggest decreased effective moisture for the time interval ~17,700-15,500 yrs BP (Figure 2-3). This dry time interval that, based on diatoms, was marked by a general lowering and frequent seasonal fluctuations of water level, and pronounced increase in lake salinity, as well as appearance of halophytic species of macrophytes (e.g. *Salicornia europaea* at ~15,800 yrs BP), corresponds to Heinrich event 1 and Greenland Stadial (GS-2), a cold oscillation (Wasylikowa *et al.* 2008: 320).

Based on high values of Rb/K ratio, two episodes of increased aeolian activity (arid conditions) have also been identified at ~19,000 and 16,800 yrs BP in the Jazmurian playa multi-proxy record (southeast Iran), with the latter episode potentially related to Heinrich event 1 (Vaezi *et al.* 2019: 765). Although the timing differs from the Lake Zeribar record, it still falls within the stadial period (GS-2) identified in the Greenland ice records.

The Lake Zeribar isotope record and the geochemical record of the Jazmurian playa are the only two records available to infer past climatic conditions, highlighting the lack of records available for the Pleniglacial period.

2.3.4 Lateglacial (15,000-11,700 yrs BP)

The Lateglacial Interstadial (GI-1 = 14,692-12,896 yrs BP) and stadial (GS-1 = 12,896-11,703 yrs BP) have been identified in the Lake Zeribar record between ~15,200-12,000 yrs BP and 12,600-12,000 yrs BP, respectively (*Figure 2-3*). A decline in oxygen isotope values between ~15,200-14,200 yrs BP (max. decline= -4.3%.) suggests an increase in effective moisture. Furthermore, the appearance of diatoms and charcophytes that prefer warmer climate indicate an increase in temperature during this time interval (Wasylikowa *et al.* 2008: 314). The increase in *Najas marina* and *Ceratophyllum demersum* between 14,600-13,000 yrs BP is argued to be related to more favourable temperature and stable water level.

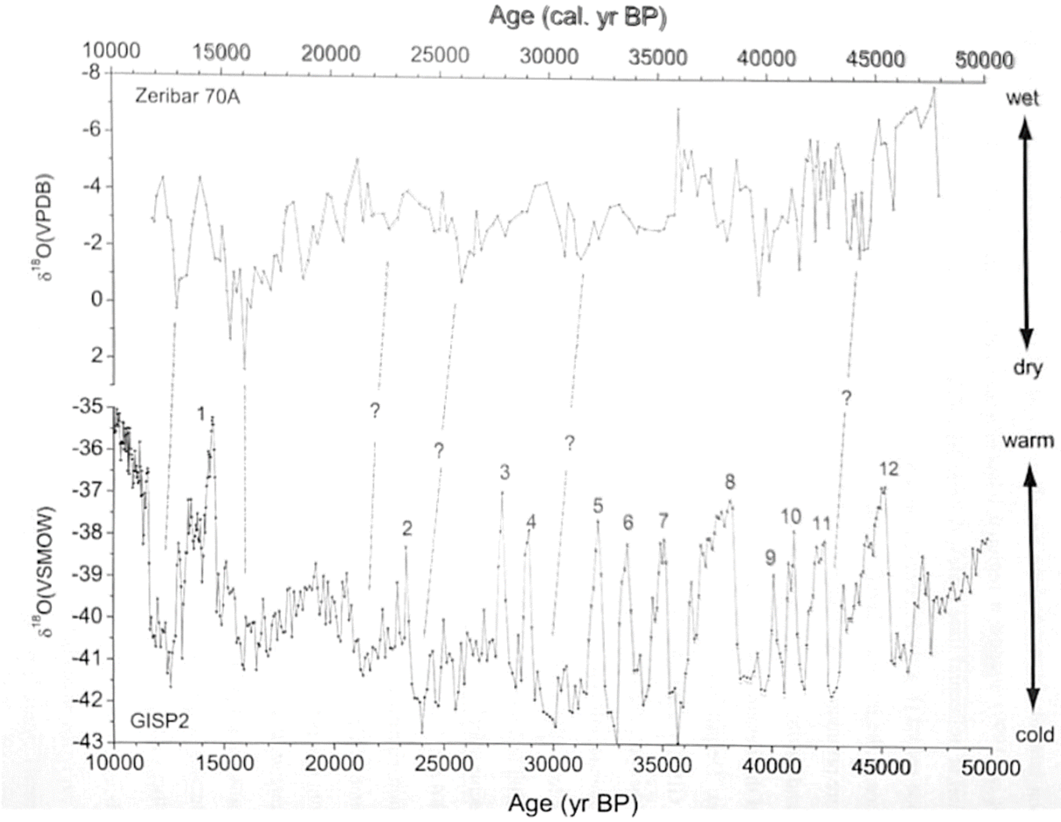

Figure 2-3: Oxygen isotope record for Lake Zeribar (top) plotted with oxygen isotope record for Greenland ice core records (bottom). Greenland Interstadials (GIs) have been labelled 1-12. Dashed lines imply potential correlations between high oxygen isotope values in the Lake Zeribar record and Heinrich events (Stevens et al. 2008: 298)

An increase in oxygen isotope values towards more positive values (max. increase= 0.5‰) after 12,900 yrs BP suggests a decline in moisture leading to a dry climatic period between 12,600-12,000 yrs BP that has been correlated to GS-1. The diatom, the glacial pollen assemblage (high Amaranthaceae and *Artemisia* pollen percentage) and presence of *Chenopodium rubrum* (plant remain), also reflect a change towards drier climate, along with low water levels and increased water salinity (Van Zeist and Bottema 1977; Snyder *et al.* 2001; Stevens *et al.* 2001; Wasylikowa 2005; Wasylikowa *et al.* 2006; Wasylikowa *et al.* 2008: 314-315).

According to the Lake Zeribar record, GS-2 and GS-1 were the driest events in the isotope record. Stevens *et al.* (2008: 299) argue that likely both low precipitation and high evaporation were acting together to create such a decline in effective moisture. Although both the GS-2 and GS-1 interval have been identified at Lake Zeribar and are portrayed as severely dry intervals, they are offset from the Greenland ice records (Table 2-2). This offset could suggest that these dry periods were not related to the cold events identified in the Greenland ice record or it could be related to Lake Zeribar's imprecise chronology (Stevens *et al.* 2008: 299), the latter one being more likely to be the reason.

The GI-1 interval has been noted in the Jazmurian record between ~14,000-13,200 yrs BP, based on an increase in fluvial input (K/Al ratio) and low abundance of evaporite minerals in the sediments suggesting an increase in IOSM activity during this time interval (wet conditions). While GS-1 has been identified between 13,200-11,400 yrs BP based on high magnetic susceptibility and deposition of coarse sand (Table 2-2) (Vaezi *et al.* 2019: 761-2). The isotope record from Lake Urmia, which suffers from a low-resolution and large age errors also, identified the start of the warm Lateglacial Interstadial (GI-1) at approximately 14,000 yrs BP, followed by drier conditions and lake level drop during the Lateglacial Stadial (GS-1) (Stevens *et al.* 2012). The Lateglacial Stadial (GS-1) has also been attested in the high-resolution multi-proxy record of Lake Neor which indicates dry and dusty conditions prevailed during this time interval (*Figure 2-4*) (Sharifi et al. 2015). Unlike at Lake Zeribar and the Jazmurian playa, the stadial at Lake Neor starts at ~12,900 BP, agreeing with the Greenland record.

Table 2-2: Timing of start of chronostratigraphic intervals across sites

Record	**Lateglacial Interstadial (yrs BP)**	**Lateglacial Stadial (yrs BP)**	**Early Holocene (yrs BP)**
Greenland ice	14,692	12,896	11,703
Lake Van	14,700	12,900	11,500
Lake Zeribar	15,200	12,600	12,000
Lake Urmia	14,000	-	-
Jazmurian playa	14,000	13,200	11,400
Lake Neor	-	12,900	11,500

Although North Atlantic climatic events have been identified in the Zagros region and neighbouring locations, confirming the existence of a teleconnection between North Atlantic climate and Southwest Asia (Sharifi et al. 2015; Mehterian et al. 2017), the timing of these events varies slightly across the sites mentioned above. This could be related to their chronology but also on the sensitivity of the proxy used to detect environmental and climate change. Rasmussen *et al.* (2014) also highlights the possibility of significant climate response lags between regions and differences in the way climatic signals are expressed by different proxies which requires precisely dated, high-resolution proxy records.

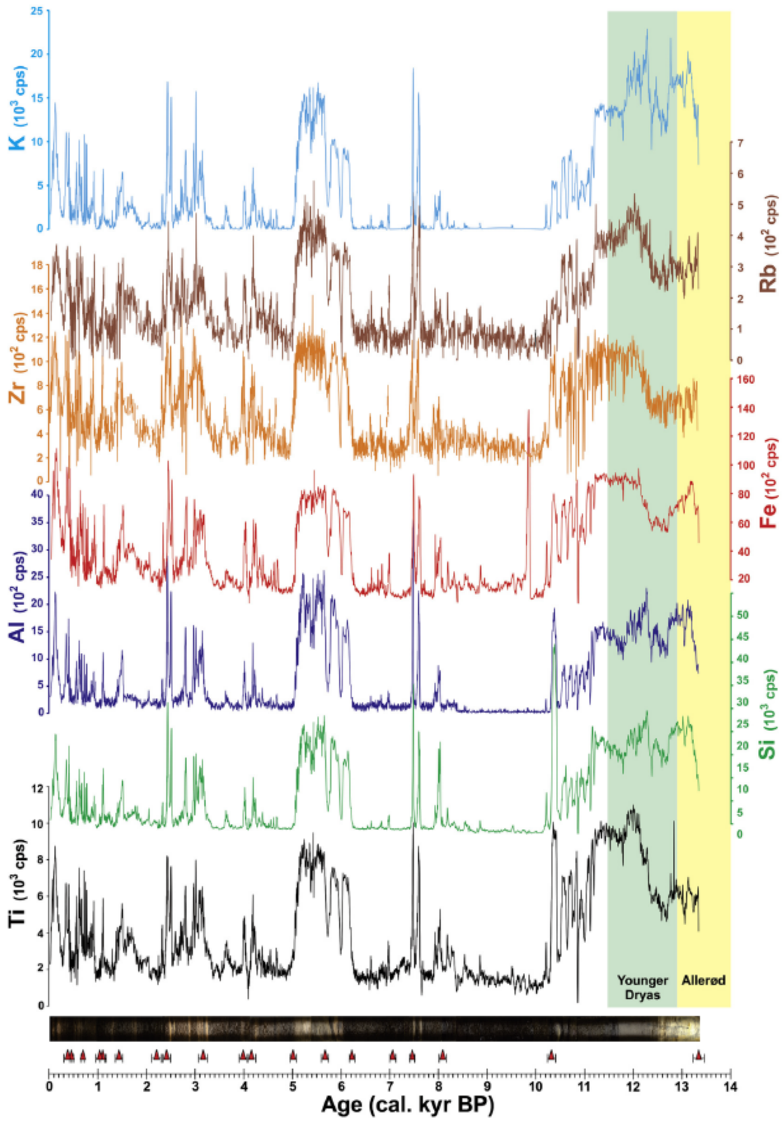

Figure 2-4: Downcore XRF profiles of elemental abundances (counts per second) linked with dust periods over the last ~13,400 yrs BP at Lake Neor. High Ti values suggest an increase in dust activity (Sharifi et al. 2015: 222)

2.3.5 Early Holocene (11,700- 8200 yrs BP)

During the Lateglacial -Holocene transition, the oxygen isotope values of Lake Zeribar record are high (~-4‰) but decline from ~11,200 yrs BP to ~-6‰ (Stevens *et al.* 2008). Based on the declining oxygen isotope values, climate changed from drier conditions during Lateglacial period to warmer and wetter climate at the onset of the Holocene period (Roberts *et al.* 2008). In contrast, however, the pollen data interpretation for Lake Zeribar suggests a relatively dry Early Holocene (Van Zeist and Bottema 1977). The presence of *Pistacia*, although in low pollen values, suggests dry climatic conditions during the Early Holocene as unlike *Quercus*, *Pistacia* is able to tolerate aridity and protracted summer droughts (e.g. shorter spring) (Freitag 1977). In the present day, *Quercus brantii Lindl.* is the dominant *Quercus* tree of the Zagros-Anti-Taurus deciduous oak woodland which prefers moisture (Figure 4).

Thus, an increase in moisture, i.e. increase in spring precipitation, can lead to an expansion in *Quercus* population. Long summer droughts, on the other hand, can inhibit seed germination leading over time to a reduction in *Quercus* tree population (El-Moslimany 1986). Therefore, the low pollen values of *Quercus* and the presence of *Pistacia* in the pollen record of Lake Zeribar during the Early Holocene suggest drier climatic conditions (Djamali *et al.* 2010a: 816-817).

This discrepancy between the low oxygen isotope values indicating a wet Early Holocene, and pollen data indicating a dry Early Holocene is known as the 'Early Holocene precipitation paradox'. Stevens *et al.* (2001) interprets the low oxygen isotope values as a shift in seasonality i.e. higher winter rainfall and protracted summers, rather than a general wet climate. It is argued that because of the strengthening of the Indian Summer Monsson (Djamali *et al.* 2010a), the Early Holocene period experienced a Mediterranean- type climate with a winter-dominated precipitation regime which can be seen in the multi-proxy study carried out at Lake Zeribar suggesting dry climatic conditions. Pollen, ostracod, oxygen isotope data and Sr/Ca ratio results (Griffiths *et al.* 2001; Stevens *et al.* 2006) from Lake Mirabad are in agreement with the Lake Zeribar pollen data, suggesting a dry Early Holocene period until ~6500 yrs BP after which less negative oxygen isotope values are interpreted to suggest a gradual increase in spring rains (Stevens *et al.* 2006).

This interpretation of drier conditions in the Early Holocene is in disagreement with the interpretation of isotope records from Turkey, where low oxygen isotope levels indicate a wet Early Holocene (Roberts *et al.* 2008). Jones and Roberts (2008) argue that this interpretation of low oxygen isotope levels suggesting a shift in seasonality rather than the amount of rainfall is oversimplified. Lake isotope systems are complex and multiple controls are exerted on the isotopic composition of lake waters that need to be taken into consideration such as changes in the precipitation evaporation ratio (P:E). Higher precipitation than evaporation rates (P>E) would cause isotope values to become more negative (low) and due to the oxygen isotope values of Eski Acıgöl being more negative (low), similar as at Lake Zeribar, they have been interpreted to represent wetter conditions (Jones and Neil Roberts 2008). Other potential reasons to explain the disagreement between the pollen and isotope data are associated with the underestimation of human impact on the environment that slowed down *Quercus* woodland expansion.

Recently, additional techniques have been employed to reconstruct palaeoclimatic conditions in the region including isotope records from speleothems (Flohr *et al.* 2017; Mehterian *et al.* 2017; Sinha *et al.* 2019b; Andrews *et al.* 2020), dust records (Sharifi et al. 2015; Safaierad et al. 2020), ostracod-based palaeoclimate record (Griffiths *et al.* 2001) and use of chironomid analysis (Aubert *et al.* 2017; Aubert *et al.* 2019), with an emphasis on employing multi-proxy studies (Sharifi et al. 2015; Vaezi et al. 2019) and producing robust and well dated age-depth models (Sharifi et al. 2015). New data from these studies in Iran suggests that the Early Holocene was wet, challenging the previous notion of it being dry (Van Zeist and Bottema 1977; Stevens *et al.* 2001). According to Sharifi *et al.* (2015), at Lake Neor low dust flux (based on Ti elemental concentration), negative compound-specific leaf wax hydrogen isotopes values and high carbon accumulation rates, suggest that the Early Holocene was relatively wetter and less dusty conditions prevailed (9000-6000 yrs BP). Sharifi *et al.* (2015) further argue that based on the results of their multi-proxy study, low oxygen isotope values from lakes in western Iran indicate wetter conditions during the Early Holocene. At Jazmurian playa in south-eastern Iran climate was also wet during the Early Holocene, starting at ~11,400 yrs BP (Vaezi *et al.* 2019). According to Vaezi *et al.* (2019), the start of the Early Holocene wet period depended on whether the site is located in the Indian Ocean Summer Monsoon or Mid-Latitude Westerlies dominated region.

The oxygen isotope record of Katalekhor cave, located in the northern Zagros Mountains of Iran, also indicates the opposite trend to Lake Zeribar. Andrews *et al.* (2020) suggest that this difference might be due to either site sensitivity, or the Katalekhor cave archive recording winter-dominated precipitation and lake archives largely recording summer-dominated precipitation. Andrews *et al.* (2020) further argue that if the isotope record of Lake Zeribar is studied on its own without considering the pollen data, it would suggest a wet Early Holocene followed by a dry Middle Holocene. To shed more light onto this issue and fully understand it, further palaeoenvironmental records are needed for the Zagros region. In particular multi-proxy studies are needed that focus on climatic reconstruction e.g. isotope studies.

Whether the Early Holocene in Southwest Asia was characterised by wet or dry climatic conditions is still being investigated by scholars. Regardless, the climatic conditions in the Early Holocene period were not stable as evidence suggests the presence of cold and dry climatic events at 11,400 and 8200 yrs BP in Southwest Asia (Vaezi *et al.* 2019; Safaierad *et al.* 2020). Unlike the 8.2 ka event, however, the 11.4 ka event has only been identified in the Konar Sandal peat bog record (south-eastern Iran) in the form of increased abundance of lithogenic elements (Safaierad *et al.* 2020), while the 9.3 ka event has not been identified at any site in the region. The 8.2 ka event is identifiable in the Jazmurian playa sediment core by an increase in the deposition of aeolian dust (peak in Zr/Al and Rb/K ratio) (Vaezi *et al.* 2019), and at Konar Sandal bog sediment core, as well, in the form of enhanced abundance of sediments of lithogenic origin (Safaierad *et al.* 2020). It has also been recorded in the Katalekhor cave speleothem record between 8300 and 7700 yrs BP based on a slow-down in stalagmite vertical growth rate and high $\delta^{13}C$ values (max.= -2.2‰) (Andrews *et al.* 2020). The 8.2 ka event in the Katalekhor cave speleothem record, however, was superimposed on a broader dry climatic event that lasted between

8300-7700 yrs BP argued to be a result of intensified Siberian High Pressure system affecting Mediterranean regional climate (Andrews *et al.* 2020). To be able to identify these climatic events, both, the resolution of the data needs to be high, and the age depth model has to be precise and reliable.

Table 2-3: Vegetation response to climatic events (11.4, 9.3 and 8.2 ka events) across different parts of Iran

Record	**11.4 ka**	**9.3 ka**	**8.2 ka**
Caspian Sea	Increasing Chenopodiaceae and declining *Artemisia* values	*Artemisia* and Chenopodiaceae increase ~24 and 43%, respectively. Poaceae declining	Sharp and short increase of Chenopodiaceae at ~8190 yrs BP, ~60% and *Artemisia* values increasing
Gomishan	Hiatus- no pollen data	Sharp increase in *Artemisia*, Asteraceae *Liguliflorae* and *Carpinus betulus* percentages at ~9475 yrs BP	Low resolution
Lake Neor	Poaceae and Cyperaceae increasing	Decline in Cyperaceae and Poaceae	*Quercus*, Cyperaceae, *Salix* and *Artemisia* increasing- more humidity?
Lake Zeribar	Poaceae increases, Chenopodiaceae declines	*Pistacia* and *Quercus* start to increase while Chenopodiaceae declines. Poaceae and Cyperaceae increase. *Artemisia* peak	Peak in *Salix*, *Myriophyllum spicatum*-type
Hashilan wetland	Low-resolution and desiccation	Low-resolution and desiccation	Low-resolution and desiccation

In terms of pollen data, it is difficult to make precise inferences for some of the records about whether vegetation changes are reflecting the cold and dry climatic events (Table 2-3). This could be partly due to resolution of the records and chronological uncertainties associated to some of the records. The Caspian Sea pollen record indicates an increase in both Chenopodiaceae and *Artemisia* during the 9.3 and 8.2 ka events which could suggest drier climatic conditions. At Lake Zeribar an increase in *Salix* is noticeable in the pollen record at ~8200 yrs BP which suggests a lowering of the water level. The lowering of the water level, however, does not necessarily imply drier climate but could also be a result of warmer temperatures. This is a good example demonstrating that the interpretation of one proxy on its own can lead to oversimplifications and thus, multi-proxy records are needed to make better, more robust inferences about the factors behind changes in the environment. Furthermore, to be able to identify these short-interval climatic events, high-temporal resolution records are needed.

2.3.6 Middle Holocene (8200- 4200 yrs BP)

According to the Lake Zeribar and Lake Mirabad isotope records, the Middle Holocene experienced wetter conditions from ~6500 yrs BP onwards indicating a shift in seasonality of precipitation from winter dominated to winter/spring dominated (Stevens *et al.* 2001). This shift in seasonality is supported by *Quercus* woodland being able to establish itself in the region. As summer drought became shorter and spring precipitation increased, *Quercus* was able to compete with drought tolerant *Pistacia* (Wasylikowa *et al.* 2008: 301). The stalagmite record, and phytolith and sedimentary results from Shalaii cave in the northeast Kurdistan region of Iraq also indicate a relatively temperate and wet Middle Holocene (Marsh *et al.* 2018). The multi-proxy study of Lake Neor also confirms the presence of a wet interval between 6700-6200 yrs BP based on high (*Artemisia*/Poaceae)/Chenopodiaceae ratio, high total organic carbon percentage, high carbon accumulation rate and negative δD values (Alinezhad *et al.* 2021). According to Djamali *et al.* (2010a), the weakening of the Indian Summer Monsoon and shift of the ITCZ southwards could have led to increased spring precipitation during the Middle Holocene. Unlike for the Early Holocene period, the isotope record of Lake Zeribar for the Middle Holocene interval agrees with other nearby records.

Based on oxygen isotope data from Lake Mirabad and Zeribar, however, a severe 600-year drought occurred at ~5600 yrs BP, suggesting a regional climatic event (Figure 2-5) (Stevens *et al.* 2006).

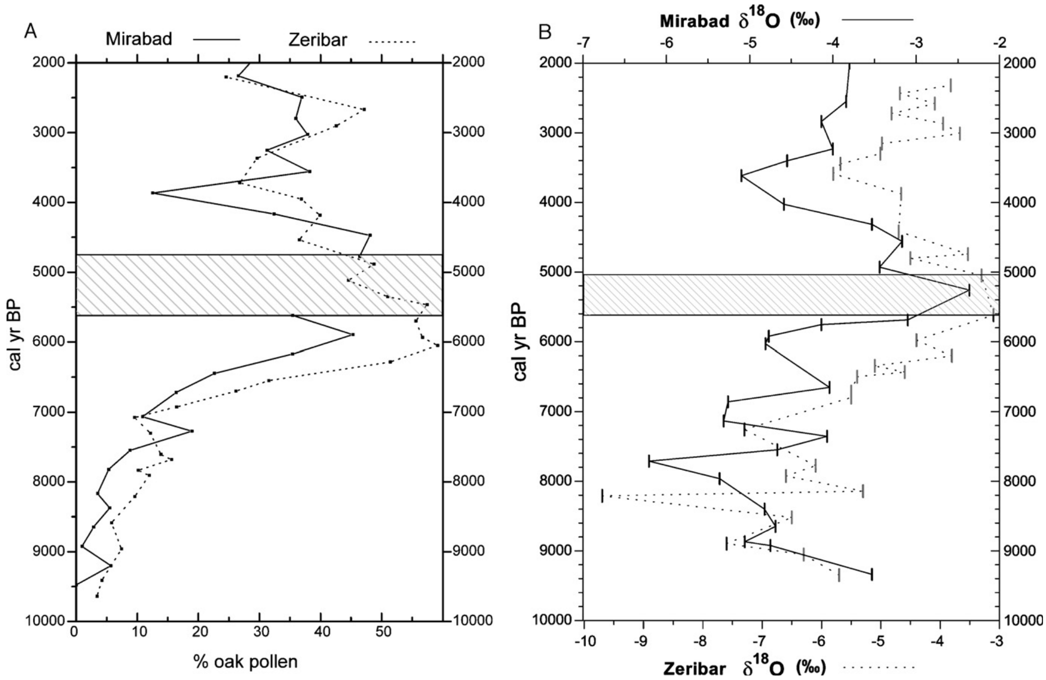

Figure 2-5: Plot A shows Quercus pollen percentages for Lake Zeribar (dashed line) and Lake Mirabad (solid line) with hatched area representing poor pollen preservation at Lake Mirabad. Plot B shows δ18O values Lake Zeribar (dashed line) and Lake Mirabad (solid line) with hatched area representing the Middle Holocene dry period at ~5500 yrs BP (Stevens et al. 2006: 497)

Although at Lake Zeribar, an increase in oxygen isotope values towards more positive values already started at ~6100 yrs BP lasting until ~5300 yrs BP (Figure 2-5). The exact duration of this dry event at Lake Zeribar is difficult to determine because the Holocene oxygen isotope record has been created by overlapping measurement data from two cores (core 63J and 70B) from ~5000 yrs BP (Figure 2-6) (Stevens *et al.* 2008: 293). Besides the oxygen isotope record, other changes in the environment noted in the Lake Zeribar record for the time interval 5500-4000 yrs BP that suggest dry conditions include: high number of *C. connivens* oospores (~5200-4800 yrs BP) that may be linked to a lowering of the water level, *Salix* expansion between ~4500-3800 yrs BP, poor diatom preservation and low number of macrofossils between 5500-4000 yrs BP (Wasylikowa *et al.* 2008: 318). This dryness could explain the decline in *Quercus* values from ~58% to ~37% from ~5500 yrs BP onwards in the Lake Zeribar pollen record.

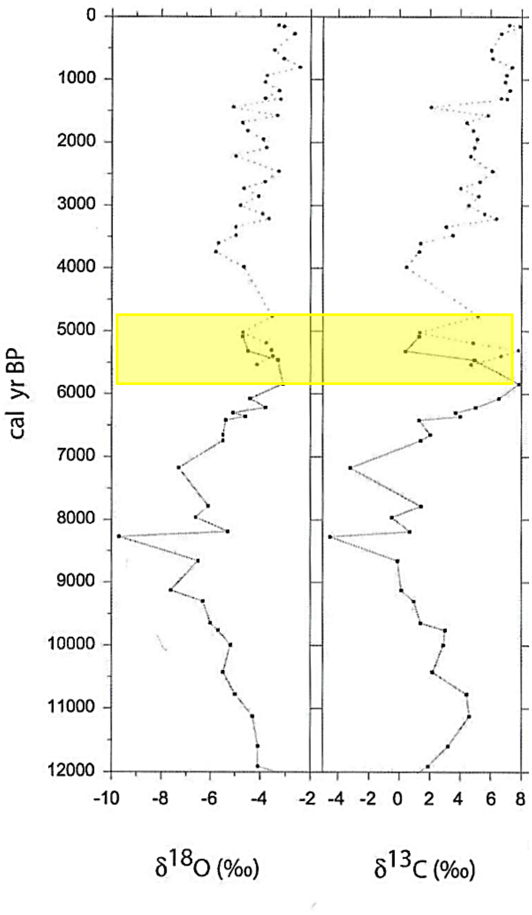

Figure 2-6: $\delta^{18}O$ and $\delta^{13}C$ record of Lake Zeribar for cores 63J (solid line) and 70B (dashed line) with yellow box highlighting the overlapping of the two cores (Stevens et al. 2008: 294)

The presence of drier climatic conditions is confirmed by the Lake Neor dust record (Sharifi et al. 2015) which indicates that relatively drier and dustier conditions prevailed during Middle to Late Holocene from ~6000 yrs BP onwards. The view that the Middle Holocene was drier (Table 2-4) is further corroborated by the Katalekhor cave record in which high Mg/Sr ratio between 6600-5400 yrs BP are interpreted to suggest an increase of aeolian dust. Furthermore, an increase in $\delta^{13}C$ in the Katalekhor cave record between 5400 and 4500 yrs BP has been identified, implying drier conditions which correlates with the dryness identified in the Levant centred at ~ 5100 yrs BP (Bar-Matthews *et al.* 2003; Bar-Matthews and Ayalon 2011). This is in agreement with the geochemical data from Jazmurian playa which also suggests dry conditions between 6000-5000 yrs BP (Vaezi *et al.* 2019: 764). The multi-proxy record for Lake Neor based on low AP values, rise in Chenopodiaceae, high Ti values and low values of palaeo-redox proxies also suggest a dry period for the period 6200-5200 yrs BP, followed by a wetter period (~5200-4450 yrs BP) (Alinezhad *et al.* 2021).

Table 2-4: Summary of dry climatic intervals during the Middle Holocene period

Record	Start of the dry climatic interval (yrs BP)	Proxies
Lake Zeribar	5600	$\delta^{18}O$, pollen, diatom and macrofossil data
Lake Mirabad	5600	$\delta^{18}O$
Lake Neor	6000	Dust record
Katalekhor cave	6600-4500	$\delta^{13}C$ and Mg/Sr ratio
Jazmurian playa	6000-5000	Geochemical record
Lake Neor	6200-5200	Pollen and geochemical data

Based on the evidence presented, the second half of the Middle Holocene (from ~6000 yrs BP), slightly earlier at Katalekhor cave, was changing towards drier conditions that lasted for different time intervals depending on the location of the site.

2.3.7 Late Holocene (4200 yrs BP onwards)

The start of the Late Holocene period is defined by the abrupt mid/low latitude aridification event, also known as the 4.2 ka event (Bond event 3).

The 4.2 ka dry event, which has been linked to the collapse of the Akkadian empire (Cullen *et al.* 2000), has been identified in the region at Lake Neor as indicated by an increase in Ti element (Sharifi et al. 2015); and at Jazmurian playa between 4500-4300 yrs BP in the form of high aeolian input, high salinity, and rise in evaporite minerals (Vaezi *et al.* 2019). It also has been identified in the marine sediment core from the Gulf of Oman by an abrupt increase in dust between 4025–3625 yrs BP (Cullen *et al.* 2000). According to Cullen *et al.* (2000), this dry event had an almost similar mineralogical and geochemical amplitude as the Lateglacial Stadial (GS-1) aridification event. In the Iranian plateau at Gol-e Zard Cave (Alborz mountains), the oxygen isotope record and Mg/Ca ratio indicate two periods of increase in dust flux and aridity starting at 4510 and 4260 yrs BP, and lasting 110 and 290 years, respectively (Figure 2-7) (Carolin *et al.* 2019).

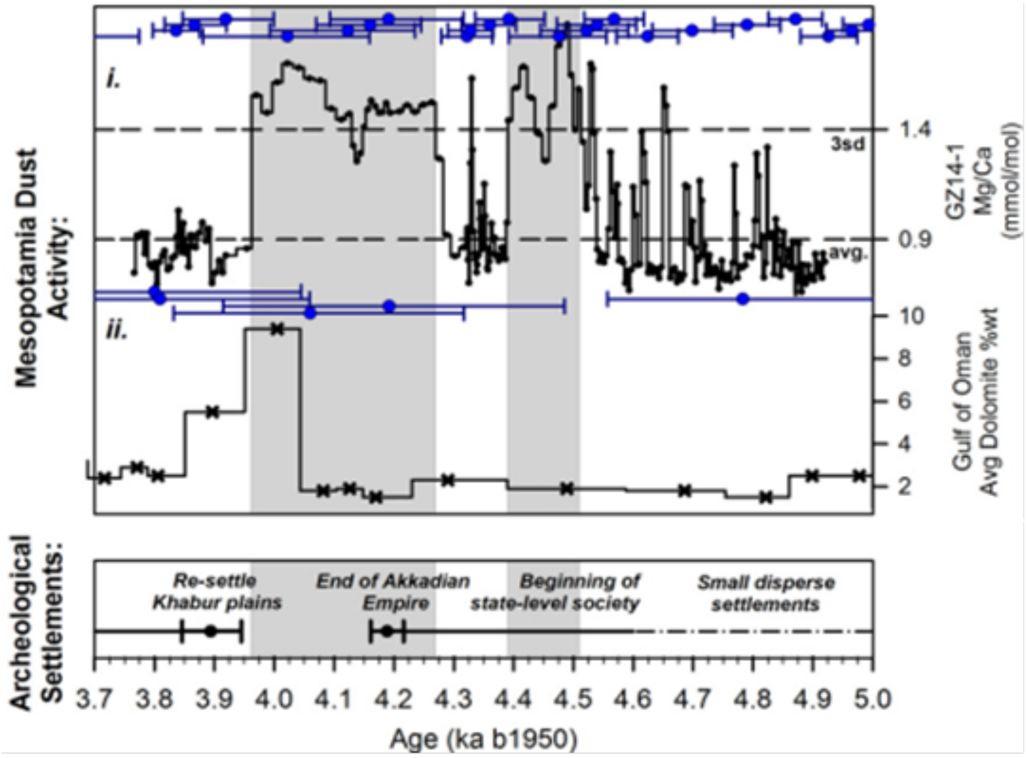

Figure 2-7: Comparison of Gol-e Zard and Gulf of Oman proxies to archaeological settlement record with grey highlights indicating the increase in dust activity in the Gol-e Zard Mg/Ca record (Carolin et al. 2019: 70)

In contrast, no increased dust flux has been registered by the trace element record from Katalekhor cave beginning abruptly at ~4510 and 4260 yrs BP. The $\delta^{13}C$ record from Katalekhor cave, in contrast, indicates an increase in aridity between 5400-4500 and 4300-2000 yrs BP (Figure 2-8) (Andrews *et al.* 2020). The reason for the 4.2 ka event not being picked up in the Katalekhor cave could be related to the sensitivity of proxy used or the event not having a strong signal.

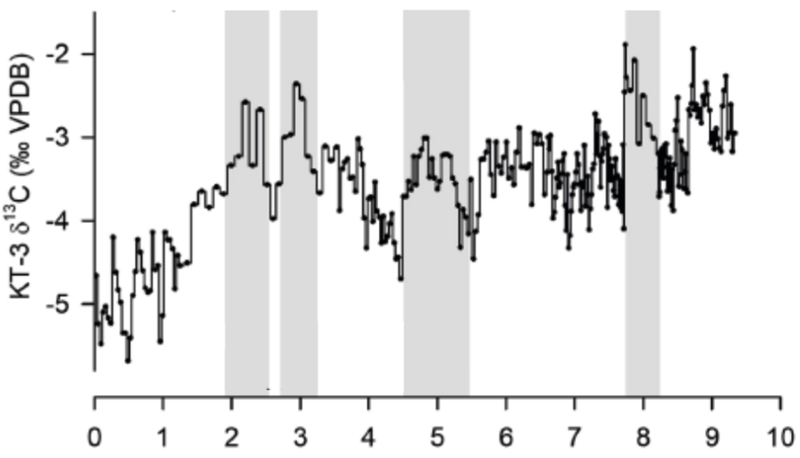

Figure 2-8: δ^{13}C record of Katalekhor cave with grey bars highlighting four periods of aridity (Andrews et al. 2020: 12)

Furthermore, at neither Lake Zeribar nor Lake Mirabad has evidence been found indicating a dry event at ~4200 yrs BP, although a pronounced lake shallowing occurred between ~5500-4000 yrs BP based on very low numbers of macrofossil at Zeribar (Wasylikowa *et al.* 2008). An increase in *Salix* between 4500-3800 yrs BP also suggests a lowering of the lake levels which coincides with a rapid climate change event identified by Mayewski *et al.* (2004). Although there is a possibility that low lake levels may suggest a decline in precipitation i.e. drier climatic conditions, an increase in evaporation or combination of both can also lead to lower lake levels. Stevens *et al.* (2006), does emphasise that due to the low resolution of these records, the 4.2 ka event could have been missed. Unlike Lake Zeribar and Lake Mirabad isotope record, recent studies have a higher sampling and temporal resolution which makes it difficult to identify and correlate any short-interval climatic event in the Lake Zeribar and Mirabad records.

In terms of pollen data reflecting changes in the vegetation that could be related to the 4.2 ka event, besides the Lake Neor pollen record no other record identified the climatic event. An increase in Chenopodiaceae between 4300-3800 yrs BP from ~15 to 28% along with a shift in δD values towards less negative values suggest a dry period that overlaps with the 4.2 ka event and a rapid climate change event (4500-3800 yrs BP) (Alinezhad *et al.* 2021: 606). Although not having registered the 4.2 ka event specifically, the Lake Maharlou and Kongor Lake pollen record indicate a general dry interval between 5100-4000 yrs BP and 5900-2700 yrs BP, respectively. As mentioned earlier, an increase in *Salix* has been noted at Lake Zeribar between ~4500-3800 yrs BP along with a slight increase in Chenopodiaceae and *Artemisia* at 4200 yrs BP which could imply drier conditions (Table 2-5).

Table 2-5: Changes in vegetation identified in the pollen records of Iran

Record	4.2 ka event
Lake Zeribar	Slight increase of Chenopodiaceae and *Artemisia*. Increase in *Salix* suggests lowering of water level
Lake Maharlou	5100-4000 yrs BP – dry period but 4.2 ka event not registered in pollen data
Lake Neor	4030-3100 yrs BP - dry period. Rise of Chenopodiaceae took place sometime between 4300-3800 yrs BP. δD values also shift towards less negative values implying drier conditions
Kongor Lake	5900-2700 yrs BP - dry period. Increase in Chenopodiaceae and *Artemisia*

The 4.2 ka event, although identifiable in some records, especially in dust records, varied in duration and amplitude across the region. This variability highlights the spatial heterogeneity of local and regional climate conditions across Southwest Asia. Mayewski *et al.* (2004) stress the point that not all sites will respond synchronously or similarly during rapid climate change events which highlights the complexity of Holocene climate. It further emphasises the need for studies involving widely distributed palaeoclimatic records to mitigate inaccurate inferences derived from using data from extrapolating data across sites through more local records (Mayewski *et al.* 2004).

Having presented evidence for the 4.2 ka event in Southwest Asian records, the following time interval is characterised by a reduction in overall effective moisture (Stevens *et al.* 2008: 301). A reduction in oxygen isotope values in the Lake Zeribar record between ~4000-3300 yrs BP towards more negative values (from ~-5 to -6‰) suggests a temporary increase in effective moisture. Stevens *et al.* (2008), however, argue that although the oxygen isotope record of Lake Mirabad also suggests a decline towards more negative oxygen isotope values, the ostracod taxa resemble that of the Early Holocene and evidence of increased salinity is indicated by the diatom assemblage. Therefore, this event at Lake Zeribar has been interpreted to suggest a return to winter-only precipitation and decline in overall effective moisture (Stevens *et al.* 2008: 301). This interpretation of relatively drier climate is confirmed by the Lake Neor multi-proxy record that indicates dry climate between ~4030-3150 yrs BP (Alinezhad *et al.* 2021). Unlike at other sites, where an increase in Ti/cps and K/cps has been interpreted to suggest increased aeolian activity, at Lake Maharlou an increase in Ti/cps and K/cps has been used to suggest an increase of detrital material by river supply i.e. wet climatic conditions. Thus based on sedimentological analysis and high K intensity, the time interval between 3800-3250 yrs BP has been interpreted as wet, followed by more stable hydrological conditions until ~2000 yrs BP (Brisset *et al.* 2019).

A high-resolution and well dated speleothem record from the Kuna Ba cave in northern Iraq identified a wet period between ~2800-2690 yrs BP, termed the Assyrian Megapluvial, followed by aridity between ~2650-2500 yrs BP. According to Sinha *et al.* (2019), the isotope data suggests that the Assyrian empire rose during this wet interval while the 125 yrs of aridity, termed the Assyrian Megadrought, contributed to the collapse of the empire. The timing of the transition from wet to arid conditions coincides with the timing of the 2.8 ka event (Sinha *et al.* 2019b). The only other indication for climate amelioration comes from Lake Kongor where a spread of *Artemisia* grass steppe has been identified at ~2700 yrs BP (Shumilovskikh *et al.* 2016a: 1688). A general trend towards aridity has been identified in other records. At Lake Zeribar, generally high and fluctuating oxygen isotope values (average -4‰) suggest dry conditions from 3000 yrs BP onwards. In contrast, based on low Ti/cps values suggesting low aeolian input, decline in Chenopodiaceae percentage, and high values of total organic carbon and carbon accumulation rates, a wet period has been identified at Lake Neor between ~3150-2215 yrs BP (Alinezhad *et al.* 2021: 607). This opposing trend between Lake Zeribar and Lake Neor could be a result of using different types of proxies to infer climatic conditions. Furthermore, to explain why the Assyrian Megapluvial and Megadrought are not visible in the Lake Zeribar and Lake Neor records could be related to not only the proxy but also reflect the location of the sites.

2.3.8 **Summary**

In conclusion, as highlighted throughout, some of the records suffer from geochronological uncertainties making it difficult to study human-environmental relationships and constrain the timings of climatic events precisely. For instance, this chapter highlighted some issues and uncertainties with the Lake Zeribar isotope record and its chronology and thus caution needs to be exercised when using this data set to infer past climatic and vegetational changes and their timings. New studies (e.g. Carolin *et al.* 2019; Sinha *et al.* 2019b; Andrews *et al.* 2020) are addressing these issues in order to understand past climate history and the mechanisms controlling them. However, there is still a gap in our understanding of climate history, especially for the Lateglacial -Early Holocene transition in the Zagros region which witnessed an important change in human lifestyle from mobile hunter-gatherers to sedentary farmers. Thus, robust and well dated palaeoenvironmental records are needed that cover a wide spatial area in order to better differentiate site-specific and regional climate trends. Further, the palaeoenvironmental records need to be of high-resolution in order to identify short-term changes that would otherwise be missed, thus affecting the interpretation of the records.

To summarise, the available palaeoclimatic data indicate a dry stadial (GS-2), wet and warm Lateglacial Interstadial (GI-1; Bølling-Allerød), dry Lateglacial Stadial (GS-1; Younger Dryas), and a warm and relatively wetter Early Holocene (Sharifi et al. 2015; Sharifi et al. 2018; Vaezi et al. 2019; Andrews et al. 2020) except at Lakes Zeribar and Mirabad where drier conditions prevailed. The Middle Holocene has been characterised at Lake Zeribar and Lake Mirabad as wet while other records indicate a generally drier period starting ~ 7000-6000 BP (Stevens et al. 2001; Stevens et al. 2006; Sharifi et al. 2015; Andrews et al. 2020) followed by a dry Late Holocene (Flohr *et al.* 2017; Sinha *et al.* 2019b; Vaezi *et al.* 2019). This, however, portrays a simplified general model which needs to be tested further by carrying out multi-proxy, high resolution palaeoenvironmental studies.

Based on the palaeorecords discussed, the Lateglacial was a period of extreme variability and there is evidence for correspondence between the records of Southwest Asia and Greenland ice records. Although climatic events in the Holocene have been picked up by the different proxies, however, possibly due to their sensitivity and chronological uncertainties, they indicate different time intervals for the events. Thus, to refine our understanding of past climatic conditions, further records of high-resolution are needed.

3 Research context: Vegetation history

Having discussed the climate trends and limitations of palaeoclimatic studies, the vegetation history for the last 17,000 yrs will be outlined and discussed. Prior to outlining the main vegetation trends identified in the pollen records of the region (Figure 3-1), it is essential to understand some of the problems and shortcomings of these records that ultimately impact our current understanding of human-environmental interactions.

3.1 Shortcomings of pollen studies in Southwest Asia

3.1.1 Time span and record resolution

To fully comprehend changes in vegetation composition and disentangle human impact from climate change impact, the record resolution needs to be high and a multi-proxy approach is required. Of similar importance are long-sequence pollen records that provide a long history of changes in vegetation composition over time. One of the issues identified in the available pollen records of this region is the lack of records extending back to the Pleniglacial period (Table 3-2). Lake Zeribar and Lake Urmia pollen records are the only ones that span the last 48,000 and 200,000 years, respectively. The lack could be explained by various reasons including a general paucity of water bodies, focus of scholars on specific time intervals, and lake sediment build-up not being deep enough to capture earlier periods. Despite the Lake Urmia pollen record covering the last 200,000 years, the resolution of the pollen record is low with samples analysed every 1m.

Figure 3-1 Map showing locations of lakes, cave, and wetlands mentioned in text except Lalabad spring and Lake Nilofar which are located in the same region as Hashilan wetland (Kermanshah region)(author's own – base map: Google maps)

This not only hinders identification of detailed trends but also makes it difficult to compare it with other data as trends in a high-resolution record might not be visible in a low-resolution pollen record. Djamali *et al.* (2008) thus argue that a detailed picture of the Lateglacial –Holocene vegetation dynamics cannot be given for Lake Urmia, and they emphasise that high-resolution analyses with better dating control are needed to study the higher-frequency changes in vegetation and climate, which will also allow more precise correlations with other records. The problem of coarse temporal resolution is further emphasised by the fact that the pollen records covering the Lateglacial -Holocene transition, a significant time interval that experienced a change in vegetation cover, prevailing climatic conditions and human lifestyle, have a sampling resolution of at least 10cm (Table 3-2). This may be due to the nature of the study which aimed to provide a general overview of vegetation changes over time.

Furthermore, the majority of the pollen records (Table 3-2) focus on the second part of the Middle Holocene and the Late Holocene (last 6000 years), highlighting the lack of pollen records covering earlier time periods. Nevertheless, pollen records spanning the Middle and Late Holocene have a higher temporal resolution, with samples taken every 1-10cm. This provides more detailed reconstruction of environmental conditions and allows a more precise correlation with other data sets.

3.1.2 Chronology issues

A major issue associated with pollen studies of this region is the chronology which is based largely on radiocarbon dating of bulk sediments (Table 3-1 and *Table 3-2*). Due to the limestone rich geology, radiocarbon dates based on bulk sediments are likely to be affected by the hard-water effect yielding older radiocarbon dates that can lead to wrong correlations and interpretations. In addition, even organic-rich bulk sediment samples will only provide an average age that is composed of all the organic components within the sample and therefore potentially produce an erroneously old radiocarbon date. The problem is the lack of organic material of terrestrial origin preserved in the sediment cores that could be radiocarbon dated. At Lake Mirabad the offset between the bulk and charcoal ages is estimated to be between 5000-2000 years (Stevens *et al.* 2006) while at Lake Maharlou the dates based on the bulk samples (Djamali *et al.* 2009b) were offset between 800 and 2500 years depending on the sedimentological facies (Saeidi Ghavi Andam *et al.* 2021). Saeidi Ghavi Andam *et al.* (2021) thus emphasise the need and use of radiocarbon dating terrestrial plant material despite their rarity in sediment cores by increasing sediment sampling size, have core replicates, and in addition use other dating methods.

At Lake Parishan, for example, to identify the extent of the hard-water effect on the sediment, along with radiocarbon dating three bulk samples, one sample was U-Th dated (Jones *et al.* 2015; Djamali *et al.* 2016). The difference between the results of the radiocarbon age and the U-Th age indicated an offset of about 330 years. To reverse the impact of the hard-water effect on the radiocarbon dates and create the final age-depth model the offset value was subtracted from the calibrated radiocarbon ages, assuming that the hard water-effect remained constant over time. However, based on the radiocarbon dating results of Lake Mirabad and Lake Maharlou it is clear that the hard-water effect is not constant over time. Besides, U-Th dating, Jones *et al.* (2015) verified their chronology using a pollen stratigraphic marker, in this case the establishment of *Olea* and deforestation of *Quercus* which is connected with the start of the Achaemenid Persian Empire at 2500 yrs BP. Using this pollen stratigraphic marker helped to confirm the estimate of the hard-water effect on the radiocarbon dates.

Other attempts to minimise the impact of the hard-water effect on bulk sediments includes treating the samples to remove chemical/biochemical carbonate fraction and siliciclastic materials, leaving behind organic matter produced only by biological processes (Talebi *et al.* 2016). Another possibility to minimise the impact of hard-water effect is to identify site locations that have low carbonate content. For instance, the bulk sediment ages for Lake Neor (Aubert *et al.* 2017) are likely to have reduced risk of hard-water effect due the lake's catchment area being dominated by Tertiary volcanic and volcaniclastic rocks and which have low carbonate content. However, the latter suggestion is more difficult to implement as one of the limiting factors to choosing a study site is the general paucity of lake bodies in Southwest Asia.

Table 3-1 Uncalibrated and calibrated radiocarbon dates of selected sites (Zagros region only) with grey boxes highlighting dates based on bulk sediments. For a full list of radiocarbon dates for each site reviewed please see Appendix

Site name	Depth (cm) and mean depth (cm)	Material dated	Uncalibrated date	Error	Calibrated date - IntCal20 (BP)	Notes
Hashilan wetland (Safaierad *et al.* 2014)	80	?	2100	25	2126-1993 (94.4%) 2143-2136 (1.1%)	Paper in Farsi
	755	?	31,500	300	36,410-35,275 (95.4%)	
	1193	?	39,500	700	44,195-42,340 (95.4%)	
Lake Maharlou (Djamali *et al.* 2009)	35.25 (34.5-36)	Bulk sediment	1815	30	1798-1692 (64.3%) 1670-1621 (28%) 1821-1805 (3.1%)	
	73.2 (72.5-74)	Bulk sediment	3075	35	3372-3207 (93.1%) 3194-3179 (2.4%)	
	113 (112.5-113.5)	Bulk sediment	4110	40	4731-4520 (69.2%) 4821-4747 (24.3%) 4465-4450 (1.9%)	
	145 (144.5-145.5)	Bulk sediment	4560	35	5192-5051 (51.3%) 5324-5231 (39.5%) 5439-5417 (3.6%) 5225-5215 (1.0%)	
Lake Maharlou (Brisset *et al.* 2019; Saeidi Ghavi Andam *et al.* 2020)	43	Charcoal, Coleoptera, seed	390	30	509-426 (67.1%) 379-320 (28.4%)	
	88	Plant fragment	655	35	607-555 (48.9%) 671-622 (46.5%)	

	159	Charcoal, Coleoptera, seed	2450	50	2622-2358 (71.7%) 2708-2627 (23.8%)	Rejected due to insufficient weight of carbon
	193	Charcoal	1950	50	1992-1741 (95.4%)	
	237	Charcoal, Coleoptera	2820	90	3171-2756 (95.4%)	
	269	Charcoal, Coleoptera, seed	3800	180	4650-3698 (93%) 4806-4756 (1.6%) 4700-4672 (0.8%)	
	321	Charcoal, Coleoptera, seed	3370	35	3693-3490 (95.4%)	
Lake Mirabad (Van Zeist and Bottema 1977)	479 (475-483)	White shelly marl	10,790	150 **or** 200	13,090-12,480 (95.4%) **or** 13,124-12,426 (87%) 12,401-12,166(6.9%) 12,131-12,102 (0.7%) 13,160-13,135 (0.6%) 12,157-12,123 (0.4%)	Too old because of 14C-depleted carbonates
	721.5 (720-723)	Dark peaty sediment	10,370	120	12,625-11,816 (94.7%) 12,666-12,642 (0.8%)	Omitted from age-depth model
Lake Mirabad (Griffiths *et al.* 2001)	90	Charcoal	350	50	496-309 (95.4%)	
	390	Charcoal	4400	50	5067-4853 (76.1%) 5278-5169 (15.9%) 5134-5103 (3.5%)	
	676	Charcoal	7970	60	9000-8638 (95.4%)	
Lake Nilofar (Van Zeist 2008)	119-122	Bulk sediment?	4960	120	5942-5465 (94.5%) 5989-5968 (0.8%) 5340-5335 (0.1%)	
	337-345	Bulk sediment?	28.400	1600	37,532-29,896 (95.4%)	
	?	Bulk organic sediment	1705	30	1630-1533 (73.5%) 1698-1660 (21.9%)	

Lake Parishan (Jones *et al.* 2015)	125.5	Bulk organic sediment	2685	35	2854-2748 (95.4%)	
	225.5	Bulk organic sediment	3750	30	4160-4063 (60.3%) 4050-3986 (23.3%) 4233-4198 (9.7%) 4183-4167 (2.1%)	
	225.5		3745	90	4405-3889 (95.4%)	U-Series age
Lake Zeribar (Van Zeist and Bottema 1977)	1415 (1410-1420)	Sediment	8100	160	9435-8596 (95.4%)	Core 63-J
	1675-1680	Plant macroremains	10,300	50	12,198-11,875 (67.2%) 12,462-12,348 (16.8%) 12,272-12,223 (5.6%) 12,330-12,298 (4.1%) 11,858-11,833 (1.7%)	
	1715 (1710-1720)	Sediment	11,480	160	13,612-13,093 (93.2%) 13,741-13,706 (1.3%) 13,657-13,630 (0.9%)	
	1745-1750	Plant macroremains	12,050	55	14,050-13,800 (95.4%)	
	1790-1800	Plant macroremains	12,750	110	15,601-14,868 (95.4%)	
	1895 (1890-1900)	Sediment	13,650	160	17,009-16,053 (95.4%)	
	2540 (2535-2545)	Sediment	22,000	500	27,294-25,326 (95.4%)	
Lalabad spring (Van Zeist 2008)	959-975	Peaty sediment	>40,000	-	>43,256-42,891 (95.4%)	

3.1.3 Geographical variability

In terms of geographic variability, seven pollen records are available for the Zagros region to investigate human- environmental interactions, namely Lake Zeribar, Lake Mirabad, Lake Maharlou, Hashilan wetland, Lake Parishan, Lalabad spring and Lake Nilofar record. All seven sites are located in the eastern part of the Zagros Mountains (present day Iran), while no pollen record is available for western Zagros (present day Iraq), except for two cave pollen records which will be discussed later, highlighting a spatial imbalance of available pollen records. There is an urgent need to rectify the spatial imbalance as the topography of the Zagros region is diverse and complex which in turn has a significant impact on local climate and environment (Simpson *et al.* 2015). Due to the orographic effect, the western side of the Zagros Mountains receives higher precipitation than the eastern side where Lake Zeribar, Lake Mirabad, Lake Maharlou, Hashilan wetland, Lake Parishan, Lalabad spring and Lake Nilofar are located which would impact vegetation composition. In turn it might also to some extent prevent reliable correlation between archaeological sites located in the western Zagros region and vegetation changes that are based on pollen records of lakes located on the eastern part of the Zagros Mountains.

The remaining pollen records, that are reviewed, are mainly from north western Iran or scattered around Iran at a long distance from the Zagros region, the region of interest of this research. Despite their distance, their vegetation trends will be outlined to emphasise differences and parallels in vegetation composition and highlight the diversity that is found across present-day Iran.

3.2 Upper Pleniglacial and Lateglacial (38,000-15,000 and 15,000-11,700 yrs BP)

Having established the shortcomings of the pollen studies that are reviewed, the remaining section will outline and discuss vegetation changes across Southwest Asia according to climatic periods to identify regional signals in the vegetation records and emphasise the need of more pollen studies for this diverse and complex region.

3.2.1 Zagros region (Lake Zeribar, Hashilan wetland, Shanidar Cave, and Zarzi cave)

Eastern Zagros (Lake Zeribar and Hashilan wetland)

The Pleniglacial period at Lake Zeribar (Van Zeist and Bottema 1977) was characterised by the absence of trees likely due to the cold and dry climatic conditions that prevented tree growth (Figure 3-3). While very low pollen values of *Quercus* (~1%) are present during this interval, it is suggested to indicate a regional signal rather than implying local presence. The Pleniglacial period, thus, was characterised by an open desert-steppe environment consisting primarily of Amaranthaceae, *Artemisia* and Apiaceae. The findings for Lake Zeribar are supported by the pollen records of Lalabad spring and Lake Nilofar, that are located in the Kermanshah valley halfway between Lake Zeribar and Lake Mirabad, indicating the presence of a dwarf-shrub steppe during the Pleniglacial (Van Zeist 2008: 92-96). Due to both of the pollen records (i.e. Lalabad spring and Lake Nilofar) being of low-resolution and the age-depth model only based on one and two radiocarbon dates along with other potential issues with the Nilofar record, the data will not be used in further discussion.

The transition into the Lateglacial period was marked by high pollen values of Amaranthaceae, indicating a local expansion along the lake and on the valley floor, while both *Artemisia* and Apiaceae declined. A major change in vegetation composition is visible in the record by the local presence of *Pistacia* (~0.6%), an underrepresented tree in pollen records, around Lake Zeribar after 15,000 yrs BP indicating a return of trees in the area. As in the Pleniglacial period, the low pollen values of *Quercus* are likely to be a regional signal. The increased aridity, as indicated by the high Amaranthaceae values, must have prevented *Quercus* from resettling in the Zeribar area whereas *Pistacia* would have preferred the dry climate.

This is consistent with the findings from Hashilan wetland which indicates the presence of a treeless landscape with steppic plants Amaranthaceae, *Artemisia* and Poaceae dominating during the Pleniglacial and Lateglacial period (Figure 3-3) (Safaeirad *et al.* 2014). Due to the low-resolution of the Hashilan wetland record and the record being published in Farsi language no further comments about vegetation cover can be made including identification of interstadial and stadial intervals during the Lateglacial.

The authors of the Lake Zeribar pollen study identified an interstadial period (~15,400-12,600 yrs BP) followed by a short stadial period (~12,600-12,000 yrs BP) that correspond to GI-1 and GS-1 identified in the Greenland ice core record. The increased Amaranthaceae and *Artemisia* pollen values between 12,600-12,000 yrs BP suggest increased climatic aridity, while lower *Artemisia* values for the interval 15,400-12,600 yrs BP suggest slightly less drier climate. The timing and duration, however, differ from the Greenland ice core record (GI-1= 14,692-12,896 yrs BP; GS-1= 12,896-11,703 yrs BP). This discrepancy could be potentially a result of the radiocarbon dating uncertainty and precision of the Lake Zeribar record. The dating precision also prevents identification of the interstadial GI-1 sub-events in the pollen record.

Western Zagros (Shanidar cave, Zarzi cave, and Palegawra cave)

Pollen analysis on the sediments of Shanidar cave and Zarzi cave has been carried out to reconstruct the local vegetation that was exploited by hunter-gatherers occupying the cave (Figure 3-2). Despite, caves potentially providing a good representation of the local vegetation cover, the pollen record for Shanidar cave suffers from a few issues including poor pollen preservation (i.e. external pollen exine has turned transparent) and sample contamination by incorporation of older pollen grains (tertiary age) into younger sediments possibly as a result of snow melting causing flooding of the cave that led to sediment mixing (Solecki and Leroi-Gourhan 1961: 734-5). Further challenges lie in the sampling resolution i.e. samples were taken too widely spaced in the stratigraphic sequence, thus providing only a broad environmental picture (Wahida 1981: 33). Furthermore, the 'B2 layer' sample which corresponds to the Epipalaeolithic period, consists of a small pollen count of only 84 grains.

Similarly, the pollen analysis performed on sediments of Zarzi cave suffers from a number of issues. Firstly, high percentages of Cichoriaceae have been recorded, which are highly resistant to erosion, and only one pollen grain of *Artemisia* was identified suggesting poor preservation. This suggests that the pollen record of Zarzi cave is biased and does not accurately represent the local vegetation of the Lateglacial period (Asouti *et al.* 2020: 83).

Based on the pollen record of Zarzi cave (*Figure 3-2*), trees were absent and only start to appear in the pollen record in very low percentages from ~0.92m onwards suggesting some climate amelioration that could be linked to the start of the Lateglacial (Wahida 1981: 34). *Quercus*, *Amygdalus* and *Pinus* are lower than 1%, while Cichoriaceae dominates the pollen assemblage (~90%). The pollen assemblage for Zarzi cave thus suggests a dry steppic environment comprised of Cichoriae, *Ephedra*, Rubiaceae, *Thalictrum* and Chenopodiaceae, and low, sporadic presence of trees in the surrounding area (Wahida 1981: 34). This local picture of the vegetation cover agrees with pollen records of the eastern Zagros (see Van Zeist and Bottema 1977; Djamali *et al.* 2008) which suggests that the Late Pleniglacial was too dry and cold for the expansion of trees and that they only start to appear in low percentage during the Lateglacial period.

Pollen analysis of the sediment sample 'B2 layer' from Shanidar cave (*Figure 3-2*), in contrast to Zarzi cave, indicates a higher tree percentage with *Pinus* (2%), *Juniperus* (~4%), *Quercus* (~6%) and *Pistacia* (~1%) present. The composition of herbs also varies from that of Zarzi cave with higher percentage of Poaceae (~28%) and *Centaurea* (~28%), while less than 10% of Cichoriae is present. However, based on the above highlighted issues with both pollen records, they only provide a glimpse of what the environment would have looked like during the Pleniglacial and Lateglacial period – a dry

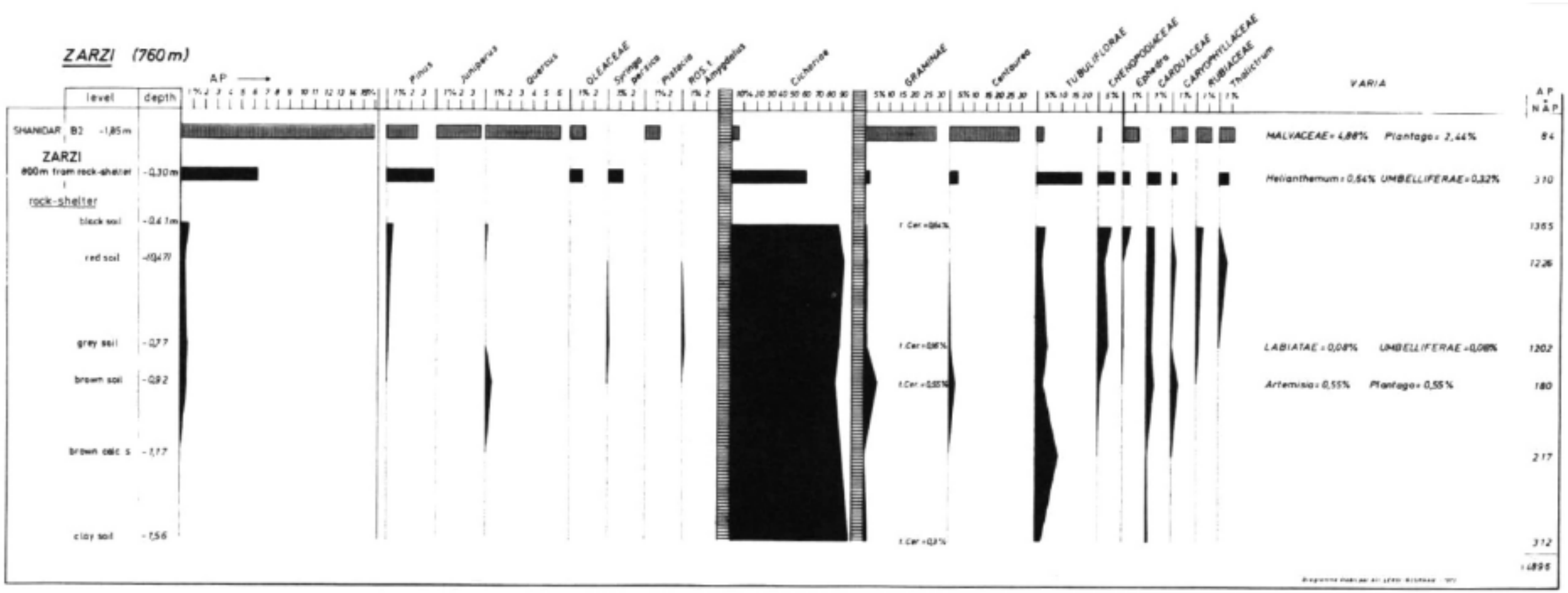

Figure 3-2: Pollen record of Zarzi cave and 'B2 layer' of Shanidar cave (Wahida 1981: 35)

steppe environment with low, sporadic presence of trees. This highlights the lack of reliable and high-resolution pollen records for this region that needs to be addressed to further our understanding on human-environmental relationships.

A recent macrobotanical study, based on 58 samples, carried out at the site of Palegawra (Asouti *et al.* 2020) sheds further light onto the environmental conditions indicating that climatic conditions during the Late Pleniglacial and Lateglacial provided suitable conditions for an open *Amygdalus-Quercus* woodland to start forming, with *Pistacia* also present near the cave, and grasses and legumes dominating the ground flora.

Asouti *et al.* (2020: 82) argue that because no charcoal of Chenopodiaceae and *Artemisia*, which are wood fuel sources, have been found, it suggests that both taxa were not routinely gathered as fuel by the hunter-gathers occupying the cave and that they were likely not the dominant components of the nearby vegetation cover (regional signal). Rather it seems like *Amygdalus* and *Quercus* were mostly used for fuel alongside Salicaceae shrubs.

Importantly, the presence of trees during the Late Pleniglacial suggests the existence of grassland and woodland refugia in the northwest Zagros piedmont zone, and clear differences in the Late Pleniglacial vegetation composition of northwest Zagros piedmont zone and the Zeribar Intramountain basin. Based on the assemblage, dry and cool climatic conditions were prevailing throughout the Late Pleniglacial and Lateglacial periods (Asouti *et al.* 2020: 82). The charcoal study at Palegawra, despite some charcoal preservation issues, provides a more reliable reconstruction of the vegetation cover than the pollen records of Zarzi and Shanidar cave. To evaluate the findings of this charcoal study new pollen records are needed for the western Zagros region.

3.2.2 **Northwest Iran (Lake Urmia and Lake Neor)**

The vegetation during the Pleniglacial and Lateglacial period at Lake Urmia (*Figure 3-3*) was represented by an *Artemisia* and Poaceae steppe with a high concentration of Amaranthaceae, with *Hippophaë rhamnoides* becoming an increasing part of the vegetation composition. Trees such as *Juniperus* and *Quercus* were rare in the landscape and restricted to refugia (Bottema 1986; Djamali *et al.* 2008) indicating, as in the Lake Zeribar record, an open landscape with a dry steppe vegetation. Similarly, the landscape around Lake Neor (Aubert *et al.* 2017) was characterised during the Lateglacial by a scarcity of trees and open landscape dominated by steppic plants such as Amaranthaceae, *Artemisia* and *Cousinia* (Figure 3-3). The Lake Neor study, although low in resolution, indicates a dry interval between 15,000-12,500 yrs BP, followed by an increase in *Cousinia*, a taxon adapted to cold and to high levels of continentality, and Artemisia between ~12,500-11,600 yrs BP. The presence of *Cousinia* could suggest cold and dry regional climate and thus could potentially reflect GS-1 which has also been identified at Lake Zeribar between 12,600-12,000 yrs BP. However, the resolution of the Lake Neor record is low hindering detailed vegetation reconstruction and thus identification of precise vegetation changes that could be reflective of the interstadial and stadial period.

3.2.3 Caspian Sea

The main vegetation composition around the Caspian basin was similar to the Zagros region and north western Iran and consisted of an open landscape dominated mainly by Amaranthaceae along with *Artemisia* and Poaceae and small numbers of *Quercus* trees (3%), based on pollen values (*Figure 3-3*) (Leroy *et al.* 2014). The authors identified a very dry interval between ~12,400-11,400 yrs BP that could be reflecting GS-1 interval which here is represented by high Amaranthaceae pollen values along with *Artemisia* and Poaceae. An emerging trend from the reviewed pollen records of Southwest Asia indicates that the GS-1 period in Southwest Asia potentially started earlier, at ~12,500 yrs BP, in contrast to the Greenland ice record.

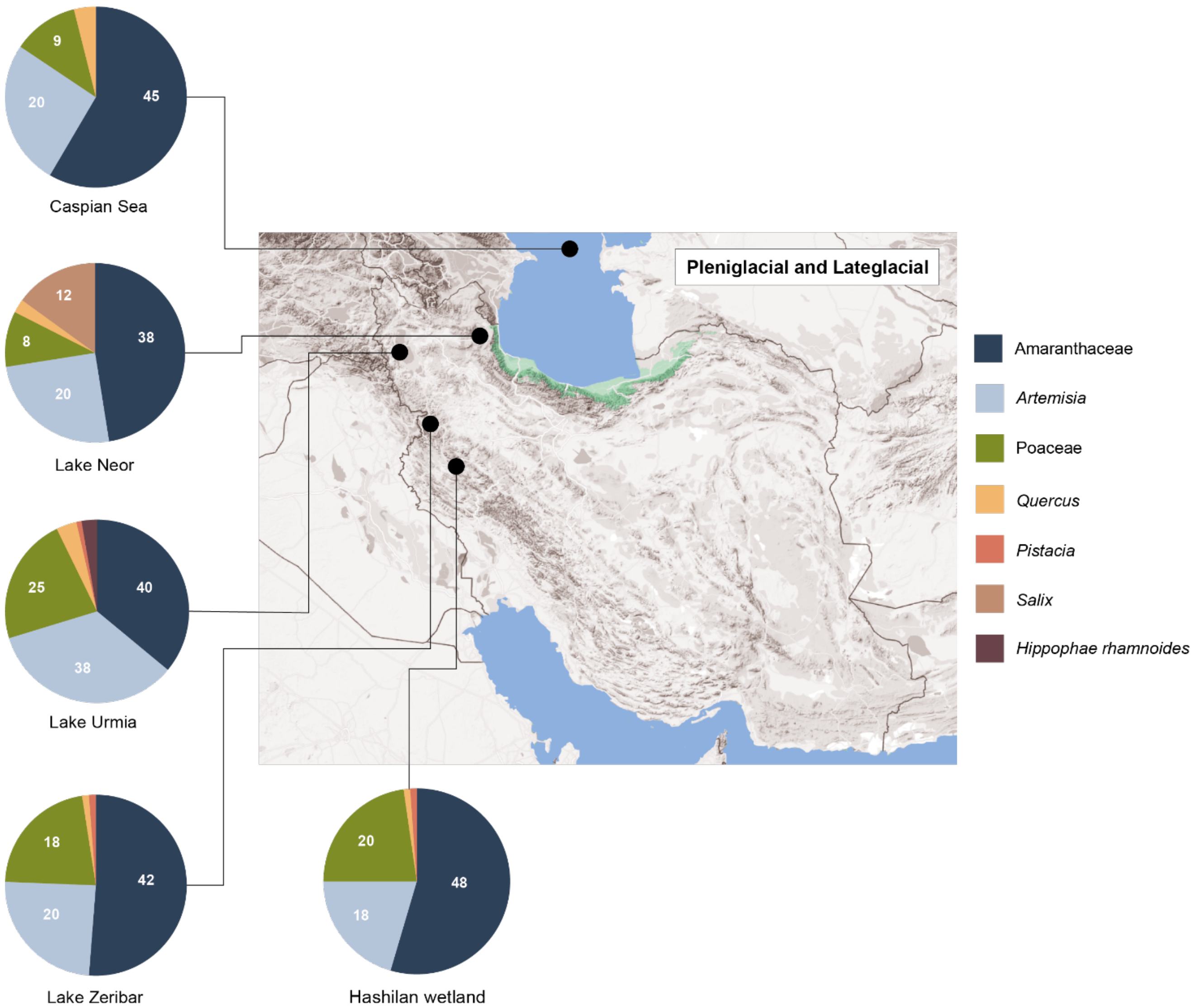

Figure 3-3: Pie charts representing approximate pollen percentages of selected key taxa for each site for the Pleniglacial and Lateglacial period. Hence, the chart segments do not total 100%. The percentage values have been taken from the original pollen data. Percentages below five have not been labelled on the pie charts (author's own - base map: Google maps).

3.3 Early Holocene (11,700- 8200 yrs BP)

3.3.1 Zagros region (Lake Zeribar, Lake Mirabad and Hashilan wetland)

The onset of the Early Holocene period at Lake Zeribar (Van Zeist and Bottema 1977) is marked by a decrease in both Amaranthaceae and *Artemisia*, and an increase in Poaceae pollen values, indicating an expansion of grasses (Figure 3-5). The Early Holocene experienced a slow expansion of trees including *Pistacia*, *Quercus* as well as *Acer* which were low in numbers based on their pollen percentages. Due to the poor pollen dispersal of *Pistacia*, it is argued that it was more common than *Quercus* and thus was likely the dominant arboreal component of the open upland *Pistacia* - *Quercus* forest steppe vegetation.

Similar to Lake Zeribar, at Hashilan wetland Amaranthaceae and *Artemisia* declined while Poaceae increased (Figure 3-5). The vegetation cover at Hashilan wetland changed from a steppic environment to a *Pistacia*-*Quercus* savanna with riparian plane trees and drought tolerant shrubs of *Amygdalus* starting to appear (Safaeirad *et al.* 2014). Vegetation changes for the early part (~205-180cm) of the Early Holocene is not available in the pollen record for Hashilan wetland due to poor pollen preservation possibly due to oxidation related to desiccation of the wetland. Nonetheless, it agrees with the findings of Lake Zeribar. However, it also emphasises the need for more higher-resolution pollen studies focussing on this time interval to shed more light onto the vegetation changes in times of changing climate and human lifestyle.

Lake Mirabad (Van Zeist and Bottema 1977) experienced similar vegetation composition changes except for Amaranthaceae which in comparison to Lake Zeribar remained high and most likely represented the predominant herb in the steppic vegetation during the Early Holocene (Figure 3-5). The high presence of Amaranthaceae at Lake Mirabad is argued to have been a result of drier climatic conditions (Van Zeist and Bottema 1977; Stevens *et al.* 2006).

The onset of the Early Holocene in the Lake Zeribar record, according to the authors, starts at ~12,000 yrs BP which is about 300 years earlier than what the Greenland ice core record indicates (~11,700 cal yrs BP). The offset of 300 years could be due to the poor precision of the age-depth model for Lake Zeribar. Thus, our understanding of the timing of the transition from the Lateglacial Stadial into the Early Holocene has some uncertainties. It can be argued that the transition from stadial into the Holocene already started before 11,700 yrs BP at Zeribar with Amaranthaceae and *Artemisia* pollen values declining and arboreal values beginning to increase in the regional pollen rain from ~12,500 yrs BP onwards. Thus, it can be argued that the environment started to change from ~12,500 yrs BP onwards but locally it took another 500 years to change and be visible in the pollen record (Figure

3-4). Given the uncertainties in the chronostratigraphy, however, it is difficult to be certain about timing of transition and change.

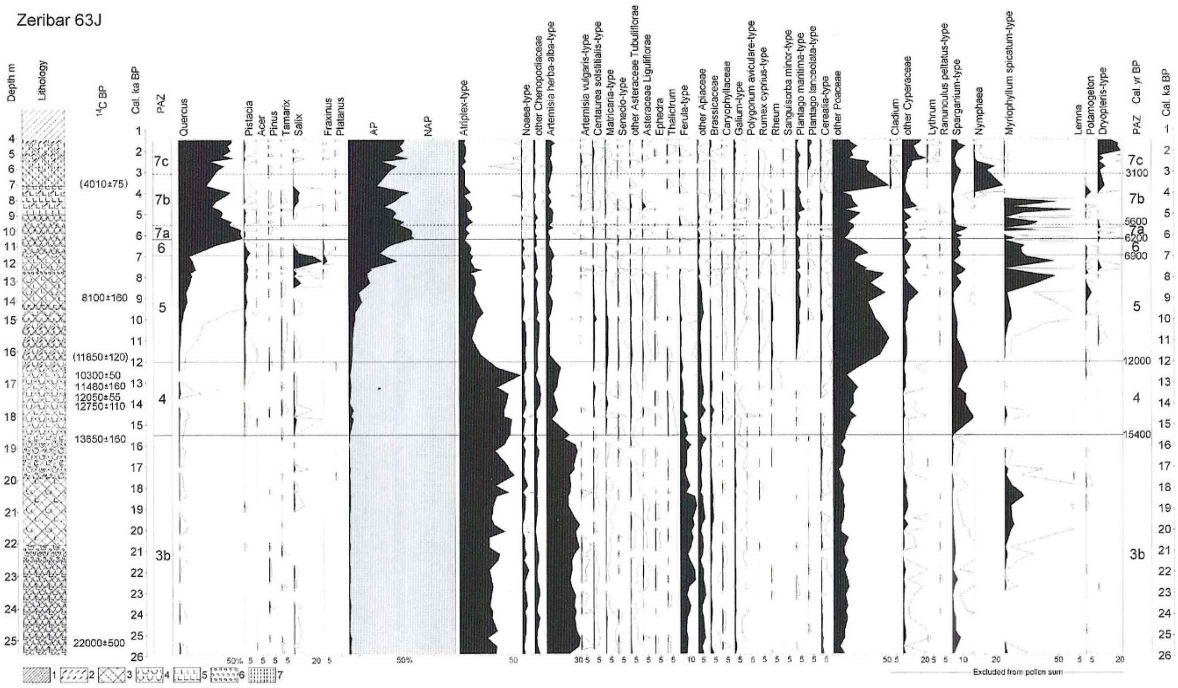

Figure 3-4: Pollen diagram of Lake Zeribar – core 63J (Van Zeist 2008: 77)

3.3.2 Northwest Iran (Lake Urmia and Lake Neor)

At Lake Urmia the transition into the Early Holocene period was marked by a succession of *Hippophaë*, *Ephedra*, *Betula*, *Pistacia* and finally *Juniperus* and *Quercus* (Djamali *et al.* 2008). The *Artemisia* steppe was replaced by a grass steppe with Amaranthaceae declining (Figure 3-5). *Quercus* trees were slowly increasing, probably growing at a distance from the lake. On the other hand, *Pistacia* was present locally and was part of the forest-steppe that was established between 9000-8000 yrs BP (Bottema 1986).

At Lake Neor, the onset of deciduous woodland expansion started at ~8700 yrs BP with pioneer trees *Betula* and *Juniper,* which started to increase from ~9700 yrs BP onwards, gradually becoming replaced by *Quercus* and *Fagus* (Figure 3-5) (Aubert *et al.* 2017).

3.3.3 Northeast Iran (Gomishan area) and the Caspian Sea

Unlike in the Zagros region and northwest of Iran, the vegetation composition in the Gomishan area (north-eastern foothill of the Alborz Mountains), between ~10,700-9500 yrs BP consisted of Amaranthaceae (>60%) along with other herbaceous taxa including *Artemisia* and Poaceae, indicating a semi-desert environment with some forested area consisting mainly of *Quercus* (Figure 3-5). From ~9400 yrs BP *Quercus* started to increase along with *Carpinus betulus* reaching its maximum at ~8200 yrs BP. This reflects a vegetation optimum and an extension of the forest belt. Unlike in other parts of Iran and south-eastern Turkey, the *Quercus* woodland expansion at Gomishan occurred in the Early Holocene, with a delay of about a millennium, possibly due to region located close to glacial refugia of trees (Leroy *et al.* 2013).

The onset of the Holocene at ~11,400 yrs BP around the Caspian basin was also marked by an open landscape dominated by shrubs mainly Amaranthaceae and *Artemisia* and some scattered trees (Figure 3-5) (Leroy *et al.* 2014). Unlike at Lake Zeribar for example, the onset of the Early Holocene occurs about 600 years later in the Caspian Sea record while in the Greenland ice core record it started at ~11,700 yrs BP.

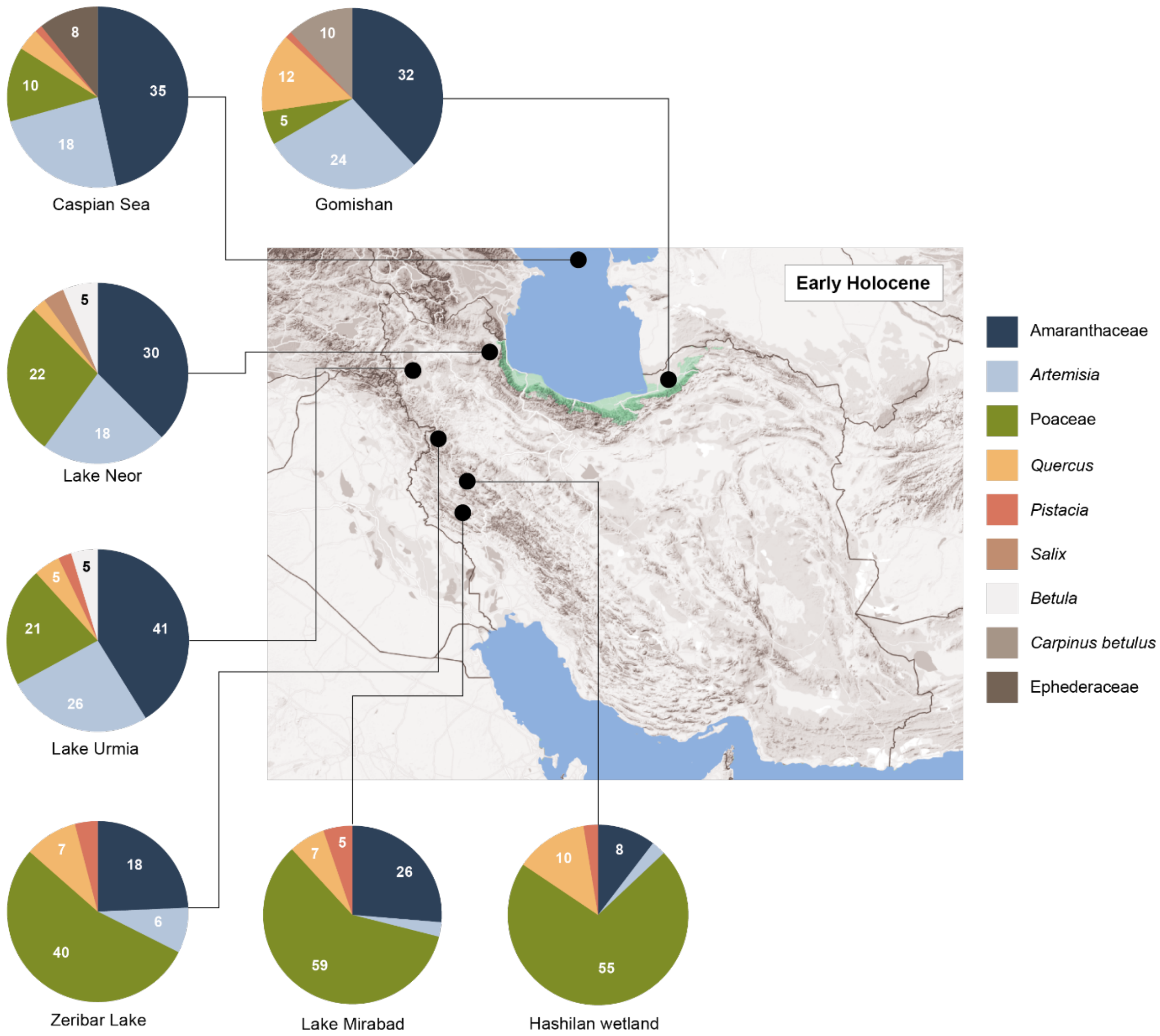

Figure 3-5: Pie charts representing approximate *pollen percentages of selected* key *taxa* for each site for the Early Holocene period. Hence, the chart segments do not total 100%. *The percentage values have been taken from the original pollen data. Percentages below five have not been labelled on the pie charts (author's own - base map: Google maps)*

3.4 Middle Holocene (8200- 4200 yrs BP)

3.4.1 Zagros region (Lake Zeribar, Lake Mirabad, Lake Maharlou and Hashilan wetland)

During the Middle Holocene period the area around Lake Zeribar experienced a decrease in the herbaceous taxa including Amaranthaceae, Poaceae and *Artemisia* while *Quercus* started to increase at ~6900 yrs BP from ~10% to 60% (pollen percentages) (Figure 3-6). This led to the replacement of the forest-steppe by the Zagros *Quercus* woodland. Within ~700 years at approximately 6200 yrs BP *Quercus* woodland reached its densest form in the Zagros region with relatively low herbaceous taxa present (Van Zeist 1967; Van Zeist and Bottema 1977). Likewise, the Hashilan wetland and Lake Mirabad record indicates the establishment of Quercus woodland at approximately the same time in the region (Safaeirad *et al.* 2014). Based on the pollen values, there is a good correspondence between the Holocene vegetation development at Hashilan, Zeribar and Mirabad (Figure 3-6). Besides *Quercus*, which was the predominant tree after 6900 yrs BP at Lake Mirabad, *Pistacia*, *Acer*, *Pyrus syriaca*, *Daphne*, *Amygdalus*, *Crataegus* and *Prunus* were also growing along *Quercus* in the woodland. It is argued that the low *Pistacia* and *Acer* pollen values are no actual measure of the actual proportions of them in the vegetation. From ~5400 yrs BP onwards, however, *Quercus* started to decline gradually according to the Lake Zeribar record (Van Zeist and Bottema 1977), suggesting a slightly more open woodland between ~5400-3100 yrs BP.

At Lake Maharlou (Djamali *et al.* 2009b), which is located in the south east of the Zagros, the vegetation composition slightly differed. *Pistacia* and *Quercus* started to increase from ~5500 yrs BP onwards with *Quercus* woodland starting to expand in the south-east later than at Lake Zeribar, possibly due to the more southerly position of Lake Maharlou in comparison to Lake Zeribar (Figure 3-6). Between 5500-5100 yrs BP, *Pistacia–Amygdalus* shrubland expanded after which it started to decline, while *Quercus* woodland remained high.

3.4.2 Northwest Iran (Lake Urmia and Lake Neor)

The Middle Holocene at Lake Urmia was also characterised by a gradual increase in trees with the replacement of the *Pistacia–Quercus* forest-steppe by *Quercus* steppe woodland starting from ~8000 yrs BP (midpoint calibrated : 8885 cal. yrs BP) onwards (Figure 3-6) (Bottema 1986).

At Lake Neor, although *Quercus* gradually replaced the pioneer trees it remained low in pollen values (~9%) (Figure 3-6) (Aubert *et al.* 2017). No pollen data is available for Lake Neor for the time interval ~7500-6700 yrs BP due to sampling strategy. From ~6600 yrs BP, the vegetation composition does not significantly vary with *Quercus* pollen values, unlike at other sites, remaining low (~9%) throughout the Middle Holocene (Alinezhad *et al.* 2021).

3.4.3 Northeast Iran (Gorgan Plain) and Caspian Sea

At Kongor Lake, which is located in the Gorgan Plain in northeast of Iran, the environment consisted of an open-steppe landscape for the last 6000 years with a riparian forest including *Salix* and *Tamarix* growing at the lake shore. Similarly, the Caspian basin was mainly characterised by a semi open steppe with some tree cover (Figure 3-6). It is not until ~4500 yrs BP that woodland expansion occurred in this region (Leroy *et al.* 2014).

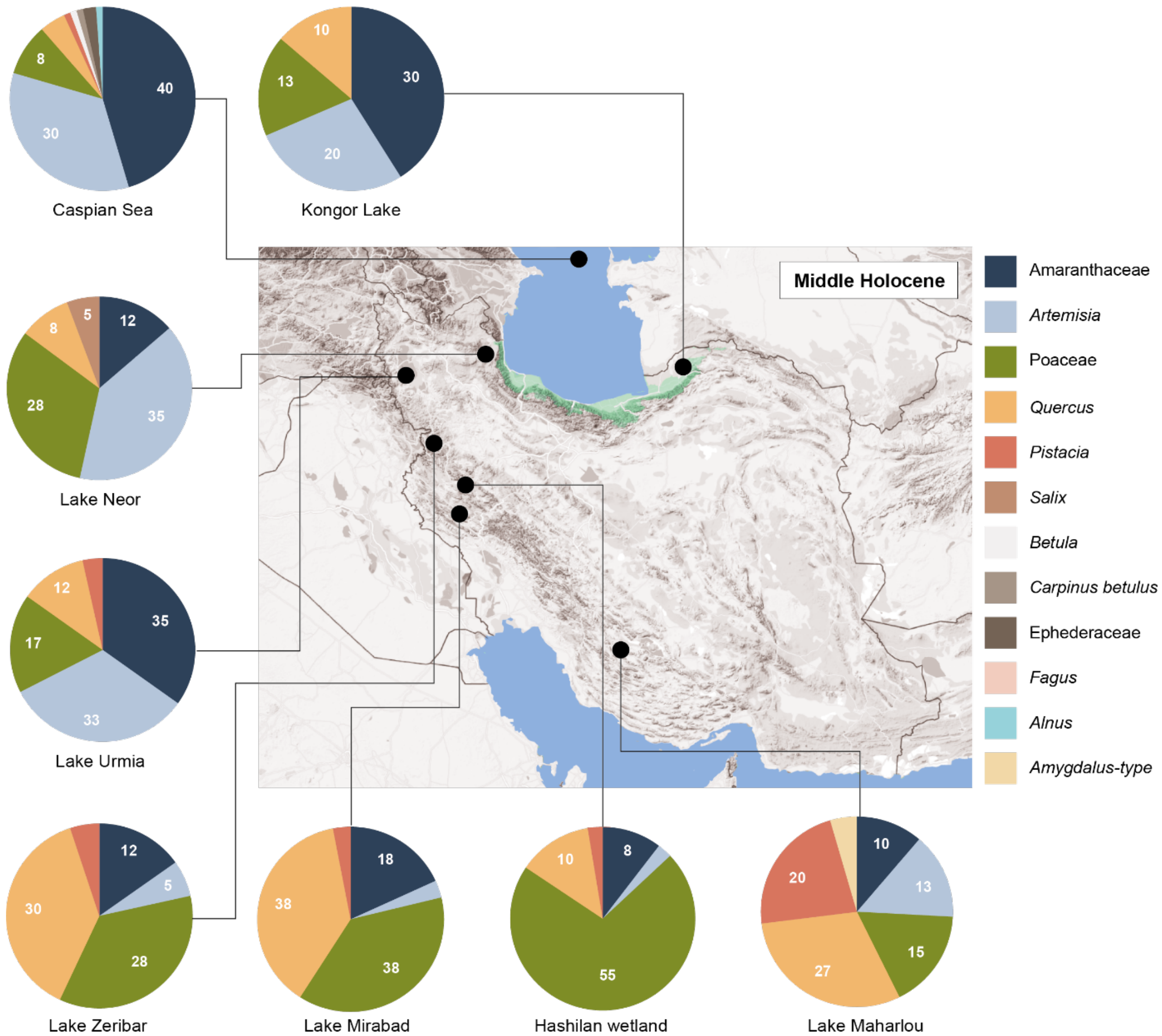

Figure 3-6: Pie charts representing approximate *pollen percentages of selected* key *taxa* for each site for the Middle Holocene period. Hence, the chart segments do not total 100%. *The percentage values have been taken from the original pollen data. Percentages below five have not been labelled on the pie charts (author's own - base map: Google maps)*

3.5 Late Holocene (4200 yrs BP onwards)

3.5.1 Zagros region (Lake Zeribar, Lake Mirabad, Lake Maharlou and Lake Parishan)

At both Lake Zeribar and Mirabad, *Quercus* woodland slightly decreased over time (Figure 3-7). The woodland cover at Lake Zeribar was dominated mainly by *Quercus* with *Pistacia*, *Pyrus*, *Acer*, *Lonicera*, *Daphne*, and *Crataegus* also being part of the woodland composition. The expansion of the herbaceous taxa, mainly of Poaceae suggests that the woodland vegetation was rather open with a decline in *Quercus* occurring from ~2700 yrs BP onwards. Increased human activity is visible in the landscape from ~3200 yrs BP onwards in the form of increased grazing activity and tree cultivation (Van Zeist and Bottema 1977). At Lake Mirabad extensive grazing is suggested by the presence of *Plantago lanceolata-type*. The presence of reduced *Quercus* could have been caused by part of the woodland being cleared for agricultural practices, thinning out of the woodland stands, or grazing activities having an impact on the natural regeneration of the woodland leading to a reduction in trees. As in the case at Lake Zeribar an expansion of Poaceae has been noted at Lake Mirabad with an increase in Compositae taxa near the lake suggesting drying of the lake at ~2700 yrs BP (Van Zeist and Bottema 1977). This coincides with the Assyrian Megadrought recorded in the Kuna Ba cave record (northern Iraq) at 2650 yrs BP, as well as a general trend towards drier climatic conditions noted across the region from ~3000 yrs BP onwards (see climate history). Thus, it is possible that both a change in climate towards drier climatic conditions, and human activity were responsible to some extent to the *Quercus* woodland reduction.

Unlike at Lake Zeribar and Lake Mirabad, cultivated trees including *Juglans*, *Olea*, *Vitis* and *Platanus* started to appear at Lake Maharlou from ~4300 yrs BP which coincides with the beginning of the Bronze Age civilisation in the region (Figure 3-7). *Pistacia–Amygdalus* scrub along with *Quercus brantii* was the dominant vegetation of the basin. The *Quercus* woodland remained relatively stable until ~2800 yrs BP (Saeidi Ghavi Andam *et al.* 2021) after which it started to decline along with the *Pistacia–Amygdalus* scrub, while a peak in the herbaceous taxa in particular in *Artemisia* and Amaranthaceae occurred (Djamali *et al.* 2009b; Saeidi Ghavi Andam *et al.* 2021). As can be seen it becomes increasingly difficult to differentiate between human vs climate impact on the vegetation from 3000 yrs BP onwards.

A decline in *Quercus* also occurred at Lake Parishan at ~ 2500 yrs BP which is argued to have been caused by human activity based on the significance increase in cultivated trees including *Olea* and *Platanus*, as well as *Cerealia*-type and *Plantago lanceolata*-type (Figure 3-7). This arboriculture expansion and a slight increase in *Sporormiella* dung spore occurred during the start of the Persian

Achaemenid Empire and, thus, suggests human impact on the environment (Jones *et al.* 2015; Djamali *et al.* 2016).

3.5.2 Northwest Iran (Lake Urmia, Lake Almalou, Arasbaran, Ganli-Gol wetland and Lake Neor)

A decline in *Quercus* steppe woodland also occurred at Lake Urmia (Figure 3-7) (Bottema 1986). *Artemisia* dominated the landscape surrounding Lake Urmia with other herbs such as Asteroideae, Cichorioideae, Caryophyllaceae, Brassicaceae and *Ephedra* present to a smaller extent. This suggests an almost treeless steppe vegetation from ~2500 yrs BP onwards. The presence of *Vitis* and *Juglans*, indicative of arboriculture, occurred at ~2500 yrs BP and 2100 yrs BP, respectively (Talebi *et al.* 2016). Lake Almalou (Djamali *et al.* 2009a), which is located east of Lake Urmia, also witnessed tree cultivation and significant agricultural activities starting in the Iron Age (~3300 yrs BP) and during the Achaemenid Empire (~2450–2220 yrs BP). The landscape at Lake Almalou, was also dominated mainly by *Quercus*, *Artemisia* and Amaranthaceae which did not change significantly over the last 3700 years (Figure 3-7). The presence of herbs such as *Plantago lanceolata-type*, *Centaurea solstitialis*, *Polygonum aviculare* as well as *Vitis* between 2350-2000 yrs BP at Ganli- Gol wetland also suggests increased agricultural activity during the latter half of the Late Holocene (Figure 3-7) (Zavvar *et al.* 2017).

The environment around Ganli-Gol wetland (Zavvar *et al.* 2017) and in the Kalan district in Arasbaran area (Ramezani *et al.* 2021) both indicate a dry steppe vegetation comprised mainly of Amaranthaceae after 3000 yrs BP. A slight increase of *Quercus* and *Artemisia* in the Ganli-Gol wetland record suggests slightly less drier conditions until 2650 yrs BP, followed by an increase in Amaranthaceae and decline in *Quercus* and *Artemisia.*

At Lake Neor the Late Holocene is characterised by fluctuating pollen values of Amaranthaceae and *Artemisia* with the first half experiencing an increase in Amaranthaceae and the second half from 3000 yrs BP onwards witnessing a significant increase in *Artemisia* pollen values and decline of Amaranthaceae. The Lake Neor pollen record, thus, suggests that an Irano- Turanian steppe vegetation prevailed in the highlands of northwestern Iran (Figure 3-7).

3.5.3 Southeast Iran (Konar Sandal)

Near Konar Sandal (Jiroft valley) (Gurjazkaite *et al.* 2018), the Late Holocene period was characterised by high aridity between ~4000-3800 yrs BP based on the high concentration of *Artemisia* and Amaranthaceae, and decline of Poaceae (Figure 3-7). From ~2800 yrs BP onwards climate amelioration followed with an expansion of Poaceae dominated grassland and decline of desert shrubs, leading to a shift from open xerophytic scrub woodland to open and degraded scrublands. The presence of herbs including *Cerealia-type*, *Centaurea solstitialis-type* (a weed indicative of cereals), Plantaginaceae and *Polygonum aviculare* indicates nearby human activity after 3800 yrs BP.

3.5.4 Northeast Iran (Gomishan area) and Caspian Sea

The environment at Gomishan area from ~3500 yrs BP was replaced by a steppe environment dominated by *Artemisia* with the coastal strip vegetated by an alder carr (Leroy *et al.* 2013). Similarly, the Caspian basin was dominated by a steppe vegetation environment with more visible tree abundance and diversity (Figure 3-7) (Leroy *et al.* 2014). Evidence for agricultural activities, including arboriculture, started to appear from ~2700 yrs BP onwards (Shumilovskikh *et al.* 2016a).

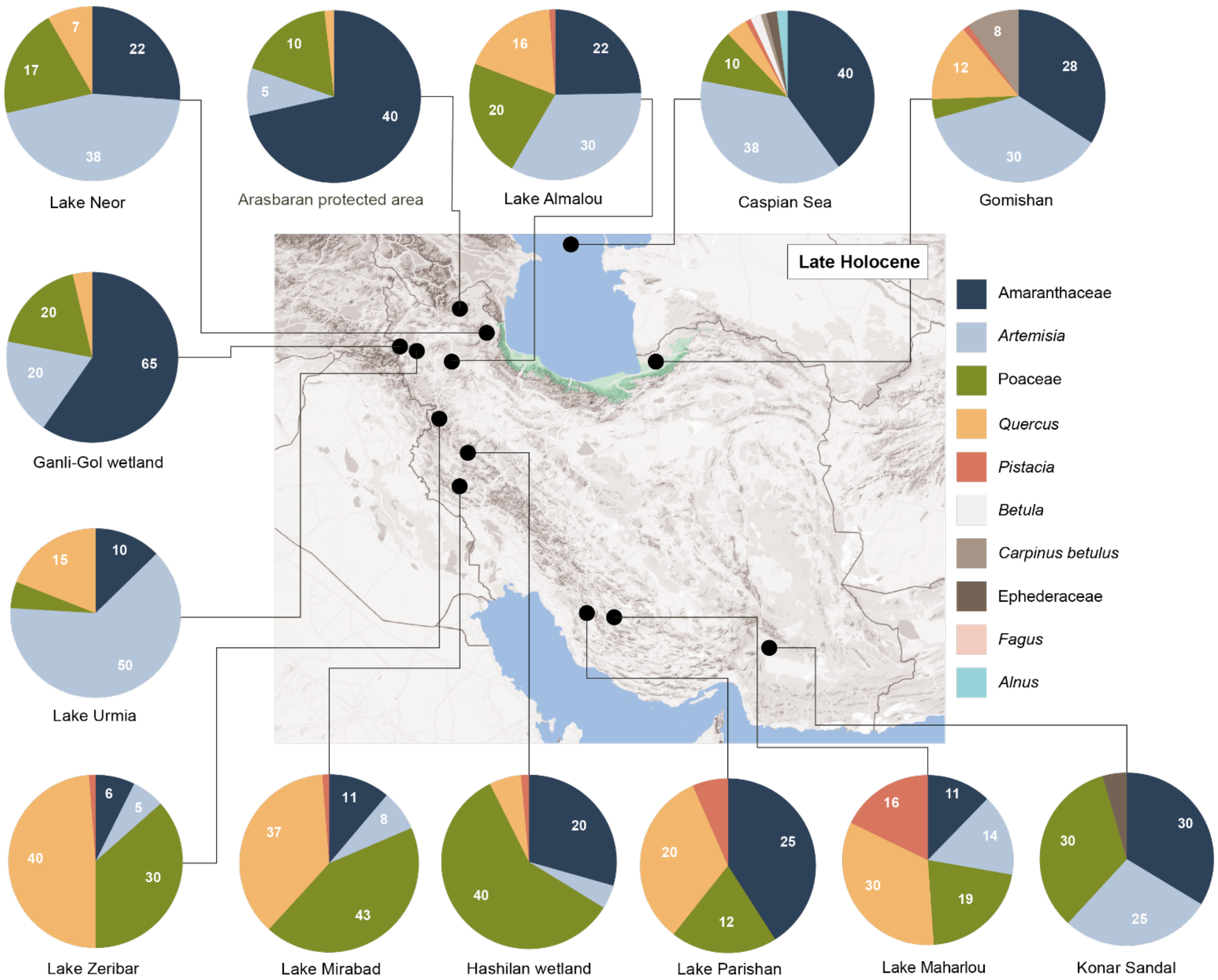

Figure 3-7: Pie charts representing approximate *pollen percentages of selected* key *taxa* for each site for the Late Holocene period. Hence, the chart segments do not total 100%. *percentage values have been taken from the original pollen data. Percentages below five have not been labelled on the pie charts (author's own)*

3.6 Critical evaluation

3.6.1 Regional vegetation history

To summarise, the regional vegetation of the Pleniglacial and Lateglacial was represented by an open landscape with a dry steppe vegetation dominated by Amaranthaceae and *Artemisia* with no tree cover during the Pleniglacial and a few scattered trees during the Lateglacial. In contrast, the western Zagros had trees already present from the Pleniglacial period. As mentioned earlier, the Lake Urmia, Hashilan wetland and Lake Neor records provide a general overview of vegetational changes over time as their resolution is low which prevents identification of vegetation changes that could reflect interstadial and stadial periods within the Lateglacial.

The transition from Lateglacial to Early Holocene on a regional scale was signified by a change from dry steppic environment composed mainly of Amaranthaceae and *Artemisia*, to an expansion of Poaceae and slow expansion of trees including *Pistacia* and *Quercus*. However, the rate at which the change occurred varied across the sites with the magnitude of change differing as well. The available pollen records covering this important transition are, however, of low resolution and low in numbers for each region which emphasises the need for new high-resolution pollen records that would provide detailed reconstruction of the environment that is not only significant from a climatic and vegetational view of point but also archaeologically. For example, although there are eight pollen records available for the eastern Zagros region, only two of them cover the Lateglacial - Holocene transition, namely Lake Zeribar, Hashilan wetland (excluding Lake Nilofar and Lalabad spring) But even they have limitations associated with them. The Lake Zeribar pollen record, for instance, suffers from chronology issues, making it difficult to correlate it with the archaeological record. This highlights the need for high-resolution palaeoenvironmental records with robust age-depth models to better understand past environmental changes and their relationship with human activity and climate change. There are local site specific variations in vegetation composition but overall, the general trend outlined above is observed at majority of the sites.

Although there is evidence of cereal cultivation, in the form of seeds, for the Early Holocene period at ~9800 yrs BP (Riehl *et al.* 2013; Riehl 2016), the pollen data is not as straightforward. Although *Cerealia-type* pollen grains are important indicator of agricultural activities, they could also be produced by their progenitor wild grass species and by naturally-occurring grass species (Djamali *et al.* 2009b). At for instance, Lake Zeribar (Van Zeist and Bottema 1977) and Lake Urmia (Djamali *et al.* 2008), *Cerealia-type* pollen grains have been identified in the Pleniglacial and at the end of the Penultimate glacial period (~ 200,000–140,000 yr BP), respectively (Djamali *et al.* 2009b). Therefore, the presence of *Cerealia- type* in the Near East is used with caution to infer definite human activity, unless other secondary anthropogenic disturbance indicators are present such as *Plantago lanceolata-type*, *Centaurea solstitialis-type*, *Rumex acetosa-type* and *Sanguisorba minor-type* (Djamali *et al.* 2009a; see Djamali *et al.* 2009b). *Centaurea solstitialis-type* pollen specifically has been noted to be produced by plants associated with cereal cultivation in the Near Eastern and circum-Mediterranean regions (Bottema and Woldring 1990).

The Middle Holocene mainly witnessed woodland formation although again the rate and magnitude varied across Southwest Asia with certain areas not experiencing a *Quercus* woodland expansion. The delay in *Quercus* woodland will be discussed in detail towards the end of the section (see 'Quercus woodland delay'). The Late Holocene experienced a decline in woodland with majority of the sites witnessing a transition into a dry steppic environment. Human impact on the environment is clearly visible in the pollen records of Southwest Asia from ~3000 yrs BP onwards, especially in the form of cultivated trees and increased grazing.

A number of reasons could explain why pre-Bronze Age environmental human activities are difficult to identify in the pollen records with certainty, including: palynological indicators of cultural activity are naturally present in Southwest Asia e.g. Cerealia-type; the magnitude of Neolithic and Chalcolithic agricultural activity was not strong enough to be visible in pollen records; overrepresentation of wind-pollinated taxa and underrepresentation of most insect-pollinated and autogamous taxa in the pollen records. Thus pollen assemblages can be biased due to differential production, dispersal and preservation processes, making it difficult to detect human impact on the environment and reconstruct the past environment accurately (Roberts 2002: 1002-1003). To overcome this problem and allow better interpretation of a pollen record, a study of the modern pollen precipitation in relation to the present-day plant cover can prove to be beneficial (Van Zeist 2008).

By outlining and discussing the pollen records, it becomes clear that in order to fully reconstruct and understand changes over time across Southwest Asia, more high-resolution pollen studies are required with reliable chronologies extending back to at least the Pleniglacial period.

3.6.2 *Quercus* woodland delay

Unlike in the Mediterranean region, *Quercus* woodland spread slower in the Irano-Anatolian region despite improvements in climate (see 'climate history') occurring roughly at the same time in both regions (Asouti and Kabukcu 2014). It is the Middle Holocene period that witnessed the expansion of woodland but it is not until ~6000 yrs BP when *Quercus* pollen reach modern values of 40% (Stevens *et al.* 2001:749). The replacement of the forest steppe by *Quercus* woodland occurred at Lake Zeribar and Mirabad at ~6200. yrs BP, at Lake Maharlou at ~5500 yrs BP, and in the Gomishan area at ~8100 yrs BP. The early expansion in the Gomishan area is due to its proximity to an area of glacial refugia of trees (Leroy *et al.* 2013).

A number of hypotheses have been put forward to explain this time lag including:

<u>*Climatic factors*</u>

Based on pollen data of this region (see 'climate history' for other proxies) climate changed from cold and dry in the Lateglacial to warmer but still relatively dry conditions during the Early Holocene. This climatic dryness is argued to have been responsible for the slow woodland expansion in this part of the Zagros Mountains (Van Zeist and Bottema 1991; Van Zeist and Bottema 1977). This would have impacted *Quercus* specifically, as it is sensitive to dry summer periods which constrains pollen release and thus acorn productivity, thereby inhibiting seedling germination (Johnson *et al.* 2002). The gradual increase of *Quercus* woodland has been interpreted as a slow increase in effective moisture over time, yet the presence of *Pistacia* in some records indicates moderately arid conditions. Further evidence for a dry Early Holocene climate that could have delayed woodland expansion has been provided by high peaks of Amaranthaceae seeds until ~6800-5750 yrs BP (6886-6791, and 5660-5843 yrs BP), suggesting several episodes of low water level at Lake Zeribar (Wasylikowa 2005).

According to Stevens *et al.* (2001), based on oxygen isotope and pollen data of Lake Zeribar, a change in precipitation seasonality from winter-dominated precipitation regime to winter and spring dominated precipitation regime in the Middle Holocene allowed *Quercus* woodland to expand. Djamali *et al.* (2010a) argue that the strengthening of the Indian Summer Monsoon and the north-westward shift of ITCZ during the Early Holocene period could have reduced spring rainfall and extended dry summer months, causing the formation of a typical continental Mediterranean- type climate. These climatic conditions would have led to *Pistacia-Amygdalus* shrubs expansion, hindering *Quercus* expansion. The weakening of the Indian Summer Monsoon and shift of the ITCZ southwards at ~6300 yrs BP, which coincides with the Holocene climatic optimum (~6900-5600 yrs BP) could have led to increased spring precipitation, allowing maximum *Quercus* woodland expansion.

The argument that the Zagros region was drier than other regions such as the Levant (e.g. Bar-Matthews *et al.* 1998:203) is based on the scarcity of trees at the beginning of the Holocene in the Lake Zeribar record (van Zeist and Bottema 1977) and a reduction in spring rains (Stevens *et al.* 2001). However, pollen records do not always represent the former vegetation accurately due to differential production, dispersal and preservation processes (Roberts 2002). This is especially the case with *Pistacia* which is a low pollen grain producer and thus is under-represented palynologically which is why Roberts (2002:1006) points out that if underrepresentation of *Pistacia* is taken into account then the Early Holocene period had a denser tree cover than what can be inferred from the pollen records in the western Zagros region. Other factors that could have led to the delayed woodland expansion include slow postglacial migration of *Quercus* from tree refugia (Van Zeist and Bottema 1977), competition, locations of primary and secondary refugia, existence of suitable edaphic conditions and physical geographical barriers (Van Zeist and Bottema 1991; Jones *et al.* 2019: 14).

Human activity

According to Roberts (2002), the delay of woodland expansion during the Holocene was a result of fire activities carried out by Neolithic communities rather than fire caused by climate aridity, as argued by Roberts and Wright Jr (1993). Roberts (2002:1005) points out that for example at Lake Van isotopic and geochemical analysis indicate greatest effective moisture during the Early-Mid Holocene (8000-4000 varve yrs BP) (see Lemcke and Sturm 1997) yet *Quercus* pollen did not reach maximal Holocene values until after 6000 varve yrs BP (see Van Zeist and Woldring 1978; Wick *et al.* 2003). Thus, according to Roberts (2002), there must be another factor that might have caused the delay in *Quercus* expansion despite the high effective moisture. Human activity such as controlled burning was used by Neolithic communities to manipulate natural vegetation and maintain landscapes for cultivation of crops, along with other activities such as woodcutting for fuel and timber and to increase grazing grounds for animals. These anthropogenic activities led to a delayed *Quercus* expansion along with other factors such as climate seasonality, vegetation fires caused by aridity and migratory lags (due to the distance from late Pleistocene arboreal refugia).

At Lake Zeribar, however, macroscopic charred herbaceous plant fragments were already present from the mid-Pleniglacial period onwards with no increase in concentration during the Neolithic period (Wasylikowa 2005), meaning that either at this particular site *Quercus* woodland was delayed due to some other factor, or potentially a number of different factors controlled the expansion of *Quercus* woodland in this area. Wasylikowa (2005:734) does point out that no archaeological sites were discovered within the vicinity of Lake Zeribar (Marivan plain) and thus more studies are needed to identify the role of Neolithic people in woodland burning. However, archaeological survey carried out by Mohammadifar and Motarjem (2008) in the Marivan alluvial plain has unearthed two Neolithic sites, Hama Avin Tepe and Hama Morad Tepe, located within close proximity to Lake Zeribar, highlighting the importance of carrying out systematic archaeological survey as otherwise it can impact interpretations.

Unlike Roberts (2002), who argues that fire played an important role in the delayed *Quercus* expansion, the high-resolution anthracological study carried out in the Konya plain by Asouti and

Kabukcu (2014), concluded that at the beginning of the Holocene, *Quercus* grew in low density and was not used much by Neolithic communities. Over time the use of *Quercus* wood increased while other woodland taxa such as Rosaceae and Maloideae (savanna grasslands) declined. This shift was a result of Neolithic activities including the selective removal of competing woody vegetation such as Rosaceaee and Maloideae trees and shrubs, and grazing of grasslands by sheep and other ruminants, allowing more ground moisture to be available for *Quercus* trees. Other Neolithic economic activities included the management of *Quercus* trees for fuel and leafy fodder production, using woodland management practices such as coppicing, pollarding and shredding. These economic activities would have provided *Quercus* with the competitive advantage over grasses and other woody plants and allow its gradual expansion. Thus, it can be argued that Neolithic communities did not impact on the delayed spread of *Quercus* woodland which is seen as the 'natural' climax vegetation type of the Irano-Anatolian region that has been constrained and destroyed by human activity. Rather *Quercus* woodland represents an anthropogenic vegetation type that spread as a result of Neolithic landscape practices (Asouti and Kabukcu 2014).

It is still an ongoing debate as to what caused the delay in woodland expansion in Southwest Asia. High-resolution multi-proxy records, focussing on this time interval, are needed to shed further light onto this debate.

Table 3-2: Summary of pollen records in Iran divided into regions by colour

Site Name	Region	Period covered	Sampling resolution	Multi-proxy study?	Radiocarbon dating	Reference
Lake Zeribar	Zagros region	40,000 years	Pollen: 10cm interval (2-5cm^3)	Yes (Plant macrofossil, diatoms, molluscs, stable isotope analysis)	Seven radiocarbon dates for core 63J (three plant remain dates and four bulk sediments)	VanZeist and Bottema 1977
Lake Mirabad	Zagros region		Pollen: 20cm interval	Yes (Ostracod, loss-on-ignition, mineralogy, oxygen-isotopic composition of authigenic calcite, and trace-element composition of ostracodes)	Two bulk dates (not used due to hard-water effect) Three charcoal dates	VanZeist and Bottema 1977
Lake Maharlou	Zagros region	5700 years	Pollen: Almost every 2cm interval	No	Four bulk dates	Djamali *et al.* 2009
Lake Maharlou	Zagros region	4000 years	Pollen: 10cm interval with high-resolution sub-sampling of 2cm between 2500–2280 cal BP	Yes (npp, microcharcoal)	One plant fragment date One sample containing charcoal, coleoptera, seed	Saeidi Ghavi Andam *et al.* 2020
Hashilan wetland (Farsi language)	Zagros region	39,500-present	Pollen: 5-20cm interval	No	Three dates (unsure about dated material)	Safaierad *et al.* 2014
Lake Parishan	Zagros region	4000 years	Pollen: 4-8cm	Yes (Ostracod, diatom isotope analyses, charcoal, magnetic susceptibility and loss on Ignition	Three bulk date One U–Th date	Jones *et al.* 2015
Lalabad spring	Zagros region		Pleniglacial only?	No	One peat bulk date	Van Zeist 2008
Lake Nilofar	Zagros region		Pleniglacial and Lateglacial ?	No	Two radiocarbon date	Van Zeist 2008

Wezmeh Cave	Zagros region	Late Pleistocene and Late Holocene	Pollen analysis performed on four coprolite samples	No	Three dates performed on three coprolites	Djamali *et al.* 2011 (add reference to biblio)
Lake Urmia	Northwest Iran	13,200 years BP (uncalibrated)	Not mentioned	No	Two dates (pellets)	Bottema 1986 (add reference to biblio)
Lake Urmia	Northwest Iran	200,000 years	Pollen: every 1m	No	Two bulk dates	Djamali *et al.*2008
Lake Urmia	Northwest Iran	2550 years	Pollen: 4-10cm interval	Yes (Magnetic susceptibility, organic matter and calcium carbonate content)	Three bulk organic sediments	Talebi *et al.* 2016
Lake Neor	Northwest Iran	15,500–7500 years	Pollen: 10cm interval	Yes (Chironomids, magnetic susceptibility and hydrogen isotope composition of precipitation)	Five bulk dates	Aubert *et al.* 2017
Ganli-Gol wetland (Farsi language)	Northwest Iran	3000-1600 years	?	No	One bulk date one plant material date? One wood date?	Zavvar *et al.* 2017
Lake Almalou	Northwest Iran	3700 years	Not provided	Yes (npp, preliminary chironomid analysis)	Eight bulk dates	Djamali *et al.* 2009
Arasbaran protected area	Northwest Iran	2980 years	Pollen: 10cm interval	No	Three bulk dates	Ramezani *et al.* 2020
Lake Neor	Northwest Iran	7000 years	Pollen: 20cm interval	Yes (AVAATECH XRF core scanning, total organic content)	Five bulk samples	Alinezhad *et al.* 2021 (add reference to biblio)
Konar Sandal	Southeast Iran	4000 years	Pollen: 1-10cm	Yes (microcharcoal, XRF, magnetic susceptibility)	Eight bulk samples	Gurjazkaite *et al.* 2018
Kongor Lake (Gorgan Plain)	Northeast Iran	6000 years	Pollen: 2-8cm	Yes: npp, botanical macroremains, molluscs and ostracods, insects,	Five bulk dates Two charred grasses dates One macroremains (seed) date	Shumilovskikh *et al.* 2016

				charcoal, ITRAX and magnetism.		
Gomishan area	Northeast Iran	11,000-1500	?	Yes (npp, dinoflagellate cysts	10 radiocarbon dates obtained from shells	Leroy *et al.* 2013
Caspian Sea	-	12,400-2400 years	?	Yes (magnetic susceptibility, dinoflagellate cysts)	Six radiocarbon dates obtained from ostracod shells	Leroy *et al.* 2014
Shanidar Cave (B2 layer)	Zagros region (Iraq)	Pleistocene	One sample (B2 layer)	No	One radiocarbon date	Solecki and Leroi-Gourhan 1961
Zarzi Cave	Zagros region (Iraq)	Pleistocene	Seven pollen samples	No	?	Wahida 1981

4 Research context: Archaeological context

This section is chronologically arranged and divided into the following archaeological periods: Epipalaeolithic, Neolithic, Chalcolithic, Bronze Age and Iron Age. In order to articulate and contextualise the current study effectively, it is important to provide a critical overview of the related cultural periods and the archaeology that characterise the Zagros region, outlining the main developments and events followed by a more in-depth discussion of the key issues related to human-environmental interactions.

4.1 The Epipalaeolithic (20,000-12,000 BP)

4.1.1 Characterisation of the Epipalaeolithic period

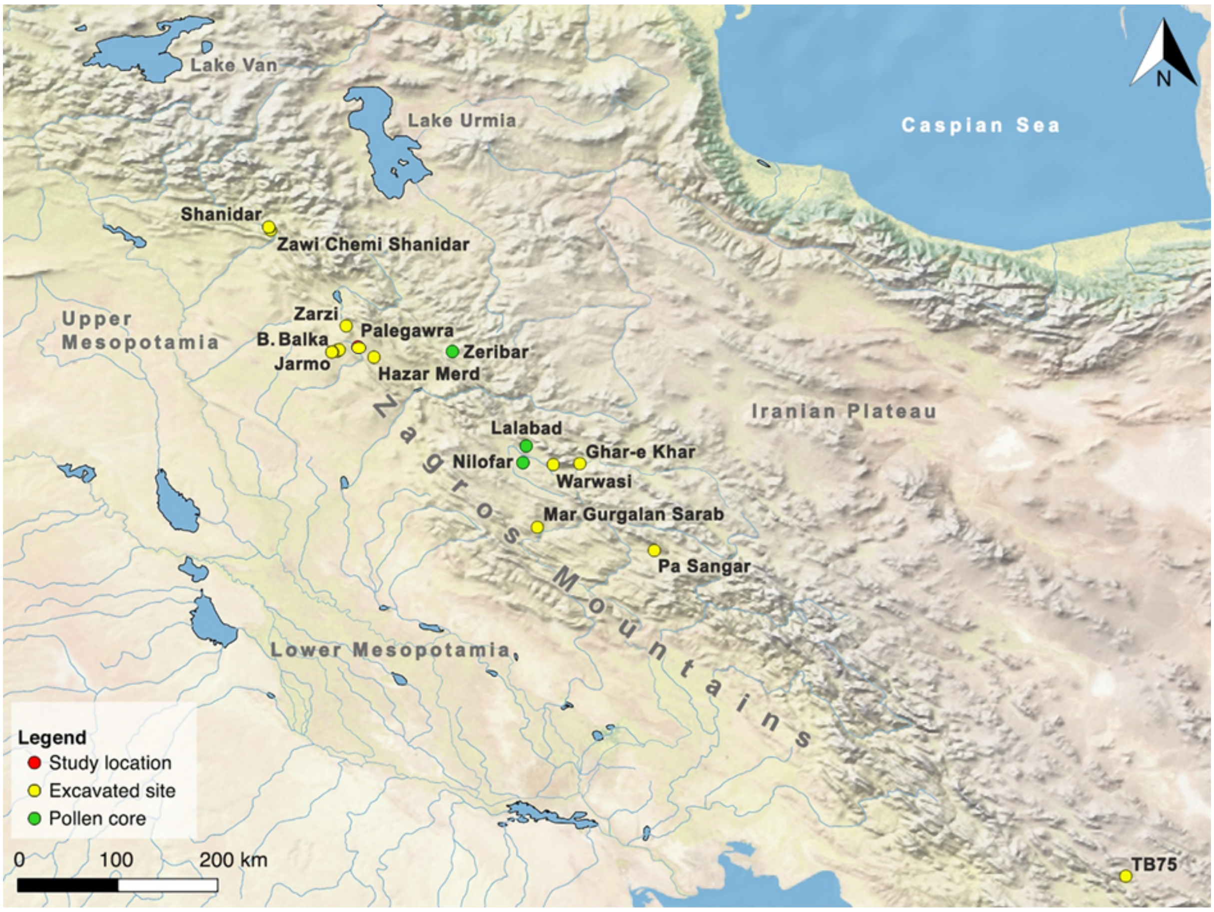

Figure 4-1: Map showing the locations of the Epipalaeolithic sites mentioned in the text (Asouti et al. 2020: 2)

The Epipalaeolithic period of the Zagros region (Table 4-1; Figure 4-1), also known as the 'Zarzian' culture (after the excavations at Zarzi rock shelter in Iraqi Kurdistan), is characterised by mobile groups of hunter-gatherers residing partly in rock shelters and cave sites that served as either temporary camps or longer-term base camps (Table 4-2Table 4-1) (Olszewski 2012; Jayez *et al.* 2019). According to the archaeological evidence, the lithic industry of this time is characterised by a change in use from non-geometric to increasingly geometric microliths, as well as thumbnail scrapers, microburins and ground stone tools, among others. The discovery of ground stone technologies intended for plant processing activities provides evidence for human interaction with the physical environment (see Palegawra; Asouti *et al.* 2020). Olszewski (2012: 7), however, points out that only a few ground stone tools have been recovered from archaeological sites possibly suggesting that plants only formed a small part of the Epipalaeolithic diet. Ground stone tools were also used for pigment preparation at the time. As few preserved charred plant remains have been found at some sites it has been suggested that plants did not form a part of the diet of Epipalaeolithic communities. Asouti *et al.* (2020: 63), however, argue that it is unclear whether this is a result of a poor archaeobotanical sampling method or whether it reflects an actual low contribution of plants in their diet.

Besides plants, a variety of different food was consumed by Epipalaeolithic communities including gazelle, onager, wild boar, hare, shellfish, crustaceans, land snails, and fish, characterised by considerable regional variability in food procurement strategies (Braidwood and Howe 1960; Wahida 1981; Olszewski 2012). At the cave site of Zarzi, for example, the recovered faunal assemblage is characterised mostly by gazelle and sheep/goat remains (Garrod 1930; Wahida 1999; Olszewski 2012), while onager remains dominate the faunal assemblage of the site of Palegawra (Turnbull and Reed 1974; Asouti *et al.* 2020). In contrast, due to the limited amount of faunal remains that have been recovered from the cave site of Warsawi, the site may have functioned as a lookout point and overnight camp site for tracking and hunting onagers (Turnbull 1975: 146). The presence of snail shells at archaeological sites including Shanidar cave, Zarzi and Warwasi indicates the consumption and incorporation of land snails into the Epipalaeolithic diet (Reed 1962; Solecki 1963: 191; Wahida 1981), a trend that continues to increase into the Neolithic period (Braidwood *et al.* 1961; Shillito *et al.* 2013). At the Neolithic site of Bestansur, for instance, evidence indicates the gathering, preparing and eating of molluscs (*Helix salomonica*) at the site, although they were likely used as a snack rather than representing a meal (Iversen 2020: 308).

Table 4-1 Cultural periods of the Palaeolithic

Cultural period	Time period (BP)
Lower Palaeolithic	500,000-200,000
Middle Palaeolithic	200,00-40,000
Upper Palaeolithic	45,000-20,000
Epipalaeolithic	20,000-12,000

There is also evidence for long-distance movement or trade and exchange in materials which is provided by the discovery of marine shells used for personal ornamentation purposes, probably originating from the Persian Gulf (Olszewski 2012). Furthermore, evidence of an emerging trans-regional exchange network between the Epipalaeolithic groups living in the northwestern Zagros region and the eastern Anatolia is provided by the identification of two pieces of obsidian material from Zarzi and one single piece of obsidian (retouched bladelet) from Palegawra, which have originated from Nemrut Dağ (Figure 4-2) (Renfrew *et al.* 1966; Barge *et al.* 2018; Frahm and Tryon 2018; Asouti *et al.* 2020: 87).

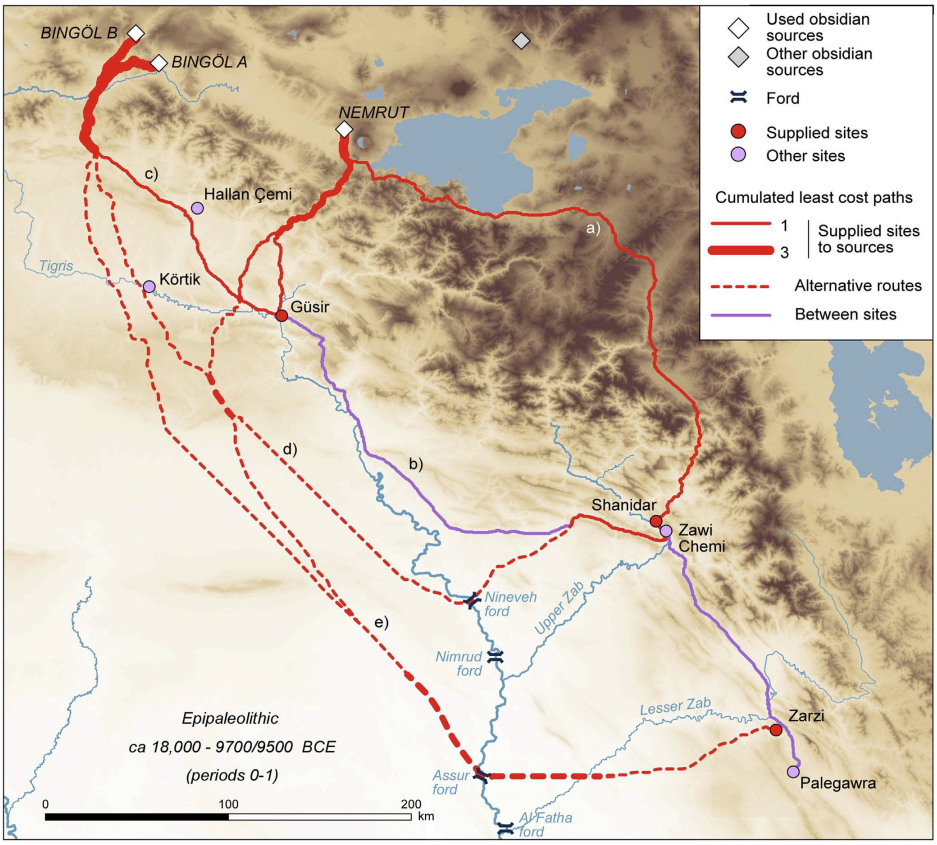

Figure 4-2: Map showing potential pathway used for trans-regional exchange of obsidian by Epipalaeolithic communities of northwest Zagros (Barge et al. 2018: 301)

Table 4-2 Summary of the Epipalaeolithic period

	Iraqi Zagros	Iranian Zagros
Diet	Variety of food including gazelle and sheep/goat, onager, red deer, bird and tortoise, river crab, fish, and land snail (Helix salomonica)	
Tools	Lithic industry includes increasing use of geometric microliths (including scalenes, lunates, trapezoids and rectangles), ground stone tools, simple bone tools, microburin tools, blades, and scrapers	
Occupation type	Rock shelter, cave sites and open sites with evidence of occupational continuity at Iranian Zagros sites	
Main archaeological sites	Shanidar Cave (Solecki 1955; Solecki 1963) Zarzi Cave (Garrod 1930; Wahida 1981) Palegawra Cave (Braidwood and Howe 1960)	Ghar-i Khar (Young and Smith 1966) Warwasi Cave (Braidwood and Howe 1960; Turnbull 1975) Pa Sangar (Hole and Flannery 1968)

4.1.2 Broad Spectrum Revolution

As mentioned, the Epipalaeolithic period is mainly characterised by a change in material culture and broadening of the human diet (Olszewski 2012). The latter development has been termed as 'Broad Spectrum Revolution' (BSR) in which subsistence diversification raised the carrying capacity of the environment leading to human migration and ultimately helped to pave the way for plant and animal domestication and the emergence of agriculture. According to Flannery (1969), the BSR is set within a demographic density model where environmental deterioration and demographic pressure (i.e. human population growth) human migration from optimal resource zones to marginal areas. This shift pushed hunter-gatherer communities to settle down and, ultimately, led to resource diversification and intensification.

Flannery's hypothesis has been, however, challenged over the years. For example, there is no evidence in the Greenland ice core record (Rasmussen *et al.* 2014) that would indicate a significant deterioration in the climatic regime of the time that might have led to resource depletion or environmental deterioration. The situation does not change until the start of GS-1, which is characterised by a return to cold and dry climatic conditions (Lateglacial Stadial) at ~12,900 yrs BP. On the contrary, the start of GI-1 (~14,700-12,900 yrs BP) brought about a warmer and wetter climate (Lateglacial Interstadial) that would have enabled Epipalaeolithic communities to thrive and flourish.

Stiner *et al.* (2000) argue that indeed a diversification of diet occurred in the Epipalaeolithic, as argued by Flannery's broad spectrum- revolution hypothesis, however, to investigate human diet breadth in further detail it is more effective to rank small game according to work of capture rather than use taxonomic-diversity approach. Stiner and her colleagues (Stiner *et al.* 2000: 42; Stiner and Munro 2002) criticise Flannery's approach of measuring and detecting subsistence diversity, which is based on Linnean taxonomic categories that involves measuring taxonomic richness (counting species and genera) and taxonomic evenness (proportionality in abundance). Adopting this approach obscures the identification of behavioural change of foragers (Stiner *et al.* 2000: 42). Furthermore, this taxonomic-diversity approach only takes into account prey body size (large vs small game), and ignores physical and behavioural properties of prey animals including differences in small game prey handling costs and the long-term implications of their heavy exploitation (Stiner *et al.* 2000: 42; Stiner and Munro 2002).

Using late Pleistocene assemblages from the Italian peninsula, the southern Levant regions, and the coastal areas of south-central Turkey, the work carried out by Stiner and her colleagues (Stiner *et al.* 1999; Stiner *et al.* 2000; Stiner and Munro 2002), suggests that although taxonomic diversity was constant over time, a change within the composition of the small game occurred. A shift from slow moving game (high-rank prey) to fast moving game which requires more effort and is more difficult (higher energetic costs) was noted. This shift, according to Stiner *et al.* (Stiner *et al.* 1999; Stiner *et al.* 2000), could only be related to demographically driven resource pressure. Thus, changes in the small game composition could be used as an indicator of demographic expansion (Stiner *et al.* 1999: 193). Stiner's approach to study human diet diversity is based upon the optimal foraging theory (OFT), which takes into account cost–benefit considerations to explain forager behaviour based upon efficiency (maximise the net rate of return (of energy or nutrient) per unit foraging time) (Smith *et al.* 1983: 626-8). According to Stiner, diet diversification to include lower ranking resources such as shellfish, snails and seeds, that lowered foraging efficiency, took place as a response to a decline in higher ranked resources. As the number of preferred preys declined due to increasing human population, low ranking preys were added and became part of the subsistence. Therefore, according to Stiner, diversification and intensification of subsistence only occurs within the context of resource depression, caused by either demographic pressure or environmental deterioration (Stiner and Munro 2002). Smith *et al.* (1983: 640), however, argue that although OFT help to improve our understanding of human foraging behaviour, it does not consider other factors or variables that might explain the complex mechanisms and culture dynamics associated with human foraging behaviour. For instance, it has been pointed out that no independent data is presented by Stiner and her colleagues, including settlement survey data, which would allow to determine if human population levels increased during the Epipalaeolithic period (Stiner *et al.* 2000: 60). Furthermore, Stiner's model does not take into account the impact of large game on small game (Stiner *et al.* 2000: 62), ignores 'human dietary preferences' as a factor that could have led to the composition of the small game assemblage, and the possibility of gathering and collecting some small game for acquiring raw materials for producing items such as clothing for example (Stiner *et al.* 2000: 65). Stiner's model also struggles to explain why snail consumption, which is regarded as a low-ranking prey, continued into the Neolithic, a period of climate amelioration in which resources became more readily available.

Zeder (2012) also questions Stiner's work because it forces or pressures human groups to adapt to the declining availability of optimal resources through the adoption of sedentism and the expansion in the diversification of their subsistence. Zeder (2012: 252) argues that OFT and Stiner's model do not take into account alternative perspectives that might explain the complexities associated with foraging behaviour such as gender roles or how foraging decisions can be detected in the archaeological assemblage. To explain BSR, Zeder (2012) proposes niche construction theory (NCT) which argues that diversification and intensification occurred in resource rich areas (rather than in depleted marginal environments), in which humans used their knowledge and skills to take advantage of their local environment and utilise their surrounding resources to their benefit. For example at the site of Hallan Çemi (south-eastern Turkey), the recovered faunal assemblage is dominated by large game, and high-ranking prey dominate the small game composition (see Starkovich and Stiner 2009). This faunal assemblage contradicts OFT with the diversity in subsistence suggesting that the people took advantage of their surrounding rich resources at the start of the Holocene (Zeder 2012: 247). Zeder (2012: 250), therefore, argues that the diversification of the human diet noticed at Epipalaeolithic sites might be explained by an increasing resource abundance that coincided with climatic amelioration, rather than increase in population size that led to resource depression. The archaeobotanical assemblage of Palegawra also disagrees with Stiner's model. The Palegawra dataset indicates the exploitation of a variety of plant resources found within close proximity of the cave and included resources from both the dryland and wetland areas (Asouti *et al.* 2020: 82). During the Late Pleniglacial and Lateglacial periods, hunter-gatherers had access to a variety of plant resources including nuts, wild grasses as well as Cyperaceae and *Phragmites* (wetland plant resources).

Zeder argues that the primary factor that encouraged increased engagement in niche construction activities was driven by a combination of social obligations and sustaining past generations' efforts of modifying their environment to provide sustenance. This highlights the active and adaptive role of humans in shaping and utilising their local environments to their advantage to construct diverse and sustainable subsistence economies that can support an increasing population size (Zeder 2012: 259). An abundance in resources enabled human groups to take advantage of their environment to settle down in locations with economic value that could facilitate and sustain communities in year-round settlements. A reduction in mobility and subsequent increase in population size in such resource rich areas likely had an impact on the capacity levels of the environment which might have encouraged human groups to engage in niche construction activities to manipulate the environment and enhance productivity by investing into new strategies and technologies, although Zeder argues that this was likely a secondary factor why communities tried to enhance productivity (Zeder 2012: 258-9).

To shed more light onto the factors that led to the diversification of the human diet in Southwest Asia, and the Zagros region in particular, the archaeological record for the Epipalaeolithic period needs to be reliable and complete. The higher the number of archaeological sites investigated, the more data there is to investigate the link between the human diet and the environment. Although Stiner's work helps to understand the economic organisation or system as well as subsistence strategies (changes in dietary choice) established during the Epipaleolithic period, it might not be applicable to every site or geographic region. New faunal and archaeobotanical data are improving our understanding about human-environmental interactions. For example, although climate changed from cold and dry conditions to warmer conditions at the onset of the Lateglacial, no change has been noted in the lithic technologies, habitation patterns and subsistence strategies at the site of Palegawra (Asouti *et al.* 2020: 88). This illustrates the point that not every site can be explained by one model.

It is important to increase our understanding and knowledge about the physical environments ancient hunter-gatherer communities lived in. Pollen records of high-resolution are needed for the Zagros region to reconstruct their environment which in turn will help to identify whether hunter-gatherer societies of the Zagros region lived in resource-rich or resource depleted environments. The spatial distribution of pollen records in the Zagros region is currently low with only five pollen data sets available for the eastern Zagros region and no non-terrestrial pollen records for the western Zagros region. The only pollen data for the western Zagros region is derived from two terrestrial pollen records – Shanidar cave and Zarzi cave (Solecki and Leroi-Gourhan 1961; Wahida 1981). Additionally, there is macrobotanical data available from Palegawra cave (Asouti *et al.* 2020).

4.1.3 Site chronology and continuity issues

Another ongoing debate revolves around the chronology of the Epipalaeolithic period and its relationship with the earlier Upper Palaeolithic and later Neolithic period. As already mentioned, there are uncertainties in the chronology of this time (Braidwood 1983: 541), which have created some interpretative problems about the occupation sequence or history of a site and its possible connection to climate change. For instance, based on two radiocarbon dates and differences observed in the material culture for Shanidar cave, it was hypothesised that the site was abandoned between 15,000 -12,000 yrs BP (Solecki 1963). The timing of the abandonment of the site coincides with the start of climate amelioration (Lateglacial Interstadial), which was followed by a return to colder climatic conditions with the onset of the Lateglacial Stadial. The research carried out by Wahida (1999), however, seems to contradict the observations made on the material culture and instead suggests cultural continuity at Shanidar. Furthermore, the two radiocarbon dates obtained Shanidar cave have been declared as unreliable by Asouti *et al.* (2020: 8) because of major standard errors among other factors. This new data emphasises the need to obtain reliable radiocarbon dates from Epipalaeolithic sites that can provide a better interpretation on the duration of the occupation of a site including any potential correlations that may exist between the climatic and archaeological records. At the site of Palegawra, for example, the lowest amount of macrocharcoal remains has been retrieved, which in combination with the faunal data, suggests a low frequency in fire-related subsistence activities that occurred between ~17,700-16,600 yrs BP. According to the age-depth model, a possible gap in the occupation history occurred between 16,600-14,200 yrs BP, which could potentially explain the noted low frequency in fire-related subsistence activities. Asouti *et al.* (2020: 76) point out that this possible gap in occupation history partly overlaps with the arid Heinrich 1 event that has been identified at Lake Zeribar between 16,000-15,300 yrs BP. Therefore, it is possible that climate had to some degree an impact on the hunter-gatherers that were using Palegawra cave. This emphasises the importance of having a reliable and secure chronology, which is critical for the accurate interpretation of the occupation history of a site and the identification of both local and regional events.

Despite colder climatic conditions that prevailed during the Pleniglacial period, there is some evidence to argue for occupation continuity throughout the Epipalaeolithic period (Young and Smith 1966; Biglari and Shidrang 2016: 46; Shidrang 2018: 152) which supports the resilience model of human communities to climate change and the associated changes in the environment. However, it is important to stress at this point that human responses to climate change probably varied across the Zagros region depending on site location, site altitude, available resources, and cultural traditions and preferences.

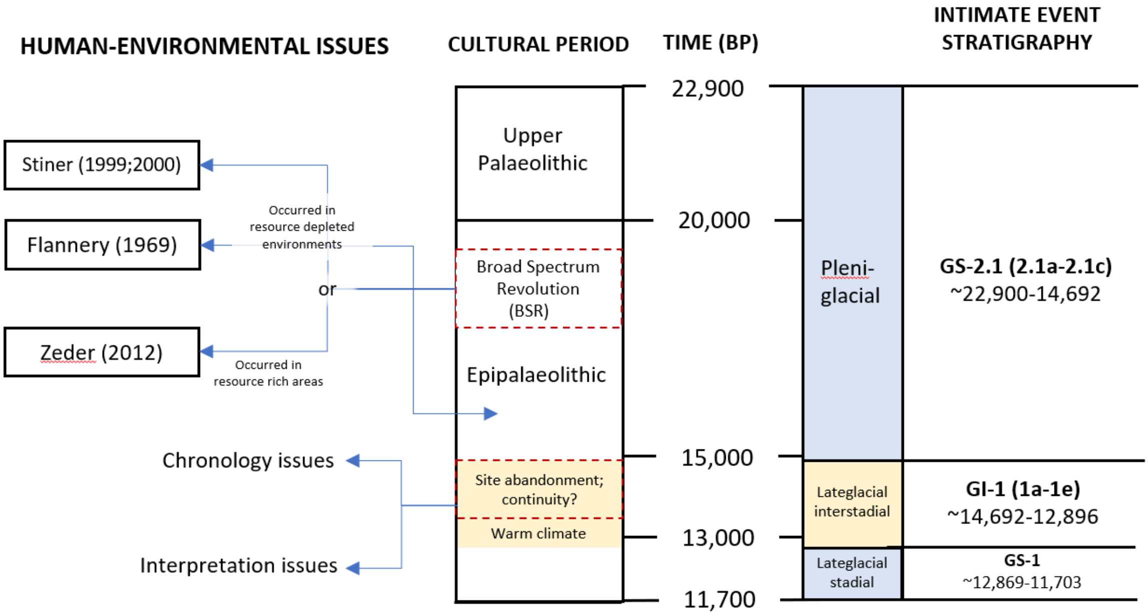

Figure 4-3: Summary diagram of the human-environmental issues in the Epipalaeolithic (author's own)

In comparison to other regions such as the Levant, the Epipalaeolithic period of the Zagros region has received little scholarly attention in terms of archaeological research. Only a few Epipalaeolithic sites have been excavated and published adequately (Olszewski 2012). Chronological uncertainties characterise the archaeological sites of this time period while the impact of climate change on past communities also remains unresolved, making it difficult to determine and understand human-environmental relationships (Asouti *et al.* 2020). To effectively understand the dynamics of long-term changes in behavioral strategies, reliable and secure site chronologies are required (Olszewski 2012).

4.2 The Neolithic period (~12,000-7200 yrs BP)

4.2.1 Characterisation of the Neolithic period

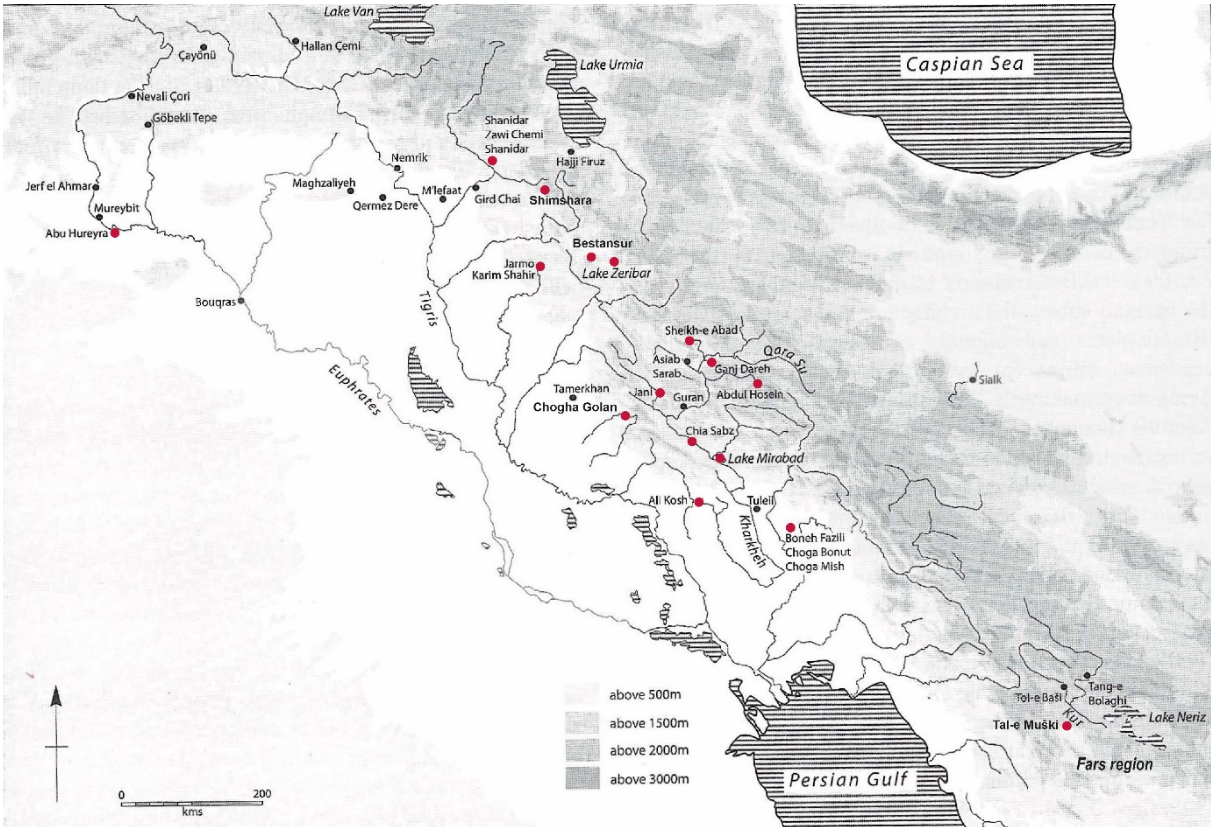

Figure 4-4: Map showing the locations of the Neolithic sites and regions mentioned in the text (red circles) (after: Matthews et al. 2013b: 20)

The start of the Neolithic period in the Zagros region roughly coincides with the end of the Lateglacial Stadial and start of the Holocene at ~11,700 yrs BP, which can be sub-divided into two main phases as follows: The Early Neolithic (~12,000-9000 yrs BP) or Pre-Pottery Neolithic period; and the Late Neolithic (~9000-7200 yrs BP) or the Pottery Neolithic period (Nashli and Matthews 2013: 7).

The Neolithic period witnessed a major episode of cultural transformation in the history of humanity that has been referred to as the Neolithic Revolution – a term first coined by G. Childe (1951) – or more appropriately the Neolithic Transition (Figure 4-4). This episode is characterised by a range of distinct regionally variable developments, which include, most notably, the transition from a seasonally-based mobile hunter-gatherer life-style to one that represents a sedentary herder-farmer way of life, accompanied by the construction of permanent dwelling units and buildings, and intensified plant and animal exploitation leading to their domestication at ~9800 yrs and 9900 yrs BP (domestication of goat), respectively (Zeder 1999; Zeder 2008; Riehl *et al.* 2013).

Other developments include changes in material culture with evidence for the use of ground, bone, and grinding tools indicative of increased plant processing; increased social complexity as evidenced by the production of clay figurines and clay tokens from ~10,000 yrs BP indicative of an initial administration or basic counting system (Schmandt-Besserat 1992); increased evidence of ritual activity including human burial practices (Croucher 2012), cultic buildings (Matthews *et al.* 2013c: 226), and body adornment activities (e.g. cranial modification) (Lorentz 2010); increased presence of obsidian stone imported principally from south-eastern Turkey, indicating long-distance exchange networks (Barge *et al.* 2018); and emergence of pottery at ~9500-8500 yrs BP (Darabi 2015: 93).

This gradual process of 'Neolithisation' has been attributed to a variety of causes including environmental-based theories, population-based theories, social-based theories, ideological-based theories, and multi-causal-based theories (see Table 4-3 for short description of the environmental-based and population-based theories). Childe (1951), for example, argues that the dry climate forced humans, animals, and plants to migrate near water resources, gradually forming a symbiotic relationship that eventually led towards animal and plant domestication in the past. In contrast, Braidwood argued that the hilly flanks (foothills of the Zagros Mountains) represented a 'Natural Habitat Zone' which was naturally populated and filled by both animals and plants, ready to be domesticated by human communities (Braidwood and Howe 1960: 3; Braidwood *et al.* 1961).

The discovery of new archaeological sites and subsequent extensive studies, however, indicate that these simplistic single-factor models of sedentism and domestication are no longer accurate as it appears that a number of complex and locally contingent factors were responsible for these cultural changes (Zeder and Smith 2009; Zeder 2015). Broad-scale factors such as climate change, economic goals, and social opportunities and constraints interacted with local factors such as availability and diversity of plant and animal resources, human occupation history (i.e. population growth and movement), and the agency of individuals (Zeder 2006; Zeder and Smith 2009). Therefore, inter-disciplinary studies are needed for each region and site to investigate different pathways to 'Neolithisation' (Matthews and Nashili Fazeli 2022).

Table 4-3: Summary of environmental and population-based theories adapted from Darabi (2015: 6-9)

Theoretical theme	Theories	Short Description	Reference
Environmental-based	Oasis theory	Dry climatic conditions forced humans, animals and plants to cluster in areas with permanent water bodies. A symbiotic relationship was formed between humans, animals and plants leading eventually to their domestication	Childe (1951)
	Pre-conditional regions	A set of pre-conditions are needed in a region to start agricultural activities including presence of wild ancestors of domesticated animal and plant species	Peake and Fleure (1927)
	Natural habitat Zone/ Nuclear zone	An area of natural environment that includes wild plants and animals that are ready for domestication which was in the foothills of the Zagros mountains (hilly flanks). Domestication did not start earlier because 'culture was not ready'	Braidwood and Howe (1960); Braidwood *et al.* (1961)
	Ecological diversity	Agriculture was not the result of shortage of food, rather ecological diversity encouraged domestication	Sauer (1952)
	Younger Dryas	The change to dry and cold climatic conditions led to a change in subsistence strategies and start of occupation in suitable areas for agriculture in the Levantine region	Moore and Hillman (1992); Bar-Yosef (2002)
	Seasonal stress	Climate desiccation and seasonal stress (i.e. long dry seasons), impacted on food resources in the Levant, forcing human communities to take up agricultural activities	McCorriston and Hole (1991)
	Levantine primacy	Agriculture first started in the Levantine region as a response to abrupt climatic changes. During wet climatic conditions, environmental resources increased and human communities preferred a sedentary life style leading to an increase in population size. While drier climatic conditions caused resource shrinkage forcing human communities to uptake food production	Bar-Yosef and Meadow (1995)
	Resource shrinkage	Periodic stress of the climate on resource availability affected human communities. To tackle resource stress, human communities increased reliability of exploited resources resulting in technological innovations that allowed resource diversification and specialised resource exploitation	Hayden *et al.* (1981)
Population- based	Population equilibrium/Marginal Zones	Population size increased once Early Natufians in the Levant became sedentary, leading to a consumption increase of locally available plants that were considered marginal	Binford (1968)

	Broad spectrum economy	At the end of the Epipalaeolithic period, a broadening of diet occurred that led to sedentism and subsequently population growth. Increase of population size in marginal areas required humans to cultivate crops to ensure adequate food supply	Flannery (1969)
	Population pressure	Sedentism at the end of the Epipalaeolithic led to increase in population size causing pressure on available resources which ultimately led to domestication. Early domestication first started in the high small valleys and then developed in open plains or valleys	Smith and Young (1972)

4.2.2 Role of the Lateglacial Stadial and the Early Holocene on the emergence of agriculture

Having outlined the possible pathways to Neolithisation and its characteristics, this section examines in further detail the role of climate change in promoting the emergence of agriculture.

At ~12,600 yrs BP, the environmental record of Lake Zeribar indicates a reversal to glacial-like climatic conditions, characterised by cold and dry climatic conditions accompanied by a return to semi-desert *Artemesia*-Chenopodiaceae steppe environment (Van Zeist and Bottema 1977). Despite the harsh climatic conditions, human occupation continued at Shanidar Cave, Zawi Chemi Shanidar and Karim Shahir indicating that the lower Zagros region was not completely abandoned during the Lateglacial Stadial (Matthews *et al.* 2013b: 18). In addition, archaeological evidence indicates a long occupation history as evidenced, for example, from various cave sites in the Bolaghi valley and the Arsanjan area (Fars region) located in the southern Zagros region spanning the Epipalaeolithic-Neolithic transition (Tsuneki 2013).

The role of the Lateglacial Stadial in crop cultivation as an agent of environmental degradation has been widely discussed (Bar-Yosef 1998; Bar-Yosef 2011). At Abu Hureyra (Syria), for example, it is argued that hunter-gatherers started crop cultivation as a response to the Lateglacial Stadial which caused a major decline in the availability of key wild plants on which hunter-gatherers relied (Hillman *et al.* 2001). However, at Chogha Golan (Iran) the number of wild barley increases with the end of the Lateglacial Stadial (Riehl *et al.* 2013) with continuously increasing intensification in the use of grasses afterwards (Riehl *et al.* 2015). Although domesticated-type emmer appeared at Chogha Golan at ~9800 yrs BP, the presence of Triticoid-type species, large-seeded barley grains, and high amount of arable weeds suggests that cultivation in the Zagros foothills might have already started in the Epipalaeolithic (Riehl *et al.* 2013). The dry conditions and low CO_2 concentrations during the Lateglacial Stadial have been argued to be responsible for the start of domestication in the Early Holocene period by impacting plant resource availability which inevitably placed food stress on human communities during this time interval (Richerson *et al.* 2001; Willcox *et al.* 2009; Riehl 2016). However, the theory that environmental constraints caused by the Lateglacial Stadial led to intensified cultivation is, unlike for the western Fertile Crescent, less likely applicable to the eastern Fertile Crescent. Early Neolithic communities in the eastern Fertile Crescent were not heavily dependent on wild cereals for their diet but rather dependent on wild goat and legumes, fruits and nuts (Arranz-Otaegui *et al.* 2016) which were not majorly impacted by the climatic conditions of the Lateglacial Stadial (Matthews and Nashili Fazeli 2022). This highlights the point that each region and site need to be investigated individually as the pathways to Neolithisation will vary from region to region and even from site to site.

If the Lateglacial Stadial was not the primary cause of Neolithisation in the eastern Fertile Crescent, what caused Neolithisation in the Early Holocene period? The Early Holocene period brought climate amelioration including an increase in temperature, water availability, nutrients, and diversification of edible plant resources (Matthews *et al.* 2020b: 655). Plant resources included grasses, which rapidly increased during the start of the Early Holocene suggesting minimum rainfall was at least ~200–300mm (Van Zeist and Bottema 1977; Matthews *et al.* 2020b: 632) nut and fruit bearing trees, and legumes (Van Zeist and Bottema 1977). These biophysical changes would have supported Early Neolithic developments (Matthews *et al.* 2020b: 632). In spite of climate amelioration, the increase in precipitation (Altaweel *et al.* 2019) was lower in the Zagros region in comparison to the eastern Mediterranean until the early tenth millennium BP (Matthews *et al.* 2020b: 632). Further Riehl (2016) argues based on stable isotope analysis of charred wild cereals from Chogha Golan, that only after 10,800 yrs BP precipitation was reliable in the Zagros region for extensive cereal cultivation (Araus *et al.* 2014; Riehl 2016). At Chogha Golan, for instance, domesticated cereal starts appearing from ~9800 yrs BP (Riehl *et al.* 2013), while at Sheikh-e Abad the use of domesticated cereals has been found between 10,230-9730 yrs BP (Whitlam *et al.* 2013: 179). Thus despite climate amelioration, the timing and rates of change from hunter-gatherers to sedentary farmers varied across the region dependent on factors such as local climate variations, cultural and material traditions, and resource availability (Nashli and Matthews 2013: 6). Even after 10,000 yrs BP, when morphologically domesticated cereals appear, they formed a minor part of the human diet (Zeder and Smith 2009).

Based on Lake Zeribar pollen and isotope data, which indicated scarcity of trees (Van Zeist and Bottema 1977) and increased seasonality (Stevens *et al.* 2001), suggesting colder and drier conditions during the Early Holocene, it was initially argued that domestication and sedentism was delayed in the Zagros region in comparison to the Western Fertile Crescent. Furthermore, the sparsity of archaeological sites and insufficient reliable rainfall for rain-fed agriculture during the Early Holocene period (Araus *et al.* 2014; Riehl 2016) suggested ecological instability (Matthews *et al.* 2020b). However, new archaeological surveys and excavations indicate no delay in occupation in the Zagros region (see Matthews *et al.* 2013a) and domestication occurring roughly at the same time as in other parts of the region (Riehl *et al.* 2013; Whitlam *et al.* 2013; Whitlam *et al.* 2018; Matthews *et al.* 2020b).

In summary, climatic amelioration that led to the formation of highly productive and stable resource environments during the beginning of the Holocene period (Asouti 2017), would have allowed Neolithic communities to respond to climate change in a number of ways depending on local factors such as local cultural and environmental conditions, leading to locally unique pathways to domestication and agriculture (Zeder and Smith 2009).

4.2.3 Delay of forest expansion – humans vs climate

Based on Lake Zeribar and Mirabad pollen records (Van Zeist and Bottema 1977), the Early Holocene period experienced a delay in forest expansion, especially in *Quercus* woodland (see Chapter 3 and 4) compared to the Mediterranean region, despite improvements in the prevailing climatic conditions occurring roughly at the same time in both regions (Asouti and Kabukcu 2014). To explain this lag in the expansion of *Quercus*, the differentiation between anthropogenic and natural or climatic causes is necessary. A number of reasons have been put forward to explain the delay, including controlled vegetation burning by Neolithic communities to manipulate natural vegetation and maintain landscapes for cultivation of crops, woodcutting for fuel and timber, to increase grazing grounds for animals (Roberts 2002), climate aridity (Roberts and Wright Jr 1993), climate seasonality (Stevens *et al.* 2001), migration lags (Van Zeist and Bottema 1977), underrepresentation of certain pollen taxa (Roberts 2002), and Neolithic activities such as selective removal of competing woody vegetation and grazing of grasslands that would have allowed more ground moisture availability for *Quercus* to expand over time (Asouti and Kabukcu 2014). For a more detailed discussion on potential causes for *Quercus* woodland delay, see Chapter 3 and 4.

The tree cover density during the Early Holocene was likely higher than what pollen records (Van Zeist and Bottema 1977) of this region indicate (Matthews 2013a: 17; Matthews 2016: 115). Pollen records do not always represent the former vegetation accurately due to differential production, dispersal and preservation processes (Roberts 2002). This is especially the case with *Pistacia*, which is a low pollen grain producer. Similarly, *Amygdalus* is insect pollinated, and, therefore, is under-represented palynologically. As Roberts (2002:1006) points out, if underrepresentation of *Pistacia* is taken into account then the Early Holocene period had a denser tree cover than what can be inferred from the pollen records in the western Zagros region. High amount of wood charcoal has been found at Tapeh Abdul Hosein (Willcox 1990), and Ganj Dareh (van Zeist *et al.* 1986) which suggests that trees were more abundant in the past than what pollen records suggest, or that they were heavily exploited explaining their low concentration in the pollen records (Darabi 2015: 20).

In particular, at sites such as Ganj Dareh and Sheikh-e Abad, which were located in the high Zagros, wood was utilised in higher quantities. In contrast, at sites such as Chogha Golan and Ali Kosh of the lower Zagros, it was less frequently used by Neolithic communities (Matthews 2016). This was however not always the case. For instance, initially at Ganj Dareh, Neolithic communities did not use *Pistacia/Celtis* or *Populus* as a fuel source, rather it was likely used as a food source and to produce timber wood, respectively (van Zeist *et al.* 1984: 221-222). At ~9900 yrs BP, however, the major food sources changed to domesticated cereal and goat. As a result, fuel selection strategies changed and included *Pistacia* wood (Matthews 2016: 130).

The low amount of wood charcoal found at Neolithic sites located in the lower Zagros, such as Ali Kosh may suggest that animal dung was the principal source of fuel (Miller 2003). Excavations at Sheikh-e Abad suggest that during the early phase of occupation, wood was the main fuel source until ~10,000 yrs BP, which is when a shift to animal dung as fuel source occurred (W. Matthews 2013b: 100). Animal management and domestication would have meant easy access and availability of dung for fuel which in turn led to animal dung becoming potentially a major fuel source in the Zagros region from ~10,000 BP onwards (Matthews 2016: 130). It is, however, unclear whether the shift in the fuel source is related to a degraded woodland as a result of human over-exploitation and/or animal grazing (Matthews and Nashili Fazeli 2022). There is a possibility that dung was used alongside wood as a fuel source at Chogha Golan. Based on the anthracological, seed botanical, micromorphological and stratigraphic data there is no evidence for an increase in the use of dung fuel over time as a substitute for depleted woodland sources (Riehl *et al.* 2015).

Lastly, fire also played a role in shaping the Early Holocene environment in Southwest Asia. Microcharcoal and charred plant macrofossil records indicate a peak in wildfire frequency during the early part of the Early Holocene (Wick *et al.* 2003; Wasylikowa 2005; Turner *et al.* 2010). The high frequency of wildfires was most likely a result of the hot and dry summer seasons and the high presence of grasses that acted as fuel source to fire (Turner *et al.* 2010; Wick *et al.* 2003). The role of human communities in causing fires, either accidentally or deliberately, has also been discussed widely (see Roberts 2002; Turner *et al.* 2010; Matthews 2016). Nevertheless, further studies are needed that include both micro- and macrocharcoal records for each site in order to obtain both a regional and local fire signal history.

In summary, human-environmental relationships across the Zagros region and their impact likely varied from site to site depending on local factors such as settlement and mobility pattern as well as mode of subsistence (Matthews *et al.* 2013b: 19). Moreover, it can be concluded that the environment during the Neolithic period was impacted by a number of factors including climate, topography, biogenic factors and human activity (Matthews 2016: 116).

4.2.4 The Impact of the 11.4 ka, 9.3 ka, and 8.2 ka climatic events

There are three major climatic events that have been identified in the Greenland ice core data (Rasmussen *et al.* 2014) which occur during the Neolithic period: the 11.4 ka, 9.3 ka, and 8.2 ka BP event.

There is currently no archaeological evidence available that could provide insight into the impact on Neolithic communities by the 11.4 ka event. In contrast, the 9.3 ka event approximately coincides with the abandonment of Early Neolithic sites including Sheikh-e Abad, Ganj Dareh, Abdul Hosein, East Chia Sabz, Bestansur and possibly Shimshara. At the same time, there is evidence for the emergence of new Late Neolthic sites on the lower plains, including Ali Kosh and Chogha Bonut (Matthews *et al.* 2013c: 233). It is argued, however, that the break in Neolithic occupation and dispersal already took place several centuries before the 9.3 ka event. Whether the climatic conditions of the 9.3 ka event led to the collapse of the agricultural system at sites located in the high Zagros and, by extension, the emergence of new sites in the lower plains, where climate was less severe, requires detailed local climatic records characterised by a precise, reliable chronology (Matthews and Nashili Fazeli 2022).

Likewise, it has been argued that the 8.2 ka climatic event led to large-scale site abandonments (Staubwasser and Weiss 2006) and migration in Southwest Asia (Weninger *et al.* 2006). There is a possibility that the 8.2 ka event was responsible for the movement of farmers into the plains of central and northern Iran, although, there is currently no evidence for this assessment (Matthews and Nashili Fazeli 2022). These interpretation models are, in fact, based on loose correlations, single-case studies, and a biased set of radiocarbon dates (Flohr *et al.* 2016).

To overcome this problem, rigorous quality-checked radiocarbon dates were analysed by Flohr *et al.* (2016). Based on the results, there is no clear evidence for a regional abandonment or migration phase during the 9.3 and 8.2 ka event or in between 9500 and 7500 yrs BP (Flohr *et al.* 2016). The timing of the 8.2 ka event also does not coincide with any significant changes in the archaeological record of the Levant region. Variations in the archaeological sequence, in fact, appear to have occurred most probably before the 8.2 ka event (Maher *et al.* 2011). Maher *et al.* (2011) argue that the relationship between climate change and cultural change are complex and correlations are not always clear due to for example imprecision of the cultural chronology. In order to make causal claims, temporal precedence is required. Thus, in order to link potential changes in the archaeological record to climatic events, the latter has to precede potential archaeological changes in time (Carleton and Collard 2020).

Flohr *et al.* (2016) argue that the reason for the absence of clear archaeological evidence for the impact of the 9.3 and 8.2 ka event may be due to climate deterioration not being severe enough to impact vegetation and thus food supply; Neolithic communities, plants and animals already adapted to adverse climatic conditions, that started from ~8600 yrs BP onwards, by diversification of resources and storage; Neolithic communities were resilient to climate change (Flohr *et al.* 2016; Matthews *et al.* 2020a). Surveys indicate that many Early Neolithic sites were located close to water sources and ecotone boundaries, maximising opportunities for flexibility in food procurement through ongoing hunting and gathering alongside cultivation and animal herding. Settlements that were potentially abandoned were not located in marginal areas (Flohr *et al.* 2016). For example, Bestansur and Shimshara were located on ecotone boundaries providing them easy access to a variety of ecosystems and topographic zones such springs, rivers, wetlands, fertile plains and foothills (Matthews *et al.* 2020b: 633). While Sheikh-e Abad and Jani had access to a rich range of ecological zones including plains, wetlands and mountain (Matthews 2013a: 18). Since Neolithic subsistence practices were diverse, they were likely to be resilient to the 9.3 and 8.2 ka events (Flohr *et al.* 2016; Matthews *et al.* 2020a).

There is, however, evidence for adaptation. The examination of the faunal and lithic materials has revealed evidence in favour of local adaptation to the 8.2 ka event at the sites of Tal-e Mushki and Hormangan, located in the Fars region, where a shift from cultivation to wild animal hunting practises has been identified between ~8200-8000 yrs BP, attested both in faunal remains and lithic tool assemblages (Abe and Khanipour 2019).

From the above, it is clear that in order to make precise correlations between the climatic and archaeological record, as well as evaluate local adaptation strategies, precise chronological archaeological data and localised palaeoclimatic and environmental records are needed (Maher *et al.* 2011; Flohr *et al.* 2016).

4.2.5 Limitations in the study of human-environmental relationships of the Neolithic period

To better understand the dynamics of human-environmental relationships, it is necessary to accurately reconstruct palaeoenvironmental conditions (Carleton and Collard 2020). With regards to the Zagros region, there is a general lack of palaeoenvironmental data covering the Lateglacial-Early Holocene transition and the Early Holocene period. There is a heavy reliance on the low-resolution records from Lake Mirabad and Zeribar for this time interval while the latter also suffers from chronology issues. To be able to expand beyond general correlations between the palaeoenvironmental and archaeological archives, both the temporal resolution and spatial scale of both datasets would need to be of high-resolution (Walsh *et al.* 2017: 403). These shortcomings highlight the urgent need to produce new, high-resolution palaeoenvironmental records characterised by robust age-depth models, covering this important cultural and climatic time interval.

Despite the cultural significance of the Neolithic period in the Zagros region, the archaeology of this time is characterised by poor chronological controls because for the Early Neolithic the chronology relies on lithic assemblages augmented by radiocarbon dating and the Later Neolithic is mainly based on the relative chronology associated with the ceramic tradition (Darabi 2015: 5). Further, many

Neolithic sites, that are located in modern Iran, have not been excavated with modern scientific methods while the use of radiocarbon dates is limited, making it extremely difficult to conduct reliable cross-comparative studies between archaeological sites and regions (Matthews and Nashili Fazeli 2022). Chronological uncertainties can have significant impact on studies investigating on human-environmental interactions as such studies make causal claims that can lead, in turn, to misinterpretations of entire datasets. Correlation between the archaeological and palaeoenvironmental records does not necessarily imply causation (Carleton and Collard 2020).

There is a need to carry out multi-disciplinary studies at archaeological sites, that are located close to pollen study sites as it would enable us to better detect evidence for anthropogenic indicators associated with human activity at or around Neolithic settlements. To overcome this issue, both study sites of this research are located close to Neolithic sites such as Sheikh-e Abad and Shimshara. The further away an archaeological site is from the pollen study area the more likely it is that a human signal will be weaker (Kozáková *et al.* 2015). Similarly, one issue of comparing palaeoclimate data and the archaeological record is the distance of some archaeological sites from the locations of major palaeoclimate archives (Riehl *et al.* 2015) which if compared does not consider possible micro-climate variations.

To better understand human-environmental relationships, local climatic and palaeoenvironmental records are needed that are of high-resolution and have a reliable chronology. The study of the Neolithic archaeological evidence, likewise, requires more reliable chronological controls in place in order to be able to make accurate correlations and make causal claims.

4.3 The Chalcolithic period (7200-5200 BP)

4.3.1 Characterisation of the Chalcolithic period

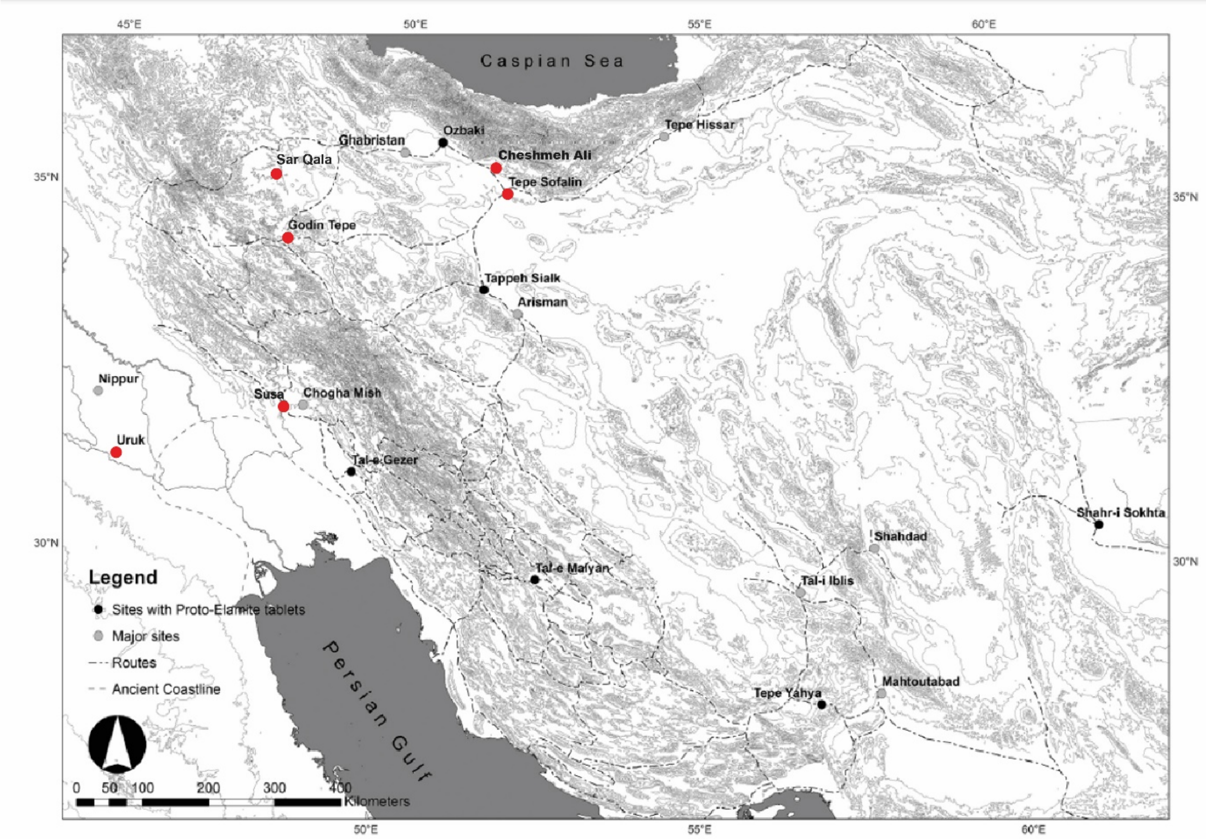

Figure 4-5: Map showing the locations of the Chalcolithic sites mentioned in the text (red circles) (Dahl et al. 2013: 354)

The Chalcolithic period (Figure 4-5), is most notably, characterised by increased social complexity and the emergence of complex, hierarchical societies in Southwest Asia. Evidence of increased social complexity includes craft specialisation in ceramic production (Fazeli 2006), technological advancements in metalworking, specifically copper, and use of irrigation technology, construction of large-scale monumental architectural structures such as communal buildings, multi-tier settlement hierarchies, and a shift towards the use of cultic iconography of seals and religion. The Chalcolithic period is further characterised by a change in funerary traditions from burials in dwelling units to major centralised internment of the dead (Álvarez-Mon 2018). The recovery of many clay tokens, seals as well as numerical tablets from archaeological excavations indicate the presence of storage systems and controlled movement of various types of goods (Alizadeh 2006: 88), related to initial systems of administration (Vidale *et al.* 2018: 28-29).

Further, evidence of long-distance trade and significant trans-regional connections has been identified (Nobari *et al.* 2012; Abedi *et al.* 2019) from ~6000 yrs BP onwards. The archaeological material record associated with the Uruk period, including the ceramic and administrative artefacts, were found at the site of Tepe Sofalin (Hessari 2011) and in the high Zagros site of Sar Qala (Mucheshi *et al.* 2013). The city of Uruk, one of the largest urban centres in Lower Mesopotamia/south Iraq, expanded to about 250 ha in the Late Chalcolithic period (Nissen 2001). Similarly, the key-site of Susa, located in the Khuzestan region of Iran, doubled in size to 25ha. In addition, Uruk outposts were established across Southwest Asia that were connected through long-distance exchange networks which is known as the Uruk expansion. With regards to the Zagros region, the location of the site of Godin Tepe provided the central link that connected the central Zagros region with Khuzestan (Iran) and Lower Mesopotamia (south Iraq) (Rothman 2013; Desset 2014; Gopnik *et al.* 2016). Besides an increase in settlement size across the wider region, substantial increase in sites and population have been identified at the start of the Chalcolithic period (Alizadeh 2008: 11; Moghaddam 2013: 110).

In terms of subsistence traditions, a change from small-scale farming, herding and hunting to agricultural intensification characterised by extensive use of irrigation and dependence on domesticated goat and sheep has been noted in the archaeological data (Mashkour *et al.* 1999; Peasnall 2002). According to Hole and Flannery (1968: 181) the extensive use of irrigation, use of a full range of cereals, and domestication of cattle played a major role in the emergence of state-level societies, possibly creating food surpluses (Yoffee *et al.* 2005) and sustaining a large population. In the Khuzestan region, for instance, subsistence included wheat and six-row barley while the main herding animals were sheep, goat and cattle (Alizadeh 2008: 12).

The Zagros region of western Iran, specifically, also experienced a possible decline in hunting and foraging and a stronger emphasis on farming and animal herding (Matthews and Nashili Fazeli 2022). Based on the available data, cereal cultivation was the primary substance of the Zagros highlands with agriculture being centred on dry farming during the Early Chalcolithic and use of irrigation employed by the Middle Chalcolithic in the Zagros region (Peasnall 2002). The presence of grape, a cultivated species, suggest use of irrigation and establishment of viticulture during the Chalcolithic period (Peasnall 2002).

Based on settlement surveys, the central Zagros region also experienced a major increase in population size accompanied by an increase in the densities of settlement sites (Zamani Dadaneh *et al.* 2019; Matthews and Nashili Fazeli 2022), suggesting an expansion of the agricultural regime to its maximum capacity (Abdi 2003).

The discovery of temporary seasonal campsites outside the agricultural zone (Abdi 2003; Abdi 2015) suggests that some form of pastoral nomadism may have potentially started in the western central Zagros region during the Chalcolithic period, an adaptive economic strategy that would have allowed sustaining an increasing population size (Peasnall 2002; Abdi 2003). Increased grazing and animal herding, especially sheep herding, along with local fires, selective wood cutting and management, suitable climatic conditions, and cultivation and settlement expansion during the Middle Holocene period would have given *Quercus* a competitive advantage over grasses and other trees such as *Juniperus* to establish and spread (Asouti and Kabukcu 2014) after 6000 ys BP in the Zagros region.

It is argued that dry climatic conditions led to these major transformations identified in the entire region (Sirocko *et al.* 1993; Hole 1994), along with other factors such as increasing technological developments in various craft industries (Adams 2000), religious ideologies (Hole 1983), increased centralisation and the development of political hierarchies (Wright 2001), central organisation of irrigation systems – 'Hydraulic theory' (Wittfogel 1957), and increased conflict and warfare as indicated by the archaeological evidence (McMahon *et al.* 2011; Asadi Tashvigh and Abbasnejad Seresti 2020)

It should be taken into account, however, that the path towards and the degree of social complexity varied across sites with different sites experiencing it at different scales and rates (Matthews and Nashili Fazeli 2022).

With the major developments and sequence of events of the Chalcolithic period outlined above, the potential impact of climate change on the Chalcolithic communities will be assessed, and human-environmental interactions in the Zagros and the wider adjacent regions will be studied and explored in the forthcoming discussions. By doing so, it will enable us to highlight gaps in the research and what is needed to overcome these issues which in turn will allow better correlation between the archaeological and palaeoenvironmental records.

4.3.2 The impact of climate change and human-environmental interactions

In order to evaluate and understand the impact of climate change on the Chalcolithic communities, it is important to briefly outline the prevailing climatic conditions of the time. Mayewski *et al.* (2004) was able to identify six major periods of climate change (RCC) that were widespread, arid and rapid. Among these, the most extensive and signigicant event occurred during the Middle Holocene, between 6000–5000 yrs BP.

Based on the study of palaeoenvironmental records, the climatic conditions during the first half of the Chalcolithic period are characterised by increased rainfall and warmer temperatures, coinciding roughly with the latter part of the 'climatic optimum' (~10,000-6000 yrs BP) (Peasnall 2002; Hole 2011). The Middle Holocene Climatic Transition (MHCT), that occurred between ~6400-5000 yrs BP, witnessed a profound environmental change with climate changing to roughly similar to that of today (Brooks 2010; Brooks 2013). Thus, the second half of the Chalcolithic period from ~6000 yrs BP onwards coincides with an episode of relative aridity (Steig 1999: 1486; Sharifi et al. 2015; Hole 2011).

According to the oxygen isotope data from Lakes Mirabad and Zeribar a severe 600-year drought occurred at ~5500 yrs BP, which was part of a longer dry interval (Stevens *et al.* 2006). Dry climatic conditions between ~5700 -5500 BP have also been inferred at Lake Maharlou by the low presence of *Pistacia–Amygdalus* scrub and *Quercus brantii* woodland as well as high values for *Artemisia* and Chenopodiaceae (Djamali *et al.* 2009b). Further, based on systematic analysis of terrestrial and marine climate proxies, Clarke *et al.* (2016) also identified an episode of heightened aridity at ~5700 yrs BP (Figure 4-6). The amount of rainfall served a vital function in the formation and expansion of settlements while slight changes in rainfall patterns could have affected subsistence economies, especially rain-fed agriculture (Hole 2007:195). According to Hole (2011), the decline in the number of settlements in the Zagros and Khuzestan region during the MHCT thus possibly was a result of decline in precipitation.

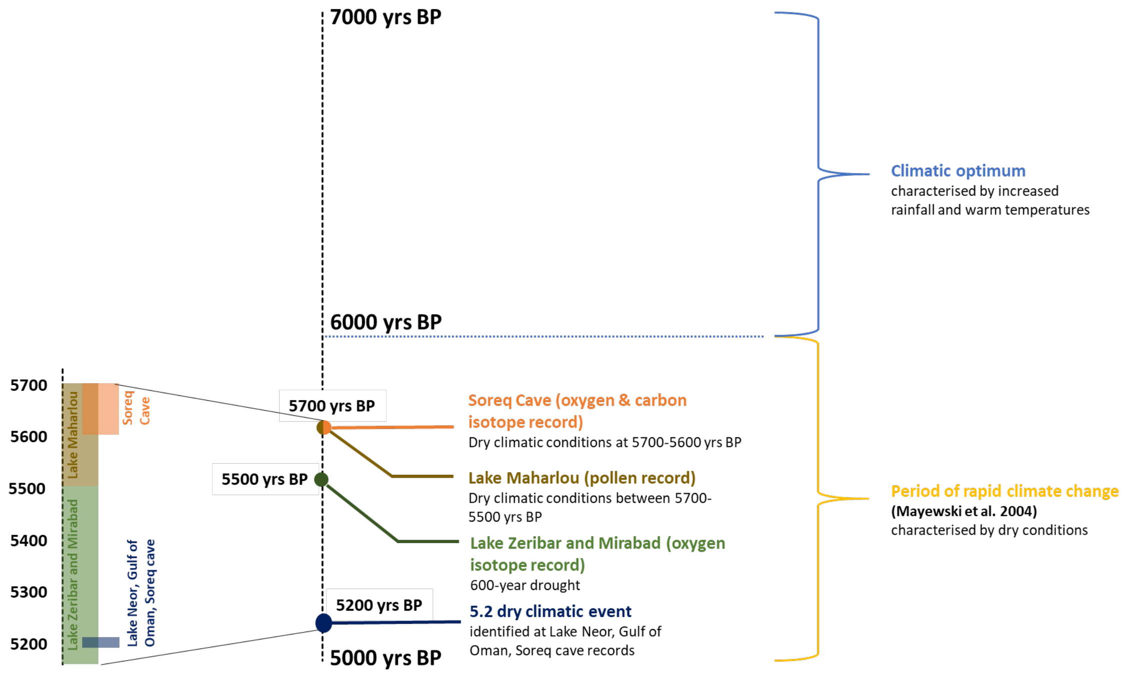

Figure 4-6: Summary of palaeoclimatic data for the Chalcolithic period (author's own)

According to Hole (1994: 123) the Uruk expansion was, largely, a result of a more stable physical environment that encouraged the development of more extensive canal systems and facilitated larger communities. Brooks (2006: 44-45), however, argues that the increase in social complexity, that can be seen in the archaeological record, was achieved by adapting to the dry climatic conditions at the end of the Chalcolithic period. The gradual receding of the Persian Gulf from ~5500 yrs BP, for example, left nearby settlements, including Uruk, in control of rich, well-watered alluvial soils (Brooke 2014: 207), and created a complex mosaic of aquatic habitats in the form of estuaries, rivers, wetlands, and marshes. These favourable environmental conditions would have promoted, for instance, a diverse diet among the people of the region (Kaser 2011: 14), potentially providing security during times of drought and crop failures, favoured increased population densities, and enhanced maritime trade (Kennett and Kennett 2006: 78). Thus according to Kennett and Kennett (2006), the receding of the Persian Gulf and the dry climatic conditions, along with other environmental changes prior to it, played a role in state development in southern Iraq.

Based on geochemical data, Sharifi et al. (2015) argue that drier and dustier conditions prevailed from ~6000 yrs BP onwards, with the highest dust influx identified at ~5200 cal yrs BP. The high-resolution oxygen and carbon isotopic record from Soreq Cave (Israel) also indicates a climatic dry period at ~5700–5600 yrs BP followed by another shorter dry event at ~5250–5170 yrs BP (Bar-Matthews and Ayalon 2011). The 5.2 ka event has also been identified in the climatic record of the Gulf of Oman where an increase in the amount of eolian dolomite and calcite concentrations has been identified (Figure 1) (Cullen *et al.* 2000: 380).

The impact of the dry 5.2 ka climatic event and the generally drier climatic conditions that started from ~6000 yrs BP onwards, have been linked to a range of different local and regional developments in the region. They include the collapse of the urban centred Uruk culture in southern Mesopotamia at ~5200 yrs BP (Anderson *et al.* 2013: 289), the collapse of the Uruk colonies, a change in settlement distribution and density (Algaze 2008: 103-105) including widespread site abandonments (Johnson 1973: 143), increased competition for favourable land and water resources, and aggregation of populations in urban centres close to rivers and estuaries such as Uruk (Matthews 2003; Brooks 2013). Arid climatic conditions would have reduced precipitation levels beyond sustainable limits in rain-fed cereal agriculture regions (Weiss 2003: 606).

The precise impact of climate change on the Chalcolithic communities remains, however, open for debate and more research. Although there is evidence for regional environmental desiccation, further palaeoenvironmental and archaeological studies are needed from local contexts to be able to link potential social change explicitly with environmental change. Thus, the critical investigation of individual settlement sites from the region will determine the precise nature of changes in livelihood strategies, social organisation and ideological frameworks and, also, how they relate to variations in the palaeoenvironmental record (Brooks 2006: 43-44). Further, as emphasised above, the impact of climate change will vary across sites, depending on various factors including geographical and cultural differentiations. As a result, the adaptation strategies of societies will, likewise, differ from one another, with each group adapting according to their own local conditions including environmental, economic, social and cultural contexts (Brooks 2013; Clarke *et al.* 2016).

In order to carry out more accurate correlations between the archaeological and climatic record, a robust and reliable chronology for both data sets is required in the first place (Brooks 2006; Brooks 2013). Further, even if there is a correlation between both data sets, it does not indicate causation and thus caution is needed when trying to establish a relationship between climatic and cultural changes (Brooks 2013; Clarke *et al.* 2016). Equally, it is important to try to fill the gap in our knowledge about the Chalcolithic period from an archaeological perspective especially with regards to the central and northern Zagros and other adjacent regions (Matthews and Nashili Fazeli 2022). This information would eventually enable us to better assess the role of climate and environmental change and, in the process, understand human-environmental interactions during this dynamic time in the history of Southwest Asia.

4.4 The Bronze Age (5200-3100 yrs BP)

4.4.1 The characterisation of the Bronze Age

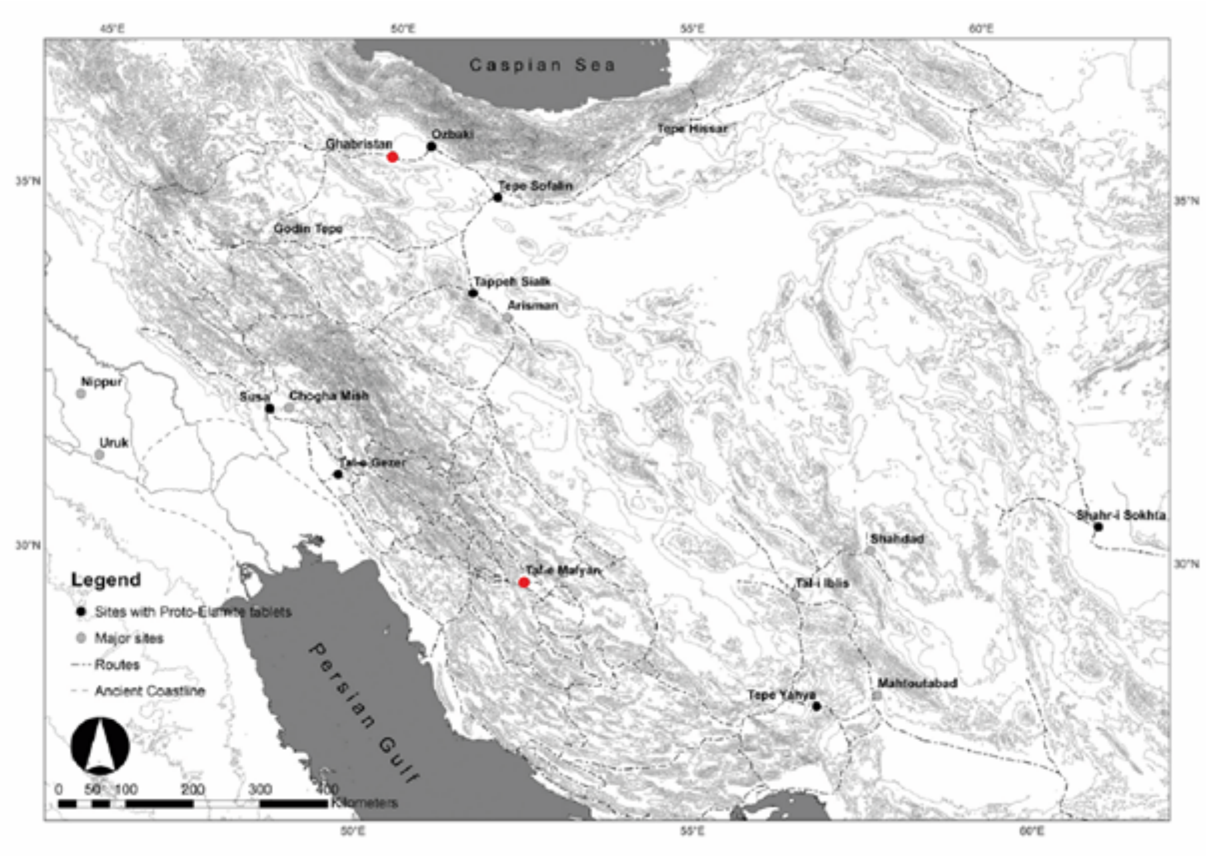

Figure 4-7: Map showing the locations of the Bronze age sites mentioned in the text (red circles) (Dahl et al. 2013: 354)

The Zagros region and Southwest Asia in general experienced a marked increase in complexity and in the volume of intra- and inter-regional trade and exchange in metals, semi-precious stones such as carnelian and lapis lazuli among other types of commodities during the Bronze Age period (Figure 4-7). The emerging city-states of this time interacted and competed with each other for control over vital resources and socio-economic and political power (Van De Mieroop 2004: 39) leading to increased instability and military conflict (Bartash 2020:532). The Bronze Age is characterised by the rise and expansion of imperial dynasties, most notably, the Akkadian Empire (4250 yrs BP) and Ur III Empire (4050 yrs BP) (Matthews 2003: 127 & 133) in Mesopotamia. The Akkadian Empire, however, did not endure for a sustained, long time leading to its collapse at ~4200 yrs BP which has been attributed to various factors including internal political instability (Bryce 2009: xli), climatic-induced drought (Weiss *et al.* 1993), and conflict through the arrival of a little-known group of people from the Zagros Mountains referred to in the cuneiform sources as the Gutians (Liverani 2014: 153).

Other characteristic features of the Bronze Age in Southwest Asia, as corroborated by the archaeological evidence, include the increased use of various types of written sources (Van De Mieroop 2004: 40); marked increase in settlement size and population levels (Van De Mieroop 2004: 43), and the construction and use of palace buildings that acted as administrative centre (Liverani 2014: 99; Collins 2016: 69). Palaces and temples also functioned as socio-political and economic centres (Bartash 2020: 532).

Human communities in the Central Zagros continued to favour pre-existing traditions in terms of transhumant agro-pastoralist and agricultural activities and strategies (Niknami *et al.* 2017: 320). The distribution of Middle-and Late Bronze Age sites depended on environmental factors especially access to water sources (Mirghaderi 2013; Niknami *et al.* 2017) and land with agricultural potential (Levine 1974: 490). Bronze Age settlements in the Zagros region, which were located in close proximity to water sources, probably based their subsistence economy on agriculture while sites further away may have practised nomadic pastoralism or were transhumant agro-pastoralists (Niknami and Mirghaderi 2019: 167). Sites in southern Mesopotamia were also located near rivers or canals due to their reliance on irrigation technology (Van De Mieroop 2004: 43), which, likewise, emphasises the role of water availability in this part of the world.

4.4.2 The impact of the 4.2 ka climatic event - Archaeological evidence

The collapse of the Akkadian Empire (Figure 4-8) in Mesopotamia has been linked to the 4.2 ka dry climatic event that lasted from 4200-3900 yrs BP (Cullen *et al.* 2000; Staubwasser and Weiss 2006; Carolin *et al.* 2019). The evidence for this link is based upon the identification of aeolian deposits identified at the archaeological site of Tell Leilan, located in the Habur Plain of modern-day Syria (Northern Mesopotamia), implying the impact of climatic-induced drought conditions (Weiss *et al.* 1993). The archaeological evidence indicates that population levels declined significantly in the Tell Leilan region with 73% of sites abandoned and a decline of 93% in the total area occupied (Figure 4-9) (Ristvet and Weiss 2005: 1). In addition, Akkadian buildings at the sites Tell Leilan, Mohammed Diyab, and Tell Mozan were abandoned (Weiss 2015: 43-44). The abandonment of settlements in the agricultural plain of northern Mesopotamia between 4200-3900 yrs BP is understood to be a major factor contributing to the collapse of the Akkadian Empire whose economy was largely based upon rain-fed agriculture (Weiss *et al.* 1993: 1002). Despite using an advanced irrigation system and grain warehouses to counter climate variability, the Akkadian Empire was apparently unable to sustain or adapt itself (Weiss *et al.* 1993) when confronted with a precipitation decline of ~30-50% (Cullen *et al.* 2000: 382; Weiss 2016: 62).

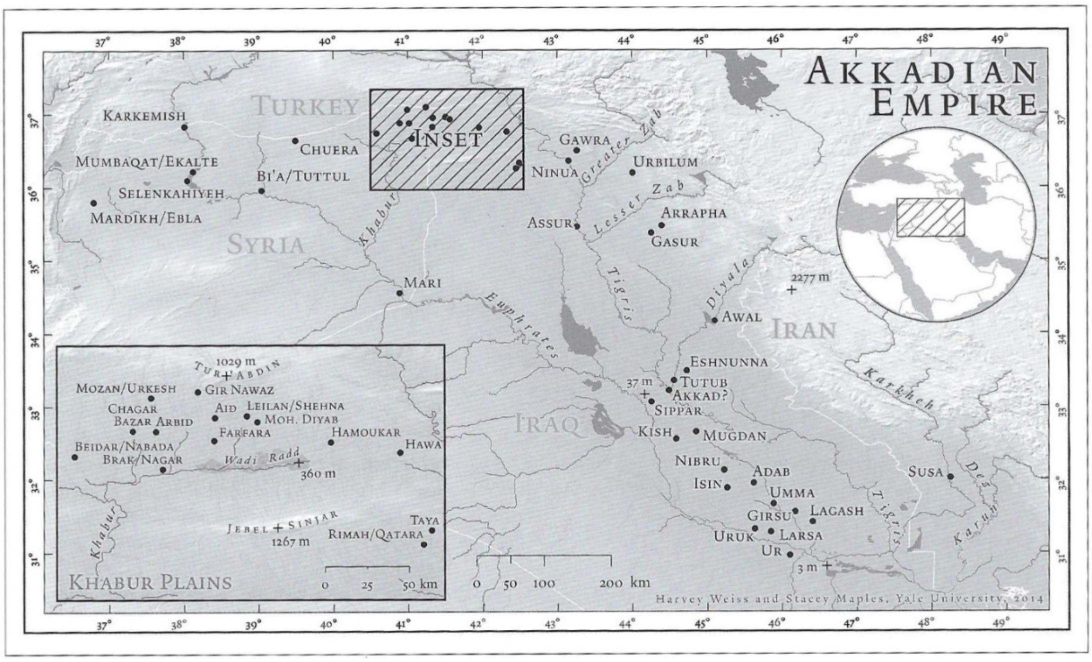

Figure 4-8: Map of the Akkadian empire and the archaeological sites mentioned in the text (Weiss 2015: 39)

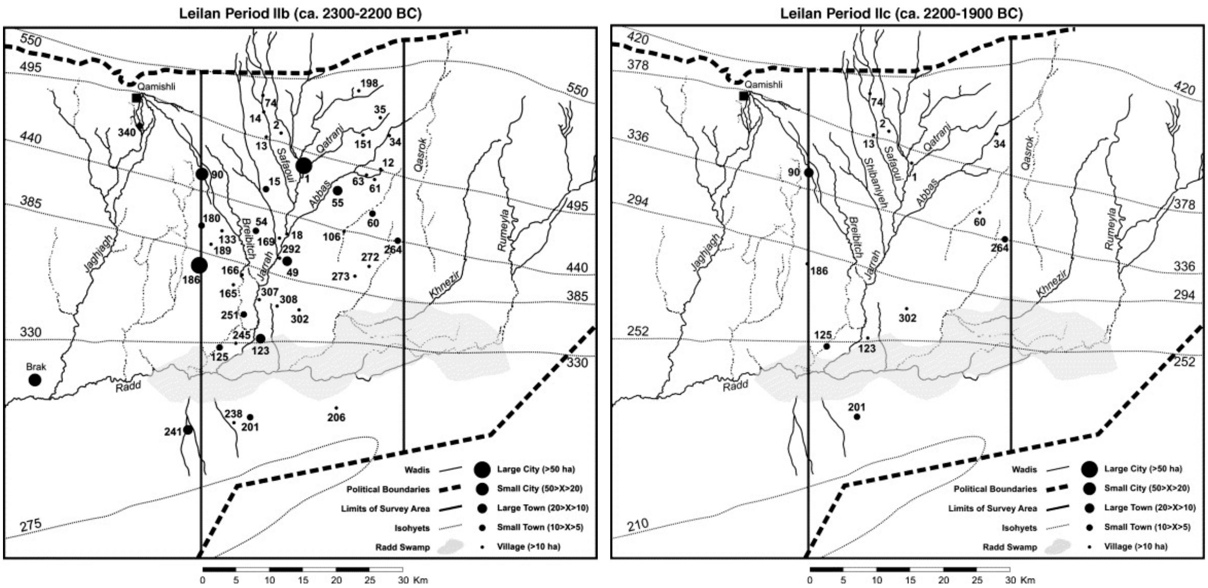

Figure 4-9: Leilan Region Survey Period before and after the 4.2 ka climatic event that led to the argued collapse of the Akkadian empire and a reduction in settellements by 73% in the Tell Leilan region (Ristvet and Weiss 2005: 8 & 10)

As a result of the abandonment of the rain-fed plains in Northern Mesopotamia, population groups migrated and settled near hydrologically varied landscapes (habitat tracking) (Weiss 2016: 63) and, as such, sought refuge in southern Mesopotamia (Weiss *et al.* 1993; Cullen *et al.* 2000: 382). It appears that a combination of complex factors, which include the onset of dry climatic conditions, the decline in agricultural production and the Gutian invasion (Miller 2014: 122), were responsible for the collapse of the Akkadian Empire in the late 5th millennium BP. As in the case of the Akkadian Empire, the collapse of the Ur III Empire in the region occurred during times of major climatic dust events (Sharifi et al. 2015: 225-226)

Based on the examination of the written records and archaeological data, Zettler (2003), however, criticises Weiss's point of view and the role of climate change in bringing about the collapse of the Akkadian Empire. Among various possible reasons, Zettler (2003: 20 & 26) argues that the extent of abandonment in northern Mesopotamia was lower than proposed by Weiss, as evidence for continued occupation is documented in a large part of Khabur and northern Mesopotamia after the 4.2 ka event (see Oates *et al.* 2001: 392-4). Although Tell Brak, a centre of Akkadian imperial administration in northern Mesopotamia, was reduced in size and public and domestic structures replaced Akkadian monumental complexes (Colantoni 2012; Weiss 2015: 43), the site continued to be occupied after the 4.2 ka event (Oates *et al.* 2001: 392-4). The site may have been occupied after the 4.2 ka event, but the evidence is inconclusive. The recovery of charred plant materials from Tell Brak also does not indicate clear evidence of the impact of climate change in the local area (Charles and Bogaard 2001). This lack of conclusive evidence challenges the existing, proposed drought model by Weiss and the related and subsequent collapse concept including the degree of resilience of concerned sites in the region.

In order to evaluate the nature of the impact of the 4.2 ka event on human communities, the climatic evidence will be examined in the forthcoming discussions together with other potential human-environmental issues visible in the archaeological and palaeoenvironmental records of the Bronze Age.

4.4.3 The role of climate change in impacting Bronze Age societies and vegetation composition

In addition to the evidence discussed above, the 4.2 ka BP event has been identified in several other climatic and environmental archives (Table 4-4) including the marine records from the Gulf of Oman (Cullen *et al.* 2000) and the Red Sea (Arz *et al.* 2006) where a prominent, short-lived, abrupt event was registered (Figure 4-10). Radiocarbon dated to 4025± 150 yrs BP, an abrupt increase in aeolian dolomite and calcite deposition has been noted from the study of the Gulf of Oman record (Cullen *et al.* 2000: 380) while the Red Sea record provides evidence of increased sea surface salinity and the termination of laminate deposition at ~4000 yrs BP (Arz *et al.* 2006). The difference noted in the timing between these two records could be indicative of the effects produced by different, prevailing reservoir conditions, which may have impacted on the obtained radiocarbon dates (Finné *et al.* 2011:

3163). This inference may, hence, represent a potential limitation in radiocarbon dating determinations, which is also an aspect that affects lake sediments in the form of the hard-water effect. Hence it highlights the importance of using suitable, reliable material for radiocarbon dating and being aware of this issue.

Figure 4-10: Map showing locations of palaeoenvironmental records mentioned in the text (author's own - base map: Google maps)

The 4.2 ka BP event is also visible in lake records, mostly in the form of enhanced aeolian input, such as of Lake Neor (Sharifi et al. 2015), Jazmurian playa (Vaezi *et al.* 2019), Lake Urmia (Haghipour *et al.* 2020), the stalagmite records from Gol-e Zard Cave (Carolin *et al.* 2019), and the oxygen isotope record from Soreq Cave - the latter shows an increase of up to 1.0‰ in oxygen isotope between 4100 and 4000 yrs BP (Bar-Matthews *et al.* 1999: 91). It should be noted, however, that the identified climatic dry event at ~4100 yrs BP at Soreq cave is understood to be part of a long-term trend towards drier climatic conditions starting from ~4500 yrs BP (Bar-Matthews *et al.* 2003: 3195). Moreover, based on the high Mg/Ca values encapsuled in the Gol-e Zard Cave record, two periods of increased dust flux were identified between 4510- 4400 and 4260-3970 yrs BP - the latter is understood to be larger in extent and/or greater magnitude (Carolin *et al.* 2019). Both periods, however, were overlying an already gradual trend towards aridity as inferred from the oxygen isotope data (Carolin *et al.* 2019: 71). Similarly, at Jeita Cave (Lebanon) dry climatic conditions are understood to have prevailed at ~4200 yrs BP, but probably representing a part within a longer dry climatic event lasting between

5300-4200 yrs BP (Cheng *et al.* 2015). As mentioned in 'Climate History', the 4.2 ka event or, alternatively, drier climatic conditions have also been identified in the climatic and environmental records deriving from the region of Anatolia (Wick *et al.* 2003; Kuzucuoğlu *et al.* 2011; Ülgen *et al.* 2012; see for example Dean *et al.* 2015). Based on the analyses of these records, it seems likely that the 4.2 ka event was superimposed on an already, pre-existing dry climatic event.

Table 4-4: Summary of palaeoenvironmental records indicating dry conditions

Record	Time (yrs BP)	Proxy	Reference
Gulf of Oman	4025± 150	Increase in aeolian dolomite and calcite deposition	Cullen *et al.* 2000
Red Sea	~4000	Increased sea surface salinity and the termination of laminate deposition	Arz *et al.* 2006
Lake Neor	~4200	Enhanced aeolian input	Sharifi *et al.* 2015
Jazmurian playa	~4200	Enhanced aeolian input	Vaezi *et al.* 2019
Lake Neor	4300-3200	Increase in chenopods and a decrease in (A+P)/C ratio; δD values increase to less negative values; increase in Ti abundance and low values of palaeoredox proxies	Alinezhad *et al.* 2021
Lake Urmia	~4200	Enhanced aeolian input	Haghipour *et al.* 2020
Gol-e Zard Cave	4510- 4400 and 4260-3970	Mg/Ca - dust flux identified	Carolin *et al.* 2019
Soreq Cave	~4100 (started from ~4500 yrs BP)	Oxygen isotope	Bar-Matthews *et al.* 1999; Bar-Matthews *et al.* 2003
Jeita Cave	~4200 – located within a longer dry climatic event lasting between 5300-4200 yrs BP	Oxygen isotope	Cheng *et al.* 2015
Katalekhor cave	4300-2000	General increase in $\delta^{13}C$ values along with a reduction in growth diameter	Andrews *et al.* 2020
Lake Zeribar	4000-3500	Increase in *Salix* pollen and detrital minerals, suggesting lowered lake levels	Stevens *et al.* 2001

With regards to the vegetation cover, a potential impact on them has been observed at Lake Neor, characterised by an increase in chenopods and a decrease in (A+P)/C ratio as indicated by the pollen record of the site dated between 4300-3800 yrs BP. This episode of environmental change is also supported by the shift in δD values to less negative values, suggesting the onset of dry climatic conditions. These drier climatic conditions are particularly visible between ~4000-3200 yrs BP, where an increase in Ti abundance and low values of palaeoredox proxies are detected (Alinezhad *et al.* 2021: 606). With the exception of the Lake Neor record, there is, however, no evidence of the 4.2 ka event in the pollen records from Lake Maharlou (Djamali *et al.* 2009b) and Zeribar (Bottema 1997) while the local archaeological evidence has, similarly, yielded no evidence of climate change (Miller 2014). Although the site of Tepe Ghabristan, which is located in northwest Iran, was abandoned at a time of drier climatic conditions (4550-3250 yrs BP), its phase of abandonment does not appear to chronologically coincide with the 4.2 ka event (Schmidt *et al.* 2011: 593).

The 4.2 ka BP event has also not been clearly detected in the isotopic records of Katalekhor cave (Andrews *et al.* 2020), Lake Zeribar, Lake Mirabad (Stevens *et al.* 2006), Sofular cave (northwestern Turkey) (Göktürk *et al.* 2011: 2441) as well as the Qunf Cave (Oman) (Jones *et al.* 2016). Despite the apparent absence of an abrupt climatic event at ~4200 yrs BP, there is some evidence available indicative of general drier climatic conditions. In this regard, for instance, a general increase in $\delta^{13}C$ values along with a reduction in growth diameter have been noted in the record from Katalekhor cave, suggesting a decrease in precipitation levels i.e. dry climatic conditions between 4300-2000 yrs BP (Andrews *et al.* 2020: 15). At Lake Zeribar, we see evidence of an increase in *Salix* pollen and detrital minerals, suggesting lowered lake levels between 4000-3500 yrs BP. A decrease in oxygen isotope values from 4000 yrs BP onwards further suggests that dry climatic conditions prevailed during this time as a result of a decrease in spring rainfall levels. Stevens *et al.* (2001: 753) point out that this dry climatic period is chronologically contemporaneous with the widespread settlement abandonment phase documented in northern Mesopotamia. However, large radiocarbon dating errors prevent robust correlations between the environmental and archaeological data. Similar to Lake Zeribar, a drop in lake level has been identified at Lake Maharlou between 5100-4000 yrs BP along with a decline in *Pistacia–Amygdalus* shrub, suggesting drier climatic conditions in the area. In addition, drier climatic conditions have been inferred from the study of the Gorgan Plain (NE Iran) between 5300-4000 yrs BP, which are characterised by the iron sulphide formation, its oxidation and gypsum precipitation (Shumilovskikh *et al.* 2016a: 1687). This evidence further supports the possibility that the 4.2 ka event was superimposed on a pre-existing dry climatic period although the magnitude of it was possibly not large enough to be detected in these local catchment areas.

According to Carolin *et al.* (2019: 71), based on a two-tailed Student t- test along with similar total duration of the dry event (~290 yrs) and the abandoned settlements (~300 yrs) (Weiss *et al.* 1993) there is a possible link between the abrupt climatic dust event at 4260 yrs BP as recorded in the Gol-e Zard cave record and the timing of settlement reductions in northern Mesopotamia at ~4190 yrs BP (Weiss *et al.* 2012: 184; Carolin *et al.* 2019). The relatively close proximity of the cave to the abandoned settlements further reinforces this interpretation of a possible link between climate change and human societal transformations in northern Mesopotamia (Carolin *et al.* 2019: 71). Although, extreme caution still needs to exercised when inferring palaeoclimate data trends and interpretations from one location to another, highlighting the importance and need for locally based records (Finné *et al.* 2011: 3169; Jones *et al.* 2019: 17), and that correlation does not necessarily imply causality (deMenocal 2001: 672).

Ön *et al.* (2021) point out that the evidence for abrupt climatic dry conditions at 4200 yrs BP derives from proxies of increased aeolian deposits including quartz (%), and Mg/Ca ratio in Lake Van (Lemcke and Sturm 1997), $CaCO_3$ (%) in the Gulf of Oman (Cullen *et al.* 2000), XRF-Ti count in Neor Lake (Sharifi et al. 2015), Mg/Ca ratio in Gol-e Zard (Carolin *et al.* 2019), and the aeolian deposits at Tell Leilan (Weiss *et al.* 1993). However, the stable isotope data does not, as stated above, indicate abrupt climatic dry conditions at ~4200 yrs BP. The recorded high aeolian deposition may, thus, potentially reflect an episode of increased aridity in the central and eastern Mediterranean regions, and stronger westerlies may have been responsible for the increased volume or strength in dust transportation and accumulation in Southwest Asia (Ön *et al.* 2021: 12). Human activity in terms of type (arable vs. pastoralism, and deforestation) and degree of intensification in agricultural activities can also contribute to aeolian deposition in the archaeological and palaeoenvironmental records (Sharifi et al. 2015: 228; Ön et al. 2021: 3). Such anthropogenic activities and processes are well-documented especially from the Middle Holocene onwards when human activity intensifies (Djamali *et al.* 2009b: 130; Finné *et al.* 2011; Ponel *et al.* 2013), which will be discussed in detail in the forthcoming sections below.

In other words, the 4.2 ka event is detectable in certain records, especially dust records, and varies in duration and amplitude across the region. Records, which do not indicate a clear, abrupt dry climatic event do, however, suggest for a general pre-existing trend towards aridity from ~5000 yrs BP onwards.

Assessing the precise role of the impact of the 4.2 ka event on ancient communities and the environment is complicated as its expression varies (see Railsback *et al.* 2018) and, thus, it cannot be explained straightforwardly and in simplistic terms as opposed to other climatic events identified in the Holocene sequence (Bini *et al.* 2019). In the Central Mediterranean region, for example, the 4.2 ka event has been expressed as a tripartite climatic oscillations, characterised by two wet phases dated to ~4300-4100 and 3950-3850 BP including one dry phase dated between ~4100-3950 yrs BP (Magny *et al.* 2009). Therefore, besides acting as a single long, dry climatic event in certain geographic parts of the Southwest Asia, the 4.2 ka event also expressed itself through a series of dry/wet events in other regions (Railsback *et al.* 2018; Bini *et al.* 2019), revealing the complex, multi-facetted nature and impact of this major climatic phenomenon in the past.

There is a range of issues, which make effective cross-comparative studies and discussion between different climatic and environmental records a challenging task. One of the main issues affecting the study of the global 4.2 ka 'megadrought' event (Weiss 2016) and its impact, concerns the existing, imprecise chronological models and uncertainties associated with the event. The signal of this climatic dry event also does not seem to have been picked up in all the proxy data (Finné *et al.* 2011), making it doubtful to view the 4.2 ka event as a generalised period of marked arid conditions (Bini *et al.* 2019: 556). In addition, chronological uncertainties and records with contrasting resolutions hinder the precise identification of the event, its timing and duration (Bini *et al.* 2019: 562).

Another methodological issue in the study and identification of a climatic event concerns the poor resolution of the palaeoenvironmental records as already mentioned above (Finné *et al.* 2011: 3169). The low-resolution of the oxygen isotope records could explain why the abrupt 4.2 ka event is currently not detectable at Lake Zeribar and Mirabad (Stevens *et al.* 2006). In this regard, the environmental record from Lake Van serves as a good example to illustrate this point. Based on the maximum oxygen isotope enrichment and increased Mg/Ca values, lake levels at Lake Van declined at ~4190 yrs BP along with a reduction in humidity, implying dry conditions in the area (Lemcke and Sturm 1997). However, a high-resolution analysis of Lake Van was carried out at a later stage, which, in contrast, indicates no significant abrupt dry climatic event at the time. In fact, the Mg/Ca and oxygen isotope values suggest the onset of dry conditions starting somewhat later from ~4000 yrs BP onwards (Wick *et al.* 2003: 673). Therefore, to improve the existing palaeoclimatic reconstruction records, higher sampling resolution are required in future research (Finné *et al.* 2011: 3169).

4.4.4 Impact of dry climatic conditions on the Zagros region

Long-term settlement trends for southwest Iran (Figure 4-11) identified a period of increased regional growth, both in terms of number of settlements and increase in the size of settlements, in the lowland (Susiana Plain, Ram Hormuz Plain and Deh Luran Plain) and highlands (upland region of the Zagros mountains – Kur River Basin and Islamabad Plain) between 7000-6000 yrs BP (Hopper and Wilkinson 2013: 42).

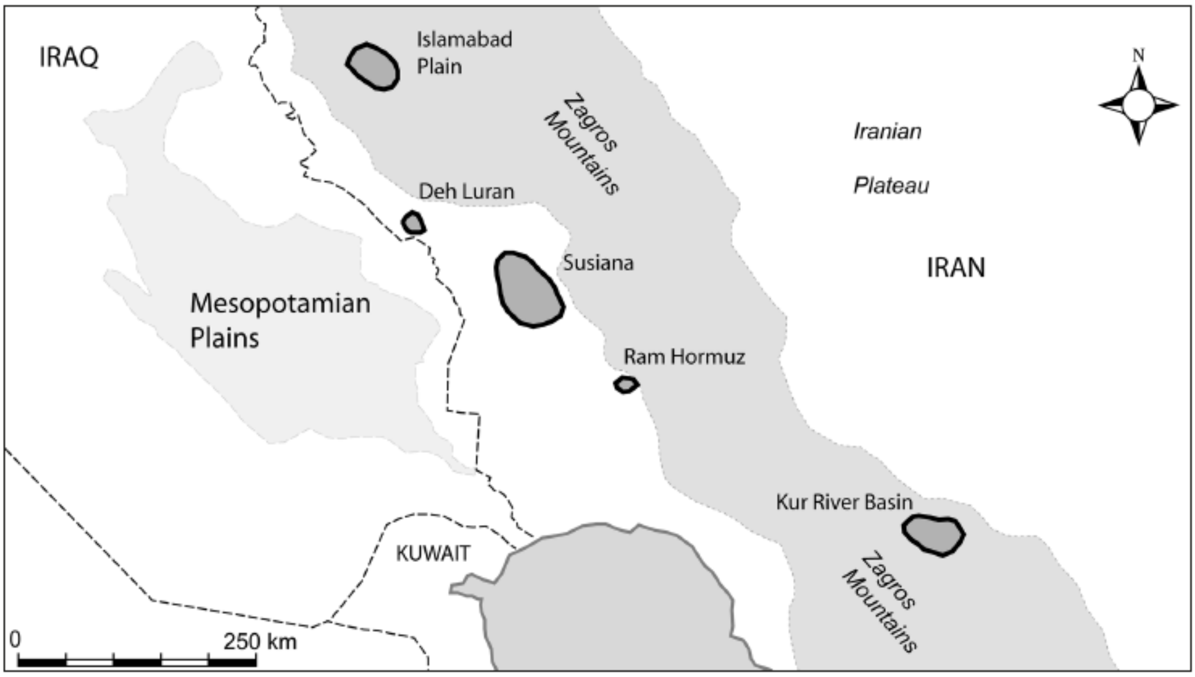

Figure 4-11: Map of southwest Iran and Mesopotamia, showing the regions mentioned in the text (Hopper and Wilkinson 2013: 36)

This was followed by settlement decline in both regions (upland and highland of southwest Iran) until ~5000 yrs BP that has been linked to major growth (increase in population and settlements) along with a settlement agglomeration trend in lowland plains of Mesopotamia, suggesting a significant influx of people from southwest Iran to the growing urban centres of Mesopotamia, leading to an increase in settled population (Adams 1981: 69-70; Hopper and Wilkinson 2013: 41). From 5000 yrs BP onwards an increase in population size has been identified in the lowlands of southwest Iran, while a decline in the Kur Basin (highland) occurred between ~ 4800-4400 yrs BP after which both the lowland and highland experienced major growth in terms of settlement size (Figure *4-12*) (Hopper and Wilkinson 2013: 43).

Based on archaeological field surveys and the study of the recovered ceramic materials, population levels that are dependent on demographic factors (i.e. birth and death rates), economic strategies and movement of people between regions (Hopper and Wilkinson 2013: 45) declined at a significant scale in the Fars region between 4800-4200 yrs BP (Sumner 1989; Sumner 2003: 54-55). A general scarcity in the number of settlement sites has also been noted in the southern and central Zagros region (Miller 2014: 124-125). The Zagros region seems to have experienced a decline in the number of proto-urban societies during the early 5th millennium BP (Thornton 2012: 596) although some sites were reoccupied by migrating Early Trans-Caucasian communities (Batiuk and Rothman 2007: 15). In addition, settlement occupation for the early 5th millennium BP in the 'eastern corridor' (area of land between Susiana and Ram Hormoz Plain) of the lowlands of southwest Iran is unclear with only a few scattered shards identified (Moghaddam and Miri 2007: 34). The decline in settled area in the Susiana Plain during the early 5th millennium BP could be related to the increase in aggregate occupied area and large settlements in southern Mesopotamia (Hopper and Wilkinson 2013: 44).

The precise reasons behind this widespread transformation in the socio-economic and cultural layout and configuration of the region are currently not clear, but it does correlate with a marked drop in temperature after the 5.2ka event, peaking at ~4800 yrs BP (Babak 2020: 40). The potential occurrence of dry climatic conditions during this time could have put major pressure and stress on Early Bronze Age communities especially on those located within vulnerable environments (Babak 2020: 40). An alternative model that has been proposed to explain the general abandonment of concerned sites during the Early Bronze Age includes a possible shift towards pastoral nomadism (see also Miroschedji 2003) which would be difficult to detect in the archaeological record, but could explain the high population size in the lowlands and low population size in the highlands of southwest Iran during the early 5th millennium BP (Alizadeh 2010: 372).

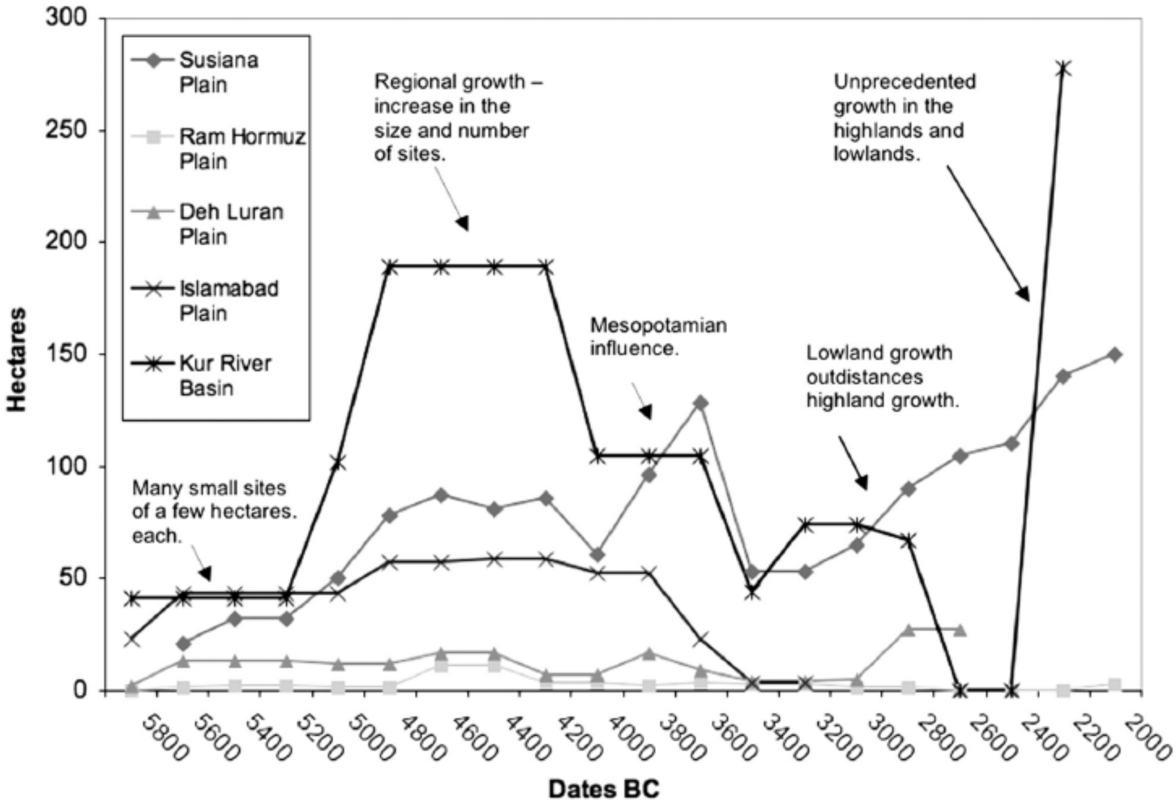

Figure 4-12: Population trend for the different regions of southwest Iran between 7800-4200 yrs BP (Hopper and Wilkinson 2013: 42)

At the site of Tal-e Malyan in the southern Zagros of Iran (Fars region), for example, there is evidence that the site increased in size to ~50 hectares between 5250-4950 yrs BP while a number of rural and hinterland sites in the region declined or were deserted at around the same time (Sumner 1972; Sumner 1986). It was only later in time, that Tal-e Malyan reduced in size to c.28 hectares between 4950-4600 yrs BP. These marked changes in settlement pattern and size may be related to transhumant pastoralist traditions being practiced in the region. Tal-e Malyan and other sites in the Kur River Basin were, in fact, occupied by small sedentary groups of communities during this time interval (Alden *et al.* 2005: 42). An apparent lack in the number of settlement sites does not necessarily indicate the absence of people during this time which is why it is reasonable to consider the incoming appearance of a pastoral nomadic population who firmly occupied the region continuously between 4800-4200 yrs BP (Sumner 2003: 55; Miller 2014: 126). This potential changing pattern suggests that Tal-e Malyan was probably not abandoned during the prevailing dry conditions in the region and that the 4.2 ka event may not have had a significant impact on the site, which in turn rose to become an important centre in the late 5th millennium BP (Sumner 1989; Petrie *et al.* 2005), increasing in size to 130 hectares between ~4200-3600 yrs BP (Thornton 2012: 598). Furthermore, a notable decline in *Juniper* trees was observed during the 400-year settlement gap in the Kur River basin during the early-mid Bronze Age period, which has been attributed to the activities of pastoral nomads rather than the effects of climate change (Miller 2014).

This evidence could suggest that the abrupt 4.2 ka climatic event was either not strong enough in magnitude to impact upon the vegetation composition and the various human communities inhabiting the Zagros region or that certain communities were resilient enough to adapt themselves when confronted with the effects of dry climatic conditions that already started at the beginning of the 5th millennium BP. It is, however, not as straightforward to investigate the link between climate and human settlement reliably. For example, gaps and missing settlement data for the Sharizor Plain (Iraq) for the first half of the 5th millennium and the mid-4th millennium BP make it difficult to make correlations between these two data sets (Altaweel *et al.* 2012: 29). It is important to highlight that a lack of sites does not necessarily imply reduction of settlements in an area but could also be a result of sites being obscured by irrigated and alluvial sediments, or incomplete archaeological record (Hopper and Wilkinson 2013: 37).

Our current inability to precisely distinguish between climatically and human-induced changes becomes more prominent when dealing with the available evidence from the 5th millennium BP (Finné *et al.* 2011: 3168). Human activities, that include pastoralism, left a bigger impact on the landscape from 6000 yrs BP onwards, which makes it incredibly difficult to determine the role of climate in their lives (Ponel *et al.* 2013; Miller 2014: 130). Thus, the exclusive use of pollen data as a proxy for climatic reconstructions reduces from the Middle Holocene period onward (Finné *et al.* 2011: 3163). To overcome this issue, multi-proxy studies are needed both to detect a change in climate, as otherwise a human activity signal may be mistaken as evidence of climate change, as well as to reveal the causes behind environmental change (climate change vs. human activity) (Finné *et al.* 2011: 3170).

Based on the currently available data, dry climatic conditions appear to be prevailing during the 5th millennium BP in Southwest Asia. Some records have, indeed, picked up the abrupt 4.2 ka climatic event while others did not. This apparent contrast would suggest that the 4.2 ka climatic event was either not a widespread and abrupt climatic event or that it was masked by the already, pre-existing drier climatic conditions in the region (Finné *et al.* 2011: 3169). The low-resolution of certain palaeoenvironmental records (e.g. Lake Zeribar and Mirabad) is probably yet another factor as to why the 4.2 ka event is not clearly visible. There is also the possibility that it may represent a regionally articulated event, having a locally different climatic expression (Bini *et al.* 2019: 569). Therefore, it is likely not to see a uniform response to the climatic event in the archaeological and palaeoenvironmental data (Ön *et al.* 2021).

To overcome the various types of limitations discussed above and detect the short-lived 4.22ka event, and to make precise correlations between the archaeological and climatological records, new multi-proxy records with a higher resolution and robust, precise age-depth models are needed (Finné *et al.* 2011: 3169; Schmidt *et al.* 2011: 593; Bini *et al.* 2019: 570).

The uneven spatial distribution of the proxy records (Finné *et al.* 2011: 3168; Bini *et al.* 2019) due to potentially a lack in suitable proxy records in Southwest Asia and the associated radiocarbon dating difficulties such as hard-water effect, which impacts the dating precision, and to a lesser extent publication obstacles such as of new data in a non-English language (see Finné *et al.* 2011: 3168; Safaeirad *et al.* 2014; Zavvar *et al.* 2017), present a substantial challenge to effectively and critically study human-environmental relationships during the Bronze Age of the Zagros region.

4.5 The Iron Age (3250 – 2330 yrs BP)

4.5.1 Characterisation of the Iron Age

The Iron age of Southwest Asia is notably known for the rise and expansion of the Neo-Assyrian empire at 2912 yrs BP that stretched at its height from Central Anatolia in the north to the Mediterranean and Egypt in the west, and eastward to the Persian Gulf and western Iran (Figure 4-13). The control and power of the Neo-Assyrian empire, however, did not last more than 300 years, concluding in its political collapse ~2609 yrs BP (Sinha *et al.* 2019b). With the fall of the Neo-Assyrian empire, a dark age started in Northern Mesopotamia with little evidence for continuity and lack of archaeological data (Kuhrt 1995; Curtis 2003). Several hypotheses have been proposed to explain the rise and collapse of the empire, including the impact of climate change (see: Schneider and Adalı 2014; Sinha *et al.* 2019b), that are discussed in detail below. In addition to the many empires that rose to power including the Neo-Assyrian empire, and the Persian empires that followed (Achaemenid, Parthian and Sassanian), the Iron age is considered an age of military campaigns, conquests, civil unrests (Collins 2016: 106-157), construction of roads and irrigation networks for agricultural purposes, parks and gardens (Wilkinson *et al.* 2005: 24; Bonacossi 2018). During the Iron age, the Zagros region witnessed the emergence of kingdoms/states (Greco 2003), including the strong state of the Medes, and continued to exercise transhuman pastoralism . According to Potts (2014: 47-46), however, there is no concrete evidence in the Iranian prehistory archaeological record that suggests transhuman nomadism was practiced and that it was only in the late medieval period that nomadism started.

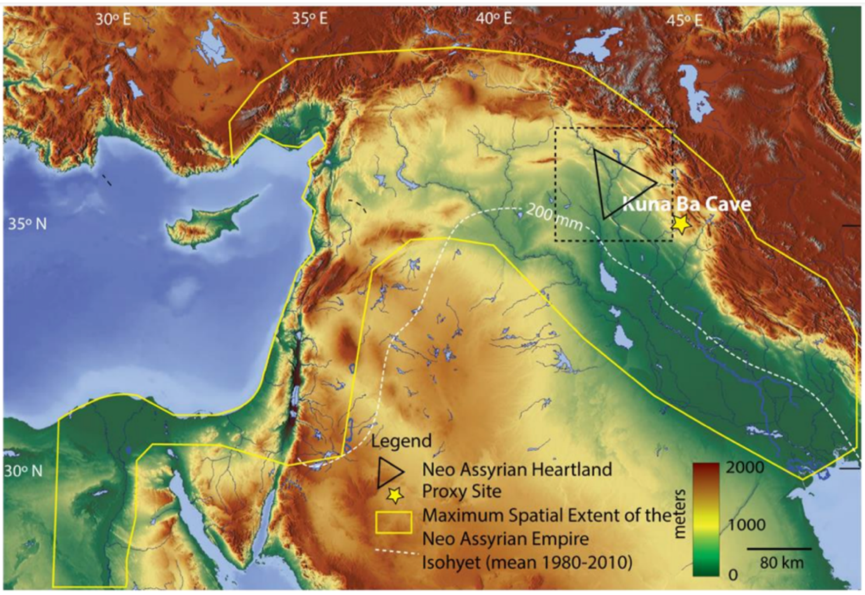

Figure 4-13: The geographic location of the Neo-Assyrian Empire. The yellow line indicates the maximum spatial extent of the empire at its peak (~2670 BP) (Sinha et al. 2019a: 7)

Furthermore, Southwest Asia hosted the emergence of tree cultivation and the start of arboricultural practices, in particular with the start of the Achaemenid empire at ~2550 yrs BP (Djamali *et al.* 2010b). The main cultivated tree species in the southern Zagros were walnut (*Juglans*), grapevine (*Vitis*), and plane tree (*Platanus*) (Djamali *et al.* 2009b), while in southwest Iran olive (*Olea*) trees were cultivated (Jones *et al.* 2015) (Figure 4-14). In the southern Zagros region, there is evidence for tree cultivation starting much earlier in time with walnuts (*Juglans*) cultivated ~4500 yrs BP and plane tree (*Platanus*) ~3900 yrs BP (Djamali *et al.* 2009b). Archaeological evidence indicates the construction of hydraulic structures such as diversion dams, tunnels, canals, kärlz (qanat) systems, and aqueducts during the Achaemenid period (Malekzadeh 2007) that played a major factor in the intensification of tree cultivation (Djamali *et al.* 2010b). Tree cultivation, however, significantly declined by 2350 yrs BP according to the Lake Maharlou pollen record, coinciding with the collapse of the Achaemenid empire at 2330 yrs BP (Djamali *et al.* 2010b: 178-179), never to reach the same extent of tree cultivation in the centuries to come.

Following on from this summary of the key characteristics and episodes of the Iron Age, the next section examines the available palaeoenvironmental and archaeological data for the time frame covering the Neo-Assyrian empire in order to investigate the role of climate change in impacting the rise and collapse of the empire.

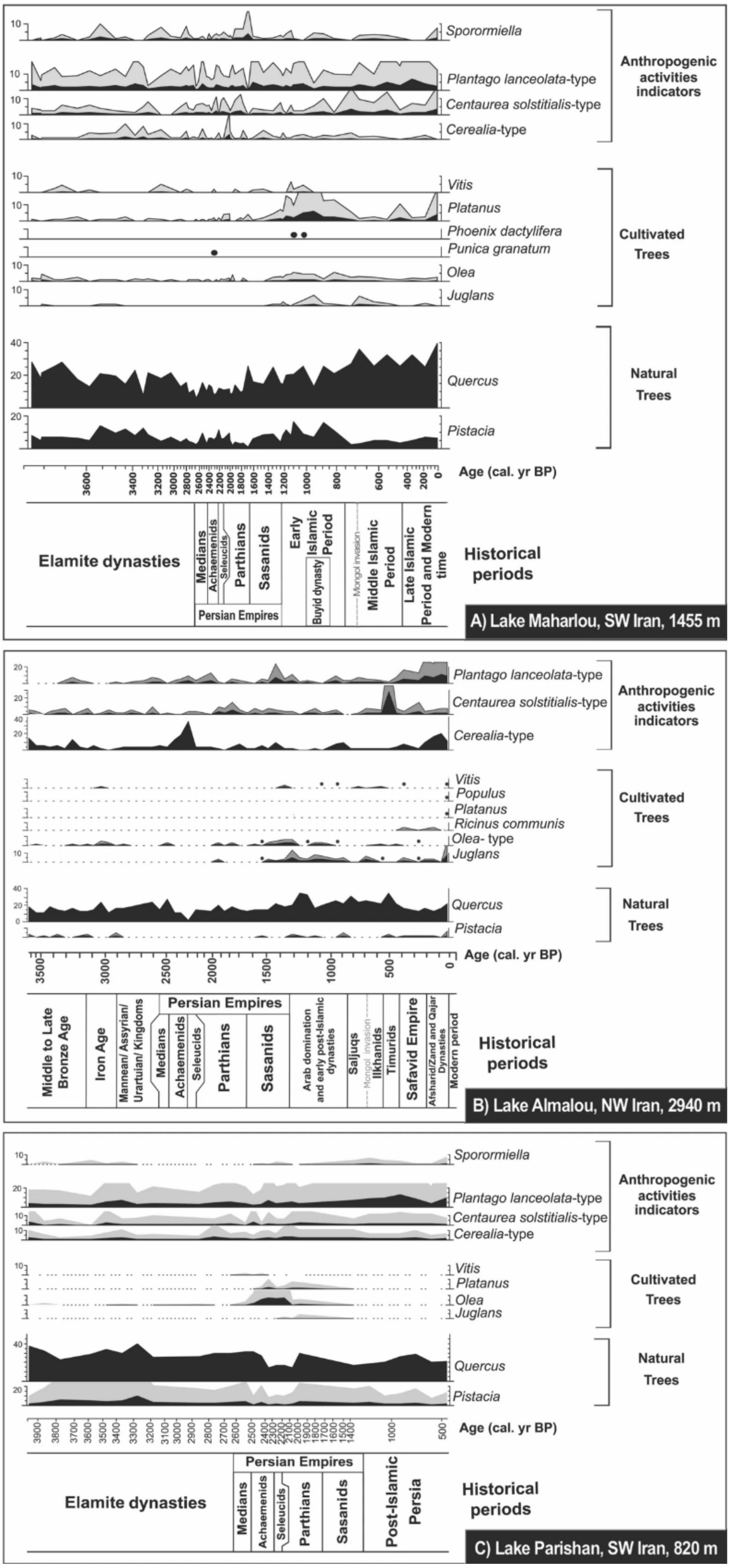

Figure 4-14: Summarised pollen diagram of A: Lake Maharlou, B: Lake Almalou, and C: Lake Parishan to compare the anthropogenic activities and tree cultivation (Saeidi Ghavi Andam et al. 2021: 606)

4.5.2 The rise and fall of the Neo-Assyrian Empire

Prior to examining the factors behind the rise and the fall of the Neo-Assyrian empire, it is necessary to consider the interannual precipitation variability and drought vulnerability of the region, which is followed by how variability and vulnerability impacted the Neo-Assyrian empire. The Neo-Assyrian heartland (see triangle in Figure 4-13) and its hinterland were located in an agricultural zone known as a "zone of uncertainty" because of a 40-60% interannual precipitation variability, causing rain-fed cereal cultivation to be risky and potentially leading to crop failures during times of low rainfall (Sinha *et al.* 2019b).

However, the Neo-Assyrian empire reaped the rewards of farming in the zone of uncertainty with a rise in power during a wet climatic interval between ~2925–2725 BP yrs BP (Figure 4-15), that peaked between ~2800 and 2690 yrs BP, as evidenced by the high-resolution and precisely dated speleothem record from Kuna Ba cave (northern Iraq). This wet climatic interval, termed the 'Assyrian Megapluvial', would have underpinned and strengthened the Neo-Assyrian agrarian economy, and was synchronous with Neo-Assyrian imperial expansion and high-density urbanization (~2920–2730 yrs BP) (Sinha *et al.* 2019b). Written records recovered from the Neo-Assyrian royal archives also confirm the presence of wet conditions during Sargon II's reign (2721-2705 yrs BP) (Radner 1999: 236). This written text along with other texts suggesting wet climatic conditions (see Parpola 1983), however, need to be used with caution as they may have been subjected to royal propaganda (Schneider and Adalı 2014: 438).

According to the Kuna Ba speleothem record, this wet period was followed by ~125 years of aridity, between 2650-2500 yrs BP (Figure 4-15). This record indicates the highest $\delta^{13}C$ and $\delta^{18}O$ values for this time interval (Sinha *et al.* 2019b). This peak aridity interval, termed the 'Assyrian Megadrought', overlaps with the decline and subsequent collapse of the Neo-Assyrian empire between 2660-2600 yrs BP, suggesting that climate may have played a factor in the downfall of the empire (Schneider and Adalı 2014; Sinha *et al.* 2019b).

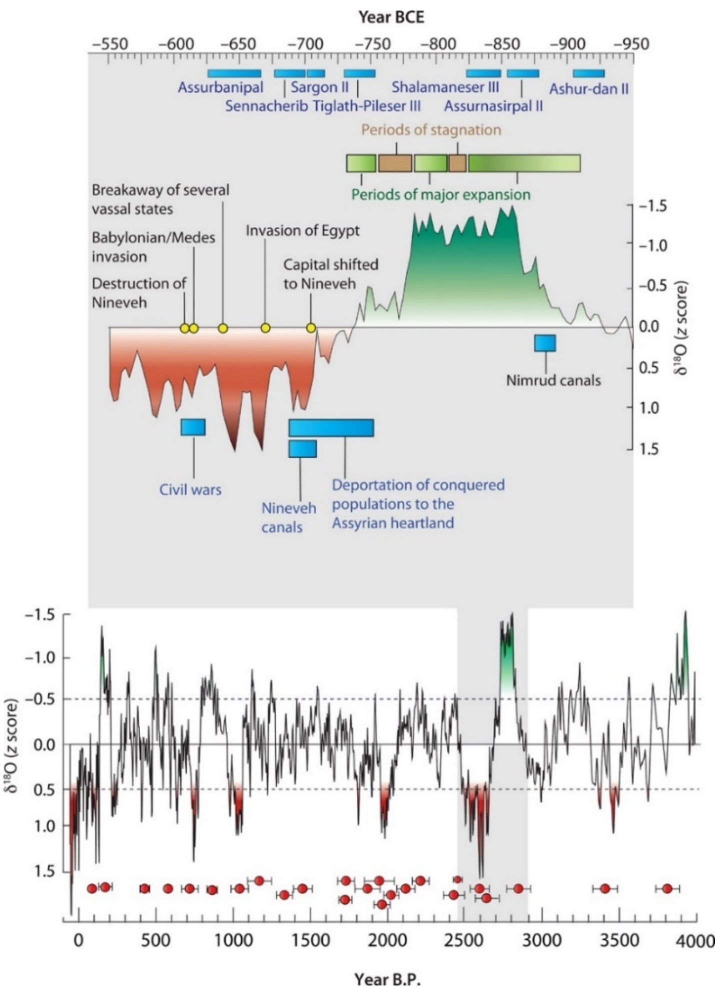

Figure 4-15: Comparisons between the detrended Kuna Ba cave z score transformed δ18O record and the key Assyrian historical events (Sinha et al. 2019b: 4)

The transition from megapluvial to megadrought conditions, between 2700-2600 yrs BP, coincides with an abrupt wet and cool climate event – the 2.8ka event, also known as the Bond event 2 (Bond *et al.* 1997; Wanner *et al.* 2014). Wet climatic conditions and high lake stand, coinciding with the 2.8ka event, have been identified at Lake Maharlou and Lake Almalou at ~2800 and 2900 yrs BP, respectively (Djamali *et al.* 2009a; Saeidi Ghavi Andam *et al.* 2021).

The megapluvial and megadrought identified in the Kuna Ba record, have also been identified in other palaeoenvironmental records of the region which have been summarised in Table 4-5. As can be seen from Table 4-5, however, the wet and subsequent dry period are not identifiable in every palaeoenvironmental record. This could be due to various reasons including low temporal resolution, sensitivity of the proxy to pick up the climatic events, as well as the geographic location. A general shift towards drier climate is nonetheless visible in the majority of the records, suggesting that the dry period may have been widespread (Schneider and Adalı 2014: 437).

Table 4-5: Summary of palaeoenvironmental records in modern day Iran and Iraq, covering the Iron Age

Site name	Proxy	Climate	Time (yrs BP)	Reference
Katalekhor Cave (Iraq)	$\delta^{13}C$	Dry	3400-2200	Andrews *et al.* 2020
Shalaii Cave (Iraq)	Sedimentary, phytolith, speleothem	Dry	2500 onwards	Marsh *et al.* 2018
Lake Neor (Iran)	Geochemical	Dust event	2800 and 2500	Sharifi *et al.* 2015
Lake Neor (Iran)	Pollen and geochemical	Wet	3150-2215	Alinezhad *et al.* 2021
Lake Urmia (Iran)	Pollen	Dry and cold	2550-1500	Talebi *et al.* 2016
Arasbaran area (Iran)	Pollen	Dry	3000-2100	Ramezani *et al.* 2020
Ganli-Gold (Iran)	Pollen	Dry and cold	3000-2850 2650-2350	Zavvar *et al.* 2017
Ganli-Gold (Iran)	Pollen	Wet period	2850-2650	Zavvar *et al.* 2017
Lake Almalou (Iran)	Pollen	High lake stand	At 2900	Djamali *et al.* 2009
Lake Maharlou (Iran)	Sedimentological and elemental analysis	Wet	3800-2000	Brisset *et al.* 2019
Lake Maharlou (Iran)	Pollen	Dry	2800-2100 Wet -4000-2800	Djamali *et al.* 2009
Kongor lake (Iran)	Pollen	Wet	2700 onwards	Shumilovskikh *et al.* 2016
Lake Mirabad (Iran)	$\delta^{18}O$	Dry	3200 onwards	Stevens *et al.* 2006
Lake Zeribar (Iran)	$\delta^{18}O$, Ostracod, and Pollen	Dry	3350-2300	Wasylikowa and Witkowski 2008; Stevens *et al.* 2008
Konar Sandal (Iran)	Pollen	Dry and decline in water table	3400-2800	Gurjazkaite *et al.* 2018
Konar Sandal (Iran)	Pollen	Wet and rise in water table	After 2800	Gurjazkaite *et al.* 2018

Since the economy of the Neo-Assyrian empire was largely based on agricultural production (dry-farming), a significant reduction in rainfall would have had an enormous impact on the Neo-Assyrian society, including shortage of food supply for cities within the core of the empire, leading potentially to a significant increase in the price of agricultural produce (Schneider and Adalı 2014: 443).

Moreover, the capital city's (Nineveh) size expansion under Sennacherib's rule (2704-2681 BP) from 150ha to 750ha by the time of its destruction at 2612 yrs BP (Stronach 1994), led to a reduction of agricultural fields as they were replaced by urban development (Wilkinson 1995: 148). Nineveh's agricultural area was further constrained by low hills of lesser agricultural productivity, making the city reliant on the import of agricultural supplies from other parts of the empire as well as intensification of agricultural production (Wilkinson *et al.* 2005: 27). To protect against the high precipitation variability and to intensify irrigation-based agricultural production, an extensive hydraulic infrastructure was constructed by Sennacherib (Figure 4-16) (Bagg 2000; Wilkinson *et al.* 2005; Ur 2005; Bonacossi 2018). Besides being used to intensify agricultural activity, the canals and rivers could have been used to transport large quantities of cereals across the Assyrian heartland when and if needed (Bonacossi 2018: 73), and in addition to rivers, springs which were often enlarged to form reservoirs were also used to feed the canals (Wilkinson *et al.* 2005: 29).

As interannual variability in rainfall was common in the dry farming areas of Upper Mesopotamia, Sołtysiak (2016) argues that local strategies were in place to mitigate against possible crop failures due to drought conditions including storage of agricultural surpluses in granaries (Pfälzner 2002; see Paulette 2013: 106-108). Despite the presence of granaries, however, it is unknown what their total carrying capacity was and how much agricultural surplus was stored within them at a particular point in time (Schneider and Adalı 2016: 397-398). Further, despite the extensive irrigation system constructed during Sennacherib's rule, due to the annual discharge rate of the water bodies feeding the canal system being influenced by the amount of precipitation (Reculeau 2011), the irrigation system would have struggled during intense drought periods (Schneider and Adalı 2014: 440).

Moreover, under Sennacherib's rule, the Neo-Assyrian heartland experienced a major increase in population size because of geographic expansion and subsequent forced deportation of people into the heartland (Oded 1979; Wilkinson *et al.* 2005: 32; Ur 2005: 343). This unsustainable population growth would have reduced the Assyrian heartland's resilience to crop shortages during severe droughts, despite the presence of an extensive hydraulic infrastructure. According to Oates (1968: 47-49), the hydraulic infrastructure would have not been sufficient to sustain the cities' growing populations, highlighting their reliance on contributions from their agricultural hinterlands. Thus the major increase of population size along with dry climatic conditions would have created considerable economic and political instability within the Neo-Assyrian empire (Schneider and Adalı 2014).

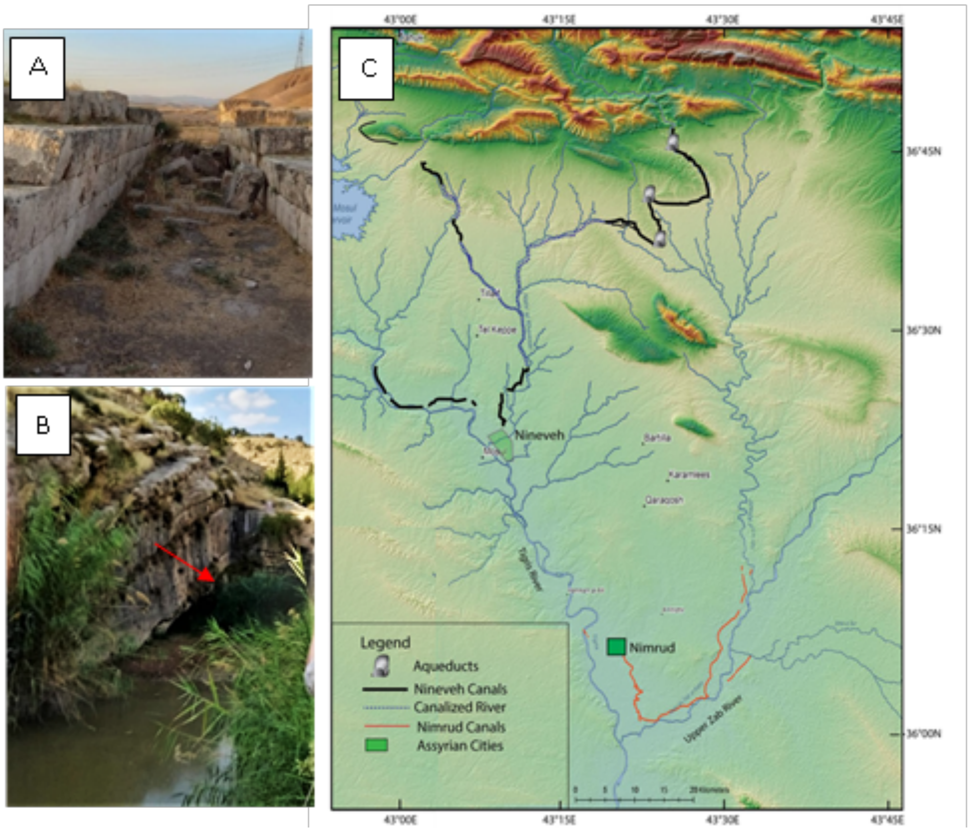

Figure 4-16: A and B: Canals at the sites Khinnes and Jerwan that were constructed to divert and supply water to Nineveh under Sennacherib's reign (author's own) C: Map of northern Assyria showing ancient city of Nineveh and Nimrud and remnants of the Neo-Assyrian canal system (Sinha et al. 2019a: 8)

As mentioned throughout the thesis, however, correlation does not mean causation. Human societies are able to adapt to changing climate and environmental conditions. For instance, although cereal cultivation declined during periods of dry climatic conditions in the Jiroft valley (3500-2800 yrs BP), the presence of Plantaginaceae and *Polygonum aviculare*-type during this dry period, suggests that settlements were not abandoned but rather extensive pastoralism was practiced between ~ 3600-2200 yrs BP to adapt to drying climatic conditions (Gurjazkaite *et al.* 2018). Therefore, in order to reliably assess the impact of climate change on human societies and their resilience, Sołtysiak (2016) argues that among other factors an estimation of available resources (i.e., humans, animals, and cereals), resource allocation and their sensitivity to the environmental conditions needs to be considered.

Thus, while dry climate could have had a potentially devastating impact on the Neo-Assyrian empire, in particular its economy, other factors also need to be considered when identifying the factors behind the empire's collapse (Figure *4-17*). These include political instability in the form of civil unrests, which according to Sinha *et al.* (2019b: 6) may have worsened to due crop failures during the Assyrian

Megadrought period, and territorial overextension. The final political factor was the destruction of the capital, Nineveh, by the alliance between the Neo-Babylonian Empire and the Medes in 2612 BP (Schneider and Adalı 2014)

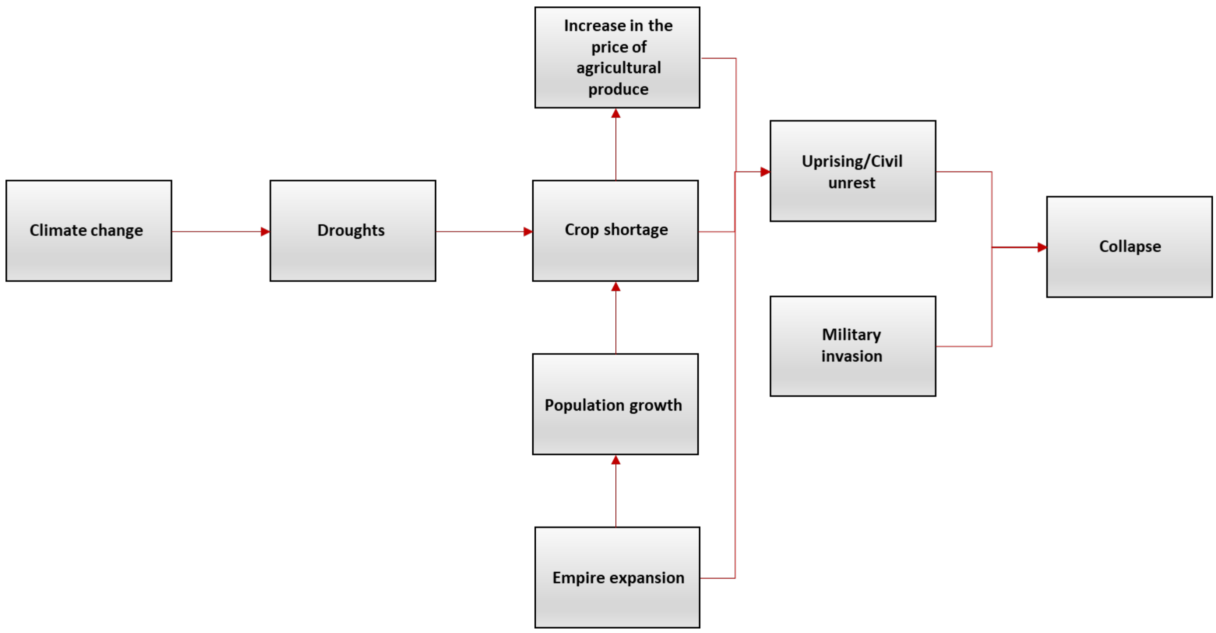

Figure 4-17: Hypothetical pathway to collapse (derived from Sinha et al. 2019 and Schneider and Adalı 2014)

In summary, according to the available palaeoenvironmental and archaeological data, a combination of dry climate conditions, internal politico-economic conflicts (including civil unrests), territorial/imperial overextension, and military defeat led to the empire's collapse (Sinha *et al.* 2019b). As in previous discussion, it becomes apparent that multiple factors contribute to the collapse of an empire or change in lifestyle with climate change playing a contributing factor. To improve our understanding of the role of climate in the changes in the archaeological and palaeoenvironmental record it is essential to increase the number of high-resolution palaeoenvironmental records for this region. Although the number of palaeoenvironmental records covering the Iron Age is higher than for earlier periods, not all of the records show similar trends which might be related to either resolution of the records or the sensitivity of the proxy used. Nonetheless, it shows how critical it can be to generalise from a single palaeoenvironmental data source. Thus, there is a need to improve the spatial coverage of palaeoenvironmental records.

4.6 Summary and knowledge gaps identified in research context (Chapters 2-4)

This section summarises key themes and highlights gaps in knowledge and limitations of previous studies. Key ongoing debates related to human-environmental relationship for each cultural time interval are as follows:

4.6.1 Key debates – human environmental relationships

Key debates across time periods are presented in Table 4-6.

Table 4-6 Summary of key debates

Time Period	Key questions/debates
Epipalaeolithic period	Did BSR take place within resource-rich or resource-depleted environments?
	Did the climate of the Lateglacial impact subsistence and habitation patterns of the Epipalaeolithic communities?
Neolithic period	The role of Lateglacial Stadial and Holocene climate in the emergence of agriculture
	To what extent were Neolithic communities resilient to climatic events?
	To what extent were Neolithic activities and climatic conditions responsible for the delay in woodland expansion in the Early Holocene period?
Chalcolithic period	The impact of climate change on settlement patterns, subsistence strategies and state complexity
Bronze period	The impact of drier climatic conditions on Bronze Age communities and the Akkadian empire
Iron period	The impact of climate change on the environment and the Neo-Assyrian empire

4.6.2 Summary of gaps in knowledge

Based on the review of the research context, the following knowledge gaps and issues have been identified:

- **Chronological issues in palaeoenvironmental and archaeological records** – as the review illustrated it is essential to have a robust and reliable chronology in order to compare different data sets but also to identify the timing and duration of an event, be it collapse of an empire or timing of a climatic event. The primary issue with pollen records, especially, is the lack of dateable organic material which leads to the dating of bulk samples that are likely affected by hard-water effect and thus yield older than expected dates. Isotope records from the Zagros region also suffer from large age uncertainties which further hinders identification of precise timing of change. In addition, these isotope records are also of coarse resolution so it is possible that these records might not capture short term climatic events.

- **Low geographic variability of palaeoenvironmental records** – there is a lack of palaeoenvironmental records for the Zagros region. Using palaeoenvironmental records located at a large distance away from the study area to understand environmental conditions ignores the fact that the Zagros region is a complex topographic region which will be reflected in both the vegetation cover and climatic conditions. To understand and appreciate local variations in the Zagros region, more studies need to be conducted within the area. As highlighted in this chapter, it appears the western Zagros already had trees present in Pleniglacial period while pollen records of the eastern Zagros indicate their presence from the Lateglacial period onwards. These differences, highlight the need to conduct more research on the western side of the Zagros Mountain to improve our understanding of variability in both the climate and vegetation composition.

- **Issues with pollen records of the Zagros region** – As already mentioned some of the pollen records for the Zagros region suffer from chronology issues, specifically the Lake Zeribar record. Only two out of five pollen records cover large time intervals including the Lateglacial/Holocene transition but both suffer from problems e.g. large age uncertainties, use of bulk samples for radiocarbon dating, and pollen preservation issue. Thus, there is a need for high-resolution pollen records covering earlier time periods. Furthermore, the age-depth models need to be constrained, robust and reliable to allow comparisons to be made with other data sets and identify the timing of potential vegetation responses to climate and human activity.

- **Correlation does not imply causation** – Within the review, it was identified that there is a tendency towards implying climate change was a primary factor in changes identified in the archaeological record such as collapse of empires and settlement changes. Although climate likely was a contributing factor in some of the changes, other factors also need to be taken into consideration such as political instability. A number of different factors will contribute to the changes that can be seen in the archaeological record. It is equally important to appreciate the local environment around the archaeological sites as some sites might have access to a variety of ecozone while others might not. Human communities would have taken advantage of the sources available to them locally which will vary from site to site. Therefore, it is important to carry out more high-resolution palaeoenvironmental studies to understand the environment human communities were utilising and living in. Furthermore, in order to compare two different data sets, in this case the archaeological and palaeoenvironmental data, both records need to have a chronology based on reliable and precise radiocarbon dates. Often a palaeoenvironmental record located at a large distance from a specific archaeological site is used to explain cultural changes identified, thereby ignoring local factors.

- **Archaeological record is incomplete** - The review found that the archaeological record is far from being complete with certain cultural periods not investigated as much as others. Similarly, certain regions have received little attention than others leading to an imbalance in knowledge of that time period. This can lead to inaccurate interpretations when comparing the archaeological record to palaeoenvironmental data and vice versa.

- **Human vs climate impact on the environment** – It has become apparent that human impact on the environment becomes visible in the pollen data from the Bronze Age onwards in the form of woodland clearance and start of tree cultivation. This makes it increasingly difficult to differentiate between climate and human impact on the environment, which requires the use of multi-proxy approach to help shed more light onto this matter.

Having highlighted the main gaps and limitations of previous studies, the subsequent chapter will introduce the study sites that are investigated to address some of the gaps discussed, followed by the methods employed to tackle limitations of previous palaeoenvironmental studies.

5 Study sites: Topography, climate and vegetation

The previous chapter provided the archaeological, climatic and environmental framework of the Zagros and surrounding areas, as well as the current human-environmental research gaps for the time interval 17,000-2000 yrs BP. This chapter outlines the present-day topography, climate and vegetation systems of the Zagros region. This chapter will be concluded by a more detailed introduction of the study sites of the current research, Hashilan wetland and Lake Ganau (Figure 5-1), which will allow us to better understand the environmental and climatic variations and complexities and the factors that may have influenced their formation.

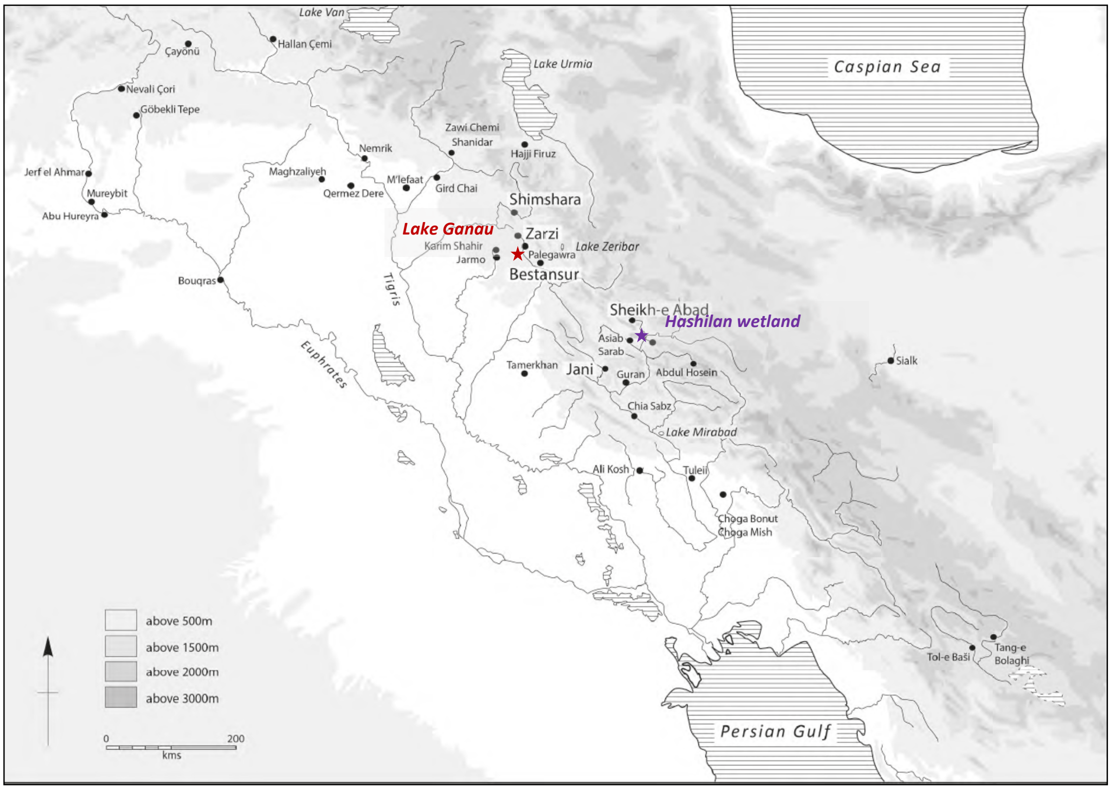

Figure 5-1: Map showing the region, Neolithic sites and the study sites Hashilan wetland (Iran) and Lake Ganau (Iraq) (Adapted from: Matthews et al. 2020a: 4)

The selection of the study sites was governed by the close proximity of archaeological sites (see Figure 5-1; Figure 5-2; Figure 5-3), allowing correlations to be made between the palaeoenvironmental and archaeological record, the possibility of retrieving long temporal records from both sites, and good preservation of microfossils suitable for palaeoenvironmental reconstruction.

Selecting Hashilan wetland and Lake Ganau for palaeoenvironmental investigation also allows the exploration of different landscapes within the region, as the sites are located at varying altitude and in different parts of the Zagros region (east vs west) that is reflected in their modern vegetation composition.

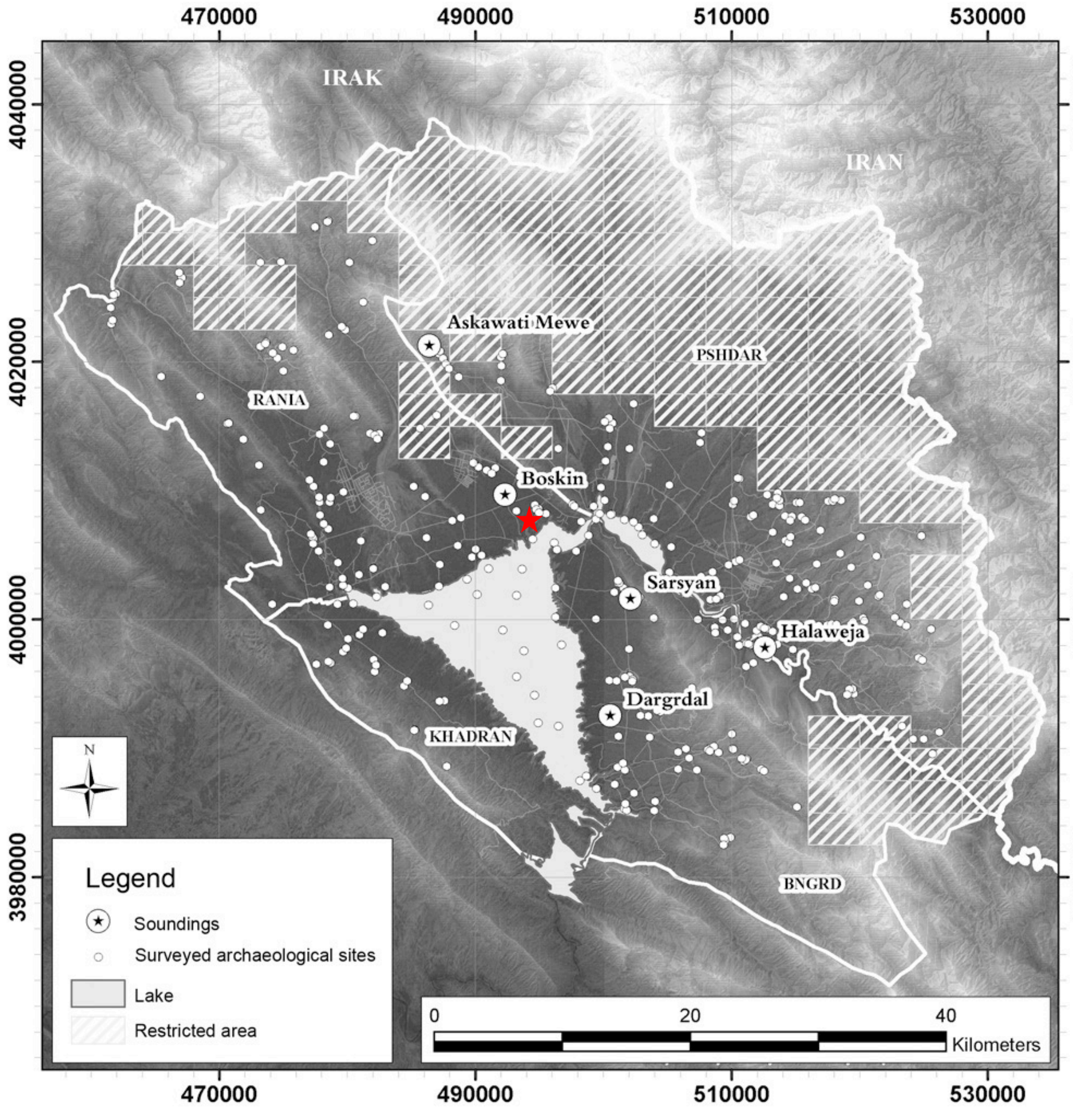

Figure 5-2: Location of 366 archaeological sites discovered around the vicinity of Lake Ganau (marked by red star) (Adapted from Giraud et al. 2019: 87)

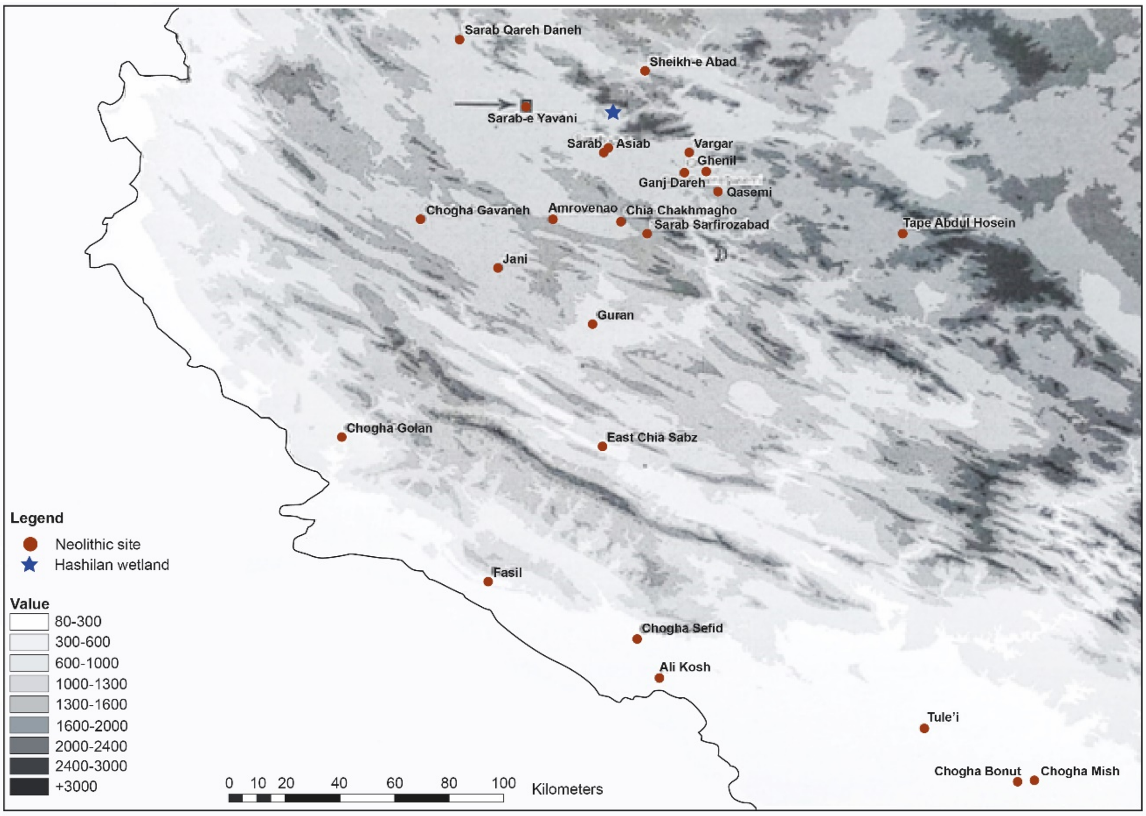

Figure 5-3: Map showing location of Neolithic sites in the close vicinity of Hashilan wetland (marked by blue star) (Adapted from Alibaigi 2013: 49)

5.1 Regional setting – The Zagros region

The Zagros mountains form the eastern arc of the Fertile Crescent, stretching from the eastern Taurus mountains in Turkey to the southeast shores of the Persian Gulf, in the south of Iran. The mountains are composed of long parallel ridges and intermontane valleys with numerous peaks over 3000 and 4000m above sea level, reaching 4548m at the highest peak. Created by the collision of the Eurasian and Arabian tectonic plates, the region is highly active tectonically with major fault lines (Talebian and Jackson 2002; Heydari-Guran 2014: 21), separating the Mesopotamian lowlands in the west from the high Iranian plateau in the east. The geology of the alternating ridges and the valleys is mainly composed of Cretaceous and Tertiary limestones and marls with the highest parts of the mountains composed of metamorphic rocks (Wright 1962; Wright *et al.* 1967: 135-136). Springs are common in the region from karstic features and along impervious sedimentary beds and tectonic fault lines (Matthews 2013a: 15).

In terms of the topography and geobotany, the region can be divided into the following zones (Figure 5-4) (Zohary 1973):

- Upper/Highland Zagros mountains and intermontane valleys, with site elevations at >1300m and peaks of >2500–3000m, classified as upper Kurdo-Zagrosian steppe-forest vegetation
- Lower/Piedmont Zagros mountains with valleys and plains, with site elevations of 400–1300m, with peaks >500–1700m, classified as lower Kurdo-Zagrosian steppe-forest vegetation
- Zagros piedmont-steppe, at the edge of the Mesopotamian steppe and plains, <500m, classified as dry Irano-Turanian *Artemisia* steppes
- Mesopotamian lowland steppe <500m, classified as dry Irano-Turanian *Artemisia* steppes
- Khuzestan alluvial plain <500m, classified as Nubo-Sindian vegetation

Based on the geobotanical map (Figure 5-4) the majority of the Zagros Mountains is covered by Kurdo-Zagrosian steppe-forest vegetation, which is composed of xerophilous deciduous steppe-forest of *Quercus brantii* in the mid-altitudes (1200–1800m above sea level); *Pistacia-Amygdalus* scrubs in lower latitudes (750–1200m above sea level); and dry Irano-Turanian *Artemisia* steppes in the east (central Iran) and the Mesopotamian lowland steppe in the west (Zohary 1973; Djamali *et al.* 2010a).

The Zagros region is sensitive to changes in climate with the topography playing a factor in the amount of precipitation received. A number of different climatic systems influence the climate in the Zagros region. The weakening of the Siberian anticyclone in central Asia and the subtropical anticyclones in southern Iran allow depressions from the North Atlantic, the Mediterranean and the Black Sea to be steered eastward by westerlies leading to rain and snowfall during the winter months. Thus while the summers are hot and dry, the winters are cold and wet (Stevens *et al.* 2001: 748; Djamali *et al.* 2010a: 814).

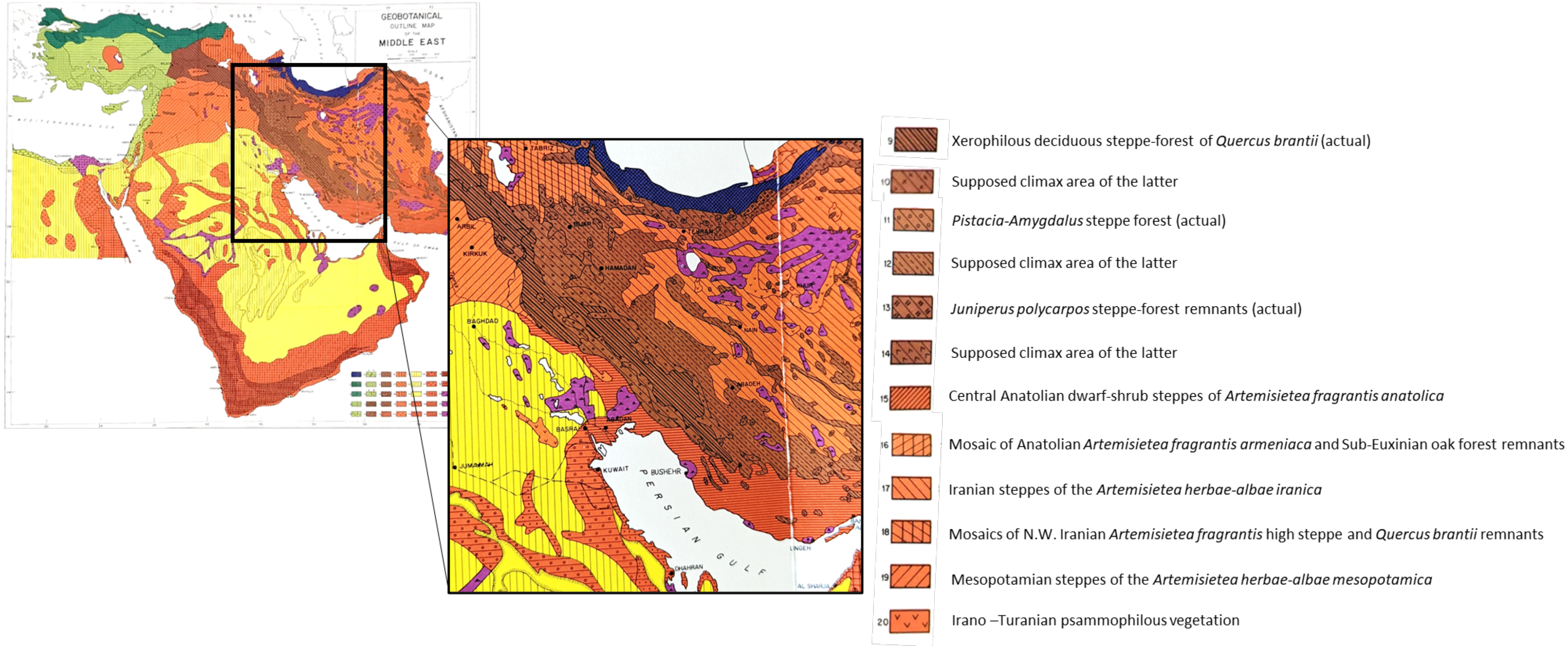

Figure 5-4: Geobotanical map of the Middle East (Zohary 1973: Map 7)

5.2 Hashilan wetland – Kermanshah province

The mean annual precipitation of Kermanshah in the central Zagros is approximately 480mm and the mean temperatures vary between 7°C in January and 27°C in July. Precipitation mostly occurs in winter and is subject to inter-annual variation depending on the nature of Mediterranean cyclonic storms reaching the Zagros Mountains from the west (Figure 5-5) (Brookes *et al.* 1982: 287). Based on the Köppen climate classification system (Köppen 1931), the Kermanshah region has a Mediterranean-type climate.

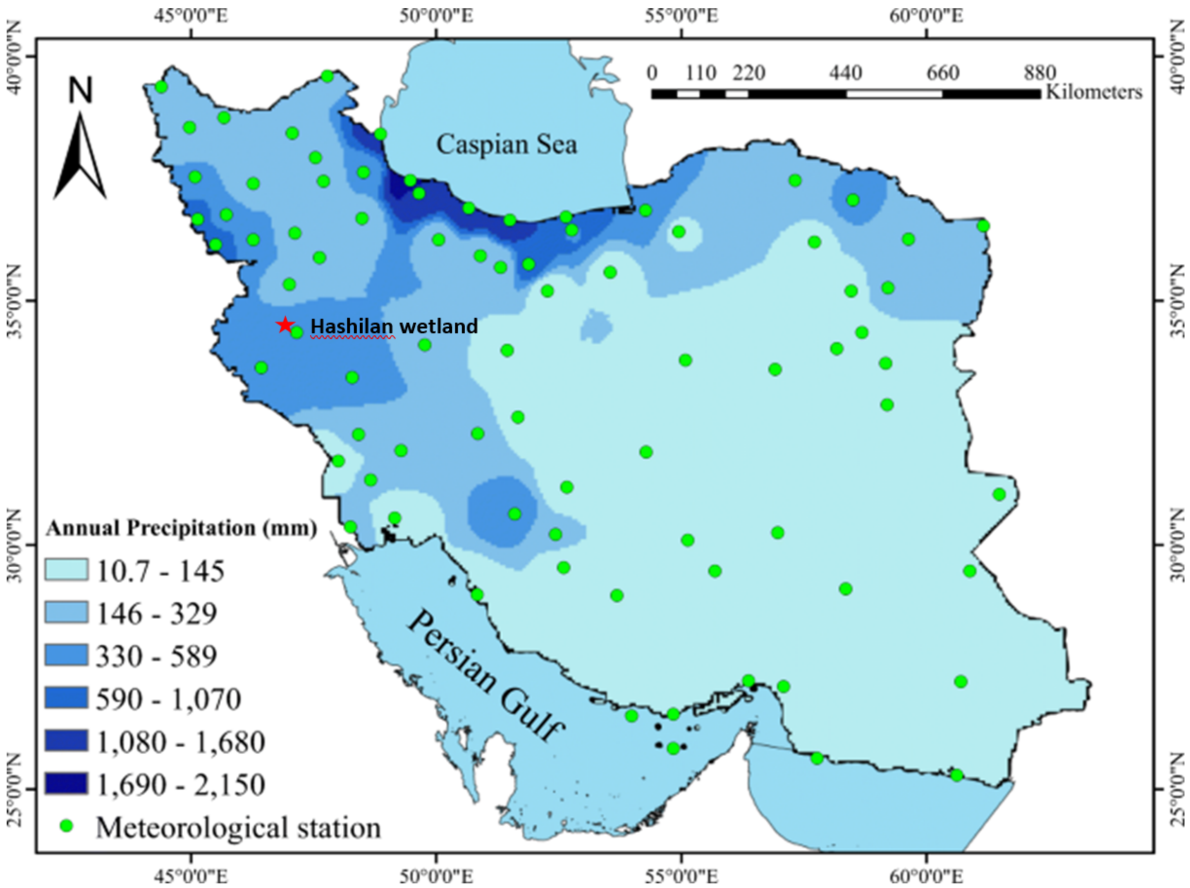

Figure 5-5: Spatial distribution of annual rainfall in Iran during 1987-2016 (Adapted from Kaboli et al. 2021: 512)

The study site Hashilan wetland (34°34′ N, 46°53′ E) is located in the Razawar valley at the foothill of the Khorin Mountain at an elevation of 1310m above sea level, 35km northwest of Kermanshah Province in the Zagros Mountains (Figure 5-6).

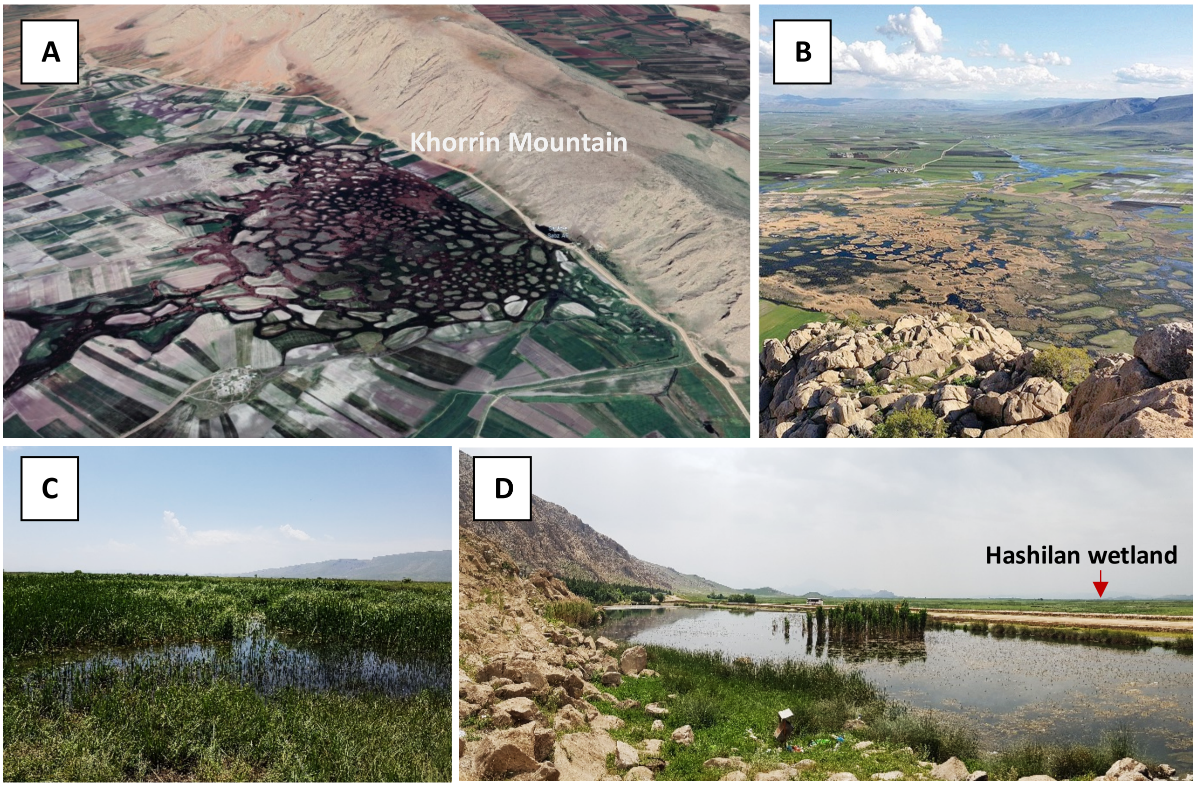

Figure 5-6: A: Google Earth image of Hashilan wetland; B: Hashilan wetland photograph from high ground (Heydari-Guran and Ghasidian 2017: 5); C and D: Photographs of Hashilan wetland taken by author during field coring in 2018

Hashilan wetland is a freshwater, palustrine wetland (karstic spring wetland), the largest among the wetlands in the Kermanshah Province, with an areal size of 450ha. The water depth is approximately 3m deep with 30% of the wetlands area covered by 120 islands ranging from 0.1 to 1ha in size (Karami *et al.* 2001: 201). Such spatial morphology has been termed as anastomosing wetland/anastomosing palustrine system (Djamali *et al.* 2018). The mean annual precipitation is 451mm with most of the rainfall occurring during the winter and early spring (Abbasi 2021: 2). The wetland area is fed by both rainwater and karstic springs including Sabz Ali, Man-e-may, Shele and Jelogire. The main input of water is brought into the wetland by Sabz Ali (95%) that originates from the Khorrin Mountains, located at the northern edge of the wetland, with the highest discharge occurring in March and the lowest in September. The average annual discharge of Sabz Ali spring, measured over the period of 13 years (1972-1985), has been 323.4 litres per second (Karami *et al.* 2001: 201-202). The dynamic storage volume of the spring is sensitive to precipitation changes (Safaierad in press).

In terms of the geology, Hashilan wetland and the aquifers of its water sources are located in the limestone formations of Triassic-Jurassic age (Biston formation), releasing high percentages of calcium carbonate into the groundwater and sediments (Figure 5-7) (Namdadi *et al.* 2016; Abbasi 2021: 3). The study area is located in the syncline plain Allahyar-Khani which is surrounded by the Veis Mountain

(1800m) in the south and in the north by the Khorrin Mountains (2500m) (Namdadi *et al.* 2016; Safaierad in press). Hashilan wetland is located between two anticlines, Khorin anticline (northeast) and Biston anticline (southwest), which is part of the Miandarband plain that also contains other wetlands and the rivers Razavar and Gareso. The main surface output is a natural drainage which joins the Razavar river (Figure 5-8) (Abbasi *et al.* 2022: 142-144).

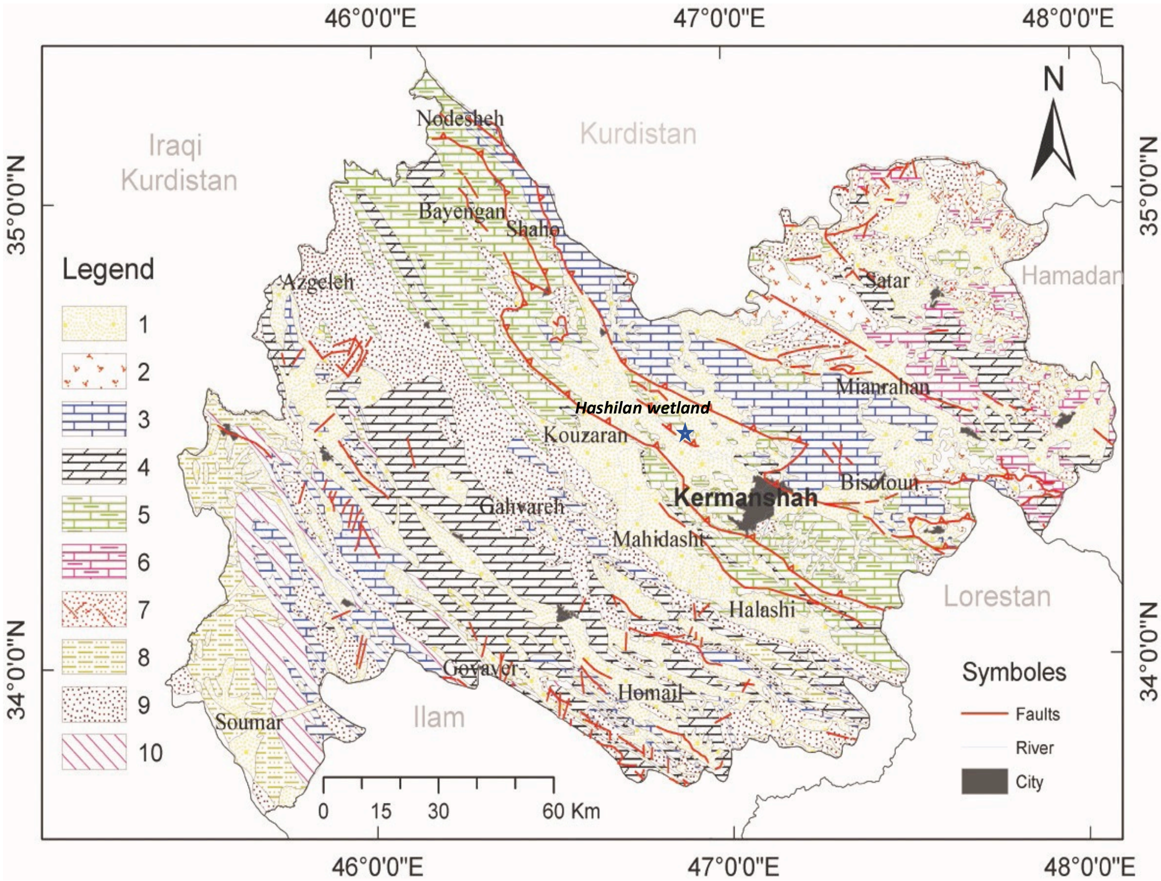

Figure 5-7: Simplified geological map of Kermanshah and approximate location of Hashilan wetland (blue star); 1: alluvium, 2: volcanic rocks, 3: limestone, 4: dolomitic limestone, 5: marly limestone, 6: metamorphic limestone, 7: volcano-metamorphics, 8: marl, 9: sandstone. and 10: gypsum (Adapted from: Taheri et al. 2015: 485)

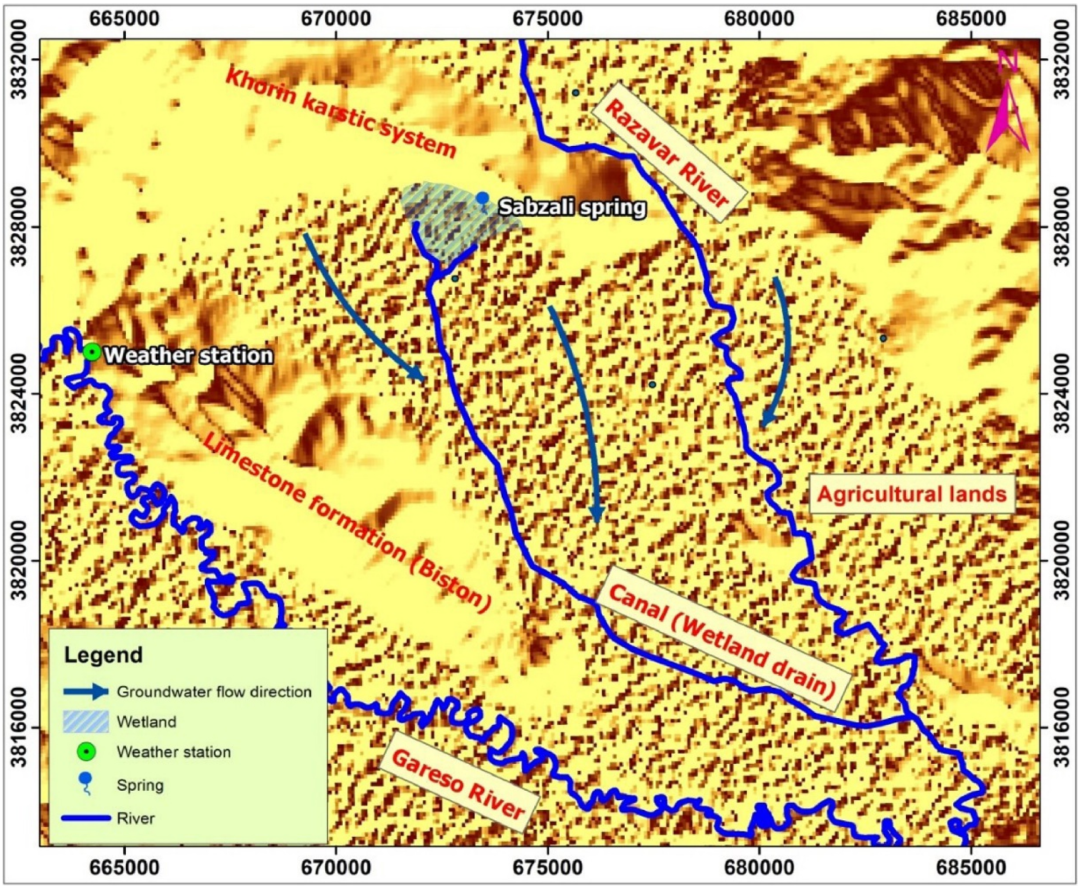

Figure 5-8: Map showing the hydrological and geological features around Hashilan wetland (Abbasi et al. 2022: 143)

The formation of Hashilan wetland has been largely affected by the karst system found in this region. Karstification processes in the Khorrin Mountains led to the formation of various karst landforms including karrens, shafts and sinkholes (Heydari-Guran and Ghasidian 2017).

Based on a recent botanical survey conducted (Safaierad in press), the regional vegetation can be characterised as an open forest-steppe and warm-temperate shrubland (Figure 5-9) . The main trees are *Pistacia khinjuk*, *P. atlantica* subsp. *mutica* and *Crataegus azarulus* var. *aronia* along with *Prunus* shrubs between 1300-2000m elevation. The nearest oak woodland is located ~30km west of Hashilan wetland with only a few scattered oak trees present on the northern slope of the Khorrin mountains. Between 2000-2500m, *Acer monspessulanum* and *Lonicera nummulariifolia* are growing, while above this elevation trees are absent, and the vegetation can be characterised as a Irano-Turanian montane steppe. The main vegetation growing on the wetland itself are Asteraceae, Poaceae and Cyperaceae (Karami *et al.* 2001). Other plants include *Phragmites australis, Typha latifolia, Typha angustifolia* and *Sparganium erectum* in addition to a few scattered *Salix alba* trees (Safaierad in press).

Figure 5-9: Trees and plants growing on and near Hashilan wetland which includes Phragmites (top left) and sedges and reeds (bottom middle and right) (author's own)

5.3 Lake Ganau - Rania plain

The Rania plain is located within the western foothills of the Zagros Mountains in north-eastern Iraq and is part of the Irano-Turanian Province also known as the Irano-Anatolian region (Asouti and Kabukcu 2014). The shallow plain, which is susceptible to seismic activity (Doski 2019), is approximately 30x20km square with the Lesser Zab River entering the plain and flowing into the artificially created Lake Dokan (Skuldbøl and Colantoni 2014: 46). Multiple springs and wadi systems contribute to making the Rania plain a rich agricultural environment ideal for settlement (MacGinnis *et al.* 2020: 89). The annual precipitation of Rania in 2020, a town about 10km southeast of Lake Ganau, was 1142.91mm mostly occurring in winter and spring (Figure 5-10). The mean monthly temperatures vary between 7°C in January and 39°C in July.

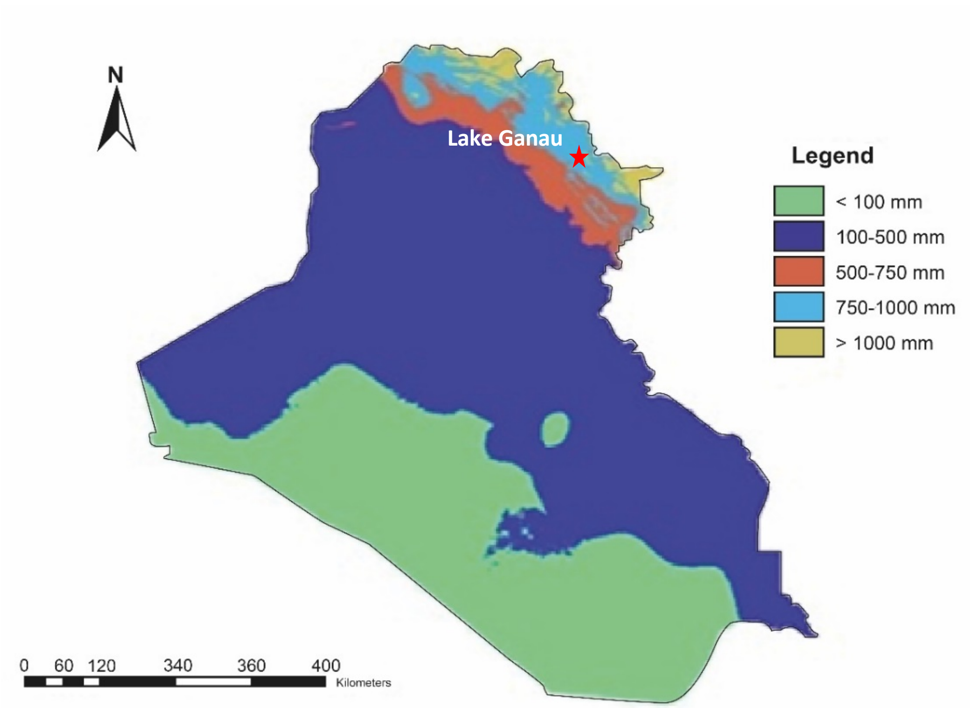

Figure 5-10: Mean annual precipitation across Iraq (Adapted from: Muhaimeed et al. 2014: 998)

The climate of northeast Iraq can be described as semi-arid Mediterranean with hot, dry summers and cold, wet winters (Frenken 2009: 199; Reuter *et al.* 2018: 3155) with the presence of mountainous chains in the Rania plain inducing higher humidity (Giraud *et al.* 2019: 89). The climate is influenced by the mid latitude westerlies from the North Atlantic and the Indian Ocean Monsoon system in the south (Rohling *et al.* 2013). The East African and Indian monsoons and the position of the Inter-Tropical

Convergence Zone (ITCZ) influence the climate in the summer, while the movement of the ITCZ to the southern hemisphere in the winter allows temperate westerly storm tracks from the North Atlantic and Eastern Mediterranean to dominate the region resulting in wet conditions (Ulbrich *et al.* 2012; Bosomworth *et al.* 2020: 36). The interaction between these two systems (i.e. East African and Indian monsoons and the North Atlantic and Mediterranean system) influences the amount of spring rainfall the region experiences (Reuter *et al.* 2018).

The vegetation of the Rania basin is characterised by an open landscape with scattered trees and shrubs. An open forest dominated by *Quercus* (*Quercus brantii, Q. aegilops, Q. infectoria* and *Q. libani), Pistacia* (*Pistacia atlantica* and *P. khinjuk*) and *Amygdalus* can be found on the mountain slopes, indicating extensive grazing/browsing and pollarding (Rösch *et al.* 2015: 1). The lower mountain slopes are used for the cultivation of fruit and vegetables, while the plain is used as crop fields (mainly wheat and barley) (Giraud *et al.* 2019: 89).

The study site Lake Ganau (36°12’ N, 44°56’ E), is a small hydrogen sulphide rich karst lake ~350m in diameter, located near the north western bank of Lake Dokan at height of 515 m.a.s.l. (Figure 5-11) (Rösch *et al.* 2015).

Figure 5-11: A and B: Google Earth images of Lake Ganau in the Rania Plain; C: Aerial image of Lake Ganau (Rösch et al. 2015: 3); D: Lake Ganau with Kewa Rash Mountains in the back (Muehl 2016)

Tectonically, Lake Ganau is located in the Zagros Fold – Thrust Belt, southwest of the main Zagros Suture Zone. The surrounding area consists mainly of high amplitude anticlines and synclines with the same strike direction (NW–SE) as the Zagros Mountain Belt. Alluvial sediments (clay, sand and gravels) cover the area around Lake Ganau which are underlain by Jurassic formations made up of limestones and dolomites (Figure 5-12 and Figure 5-13) (Karim *et al.* 2011: 28; Ali *et al.* 2012; Khanaqa *et al.* 2013). The morphology and formation of Lake Ganau has been influenced by the lake being located on the crest of the major Rania anticline with a probable fault zone (graben like fault), which causes water discharge out of the spring from the underlying bituminous Jurassic or Triassic rocks, continuous dissolution processes (chemical erosion) and subsequent collapsing (Ali *et al.* 2012: 31).

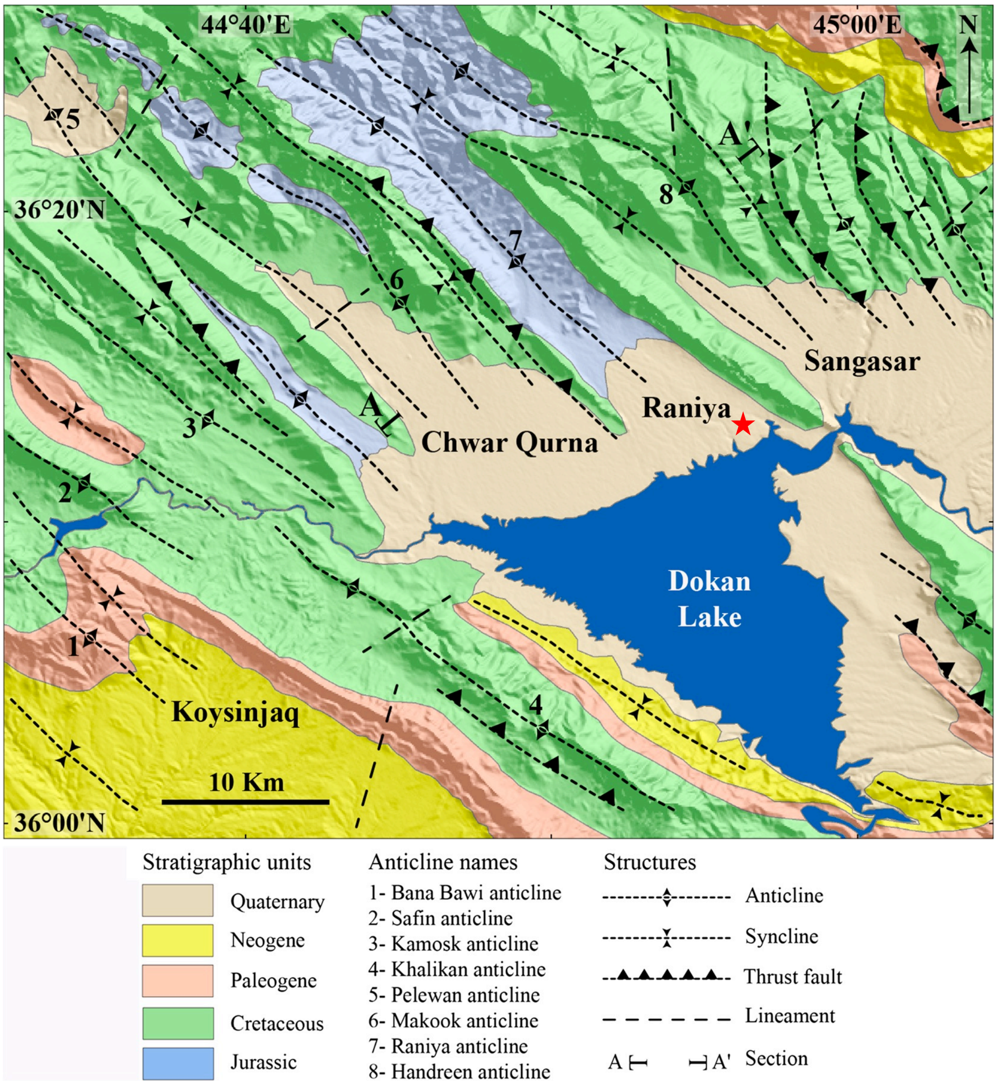

Figure 5-12: Geological map of Rania region and surrounding area, with red star marking the position of Lake Ganau (adapted from Doski 2019: 306)

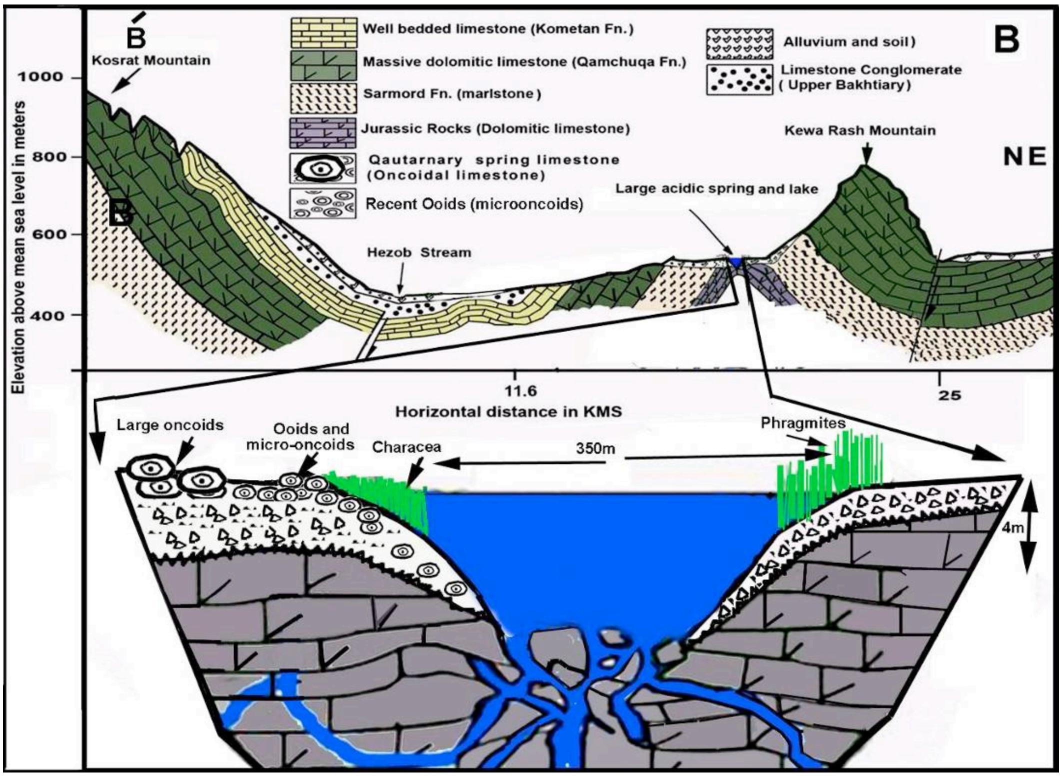

Figure 5-13: Geologic cross section of the Rania plain and Lake Ganau (Karim et al. 2011: 29)

The depth of the lake varies depending on type of equipment used to measure it. According to echo sounding the lake depth is approximately 12.6m while depth measurement using a manual lead/ sounding weight indicated varying depths of up to 30m (Rösch *et al.* 2015: 2). These measurements do not agree with previous suggested depth of the Lake which was 24m (see Ali *et al.* 2012).

Lake Ganau does not have an above ground inflow but two outflows have been identified indicating a slow but continuous water discharge (Rösch *et al.* 2015: 4). At least 24 round shaped sub-basins of varying sizes have been identified at the lake bottom (Figure 5-14) (Muehl *et al.* 2018: 7). An ascending spring supplies the lake continuously with water along with potentially high amount of sulphate, chloride, and gas. The exact location of the spring is not clear but the bituminous nature and the high organic content of the Jurassic rocks, or the sulphate rocks of the Triassic might be responsible for the high sulphate, chloride, and gas content in the lake water (Ali *et al.* 2012: 35).

In terms of the vegetation composition near or on the site, the southern and eastern shores of Lake Ganau are covered by reed (Phragmites), while the southwestern side is covered by thick and dense mats of Characeae a calcifying green algae common in carbonate-rich freshwaters (Khanaqa *et al.* 2013: 656). Micro-oncoids and large oncoids can be found on the bank of the lake (Karim *et al.* 2011).

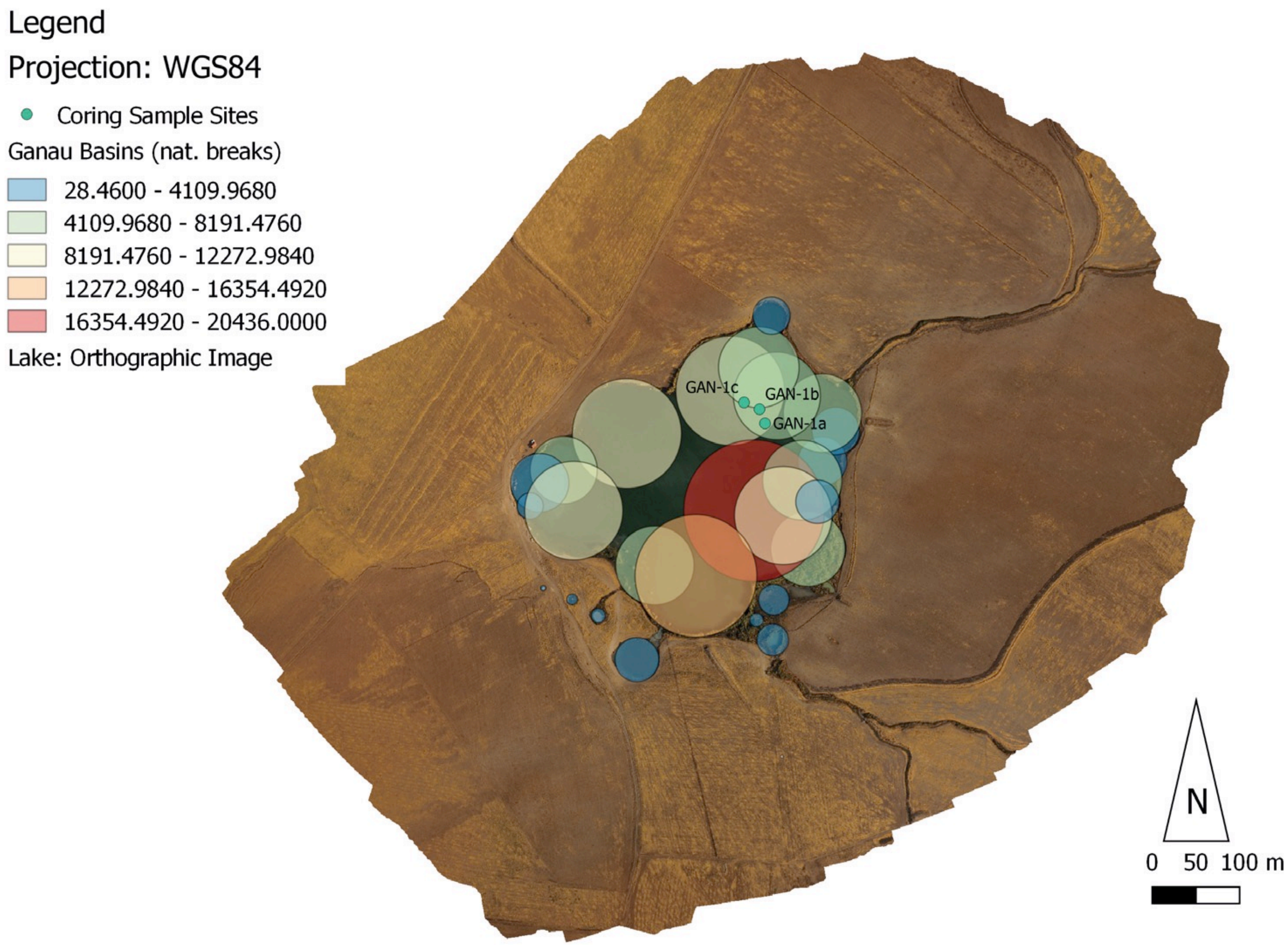

Figure 5-14: Orthographic image of Lake Ganau with reconstructed basins and the position of the core site

6 Methodology

To address the aims and research questions outlined in Chapter 1 the following analyses have been employed: Pollen, non-pollen palynomorphs (NPP), microscopic and macroscopic charcoal, organic matter and bulk carbonate determinations, ITRAX geochemistry, magnetic susceptibility and radiocarbon dating (Figure 6-1). Table 6-1 summarises the rationale behind using the methods, the limitations and challenges of each of the methods, and how these can be and were addressed, if possible.

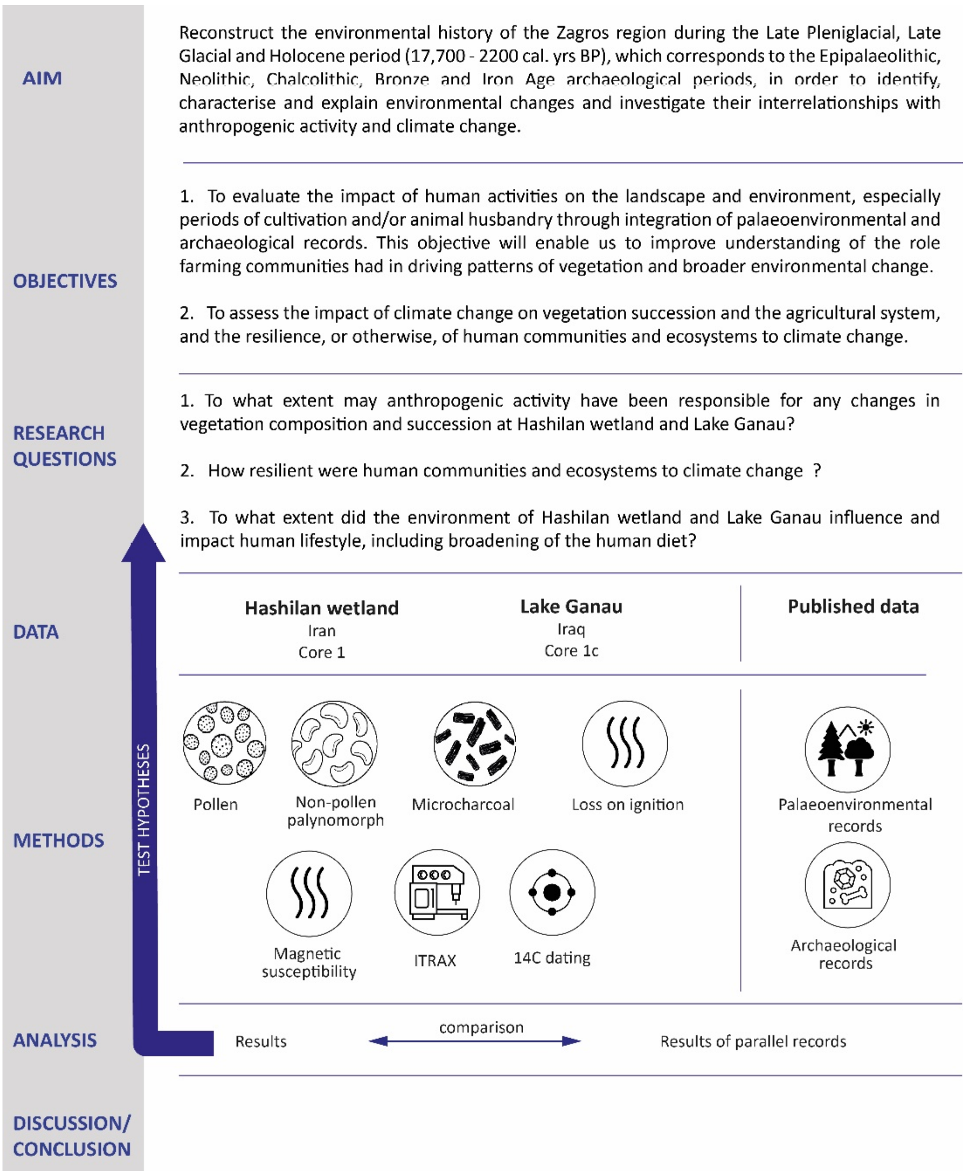

Figure 6-1: Overview of the research framework

Table 6-1: Summary of rational and challenges of the methods

Methodology	Rationale	Limitations and uncertainties	Mitigation used
Pollen analysis	To reconstruct the history of vegetation changes over time, allowing the investigation of human-environmental relationships	Contamination of samples in the laboratory Over and under-representation of certain pollen taxa in the pollen record Pollen preservation which can be dependent on environmental changes, i.e. drying conditions. This can cause difficulty in the palynology interpretation especially if key indicator species for agricultural activity such as cereal pollen grains are affected	To avoid contamination during pollen slide preparation, deionised water was used to wash tools in between sampling and sieving. A good understanding of the processes that lead to pollen deposition and preservation are needed to correctly interpret the pollen diagram
Non-pollen palynomorph analysis	To detect the presence of herbivores and provide information on local ecological conditions and changes	To correctly identify certain spores it is necessary to rotate them by tapping the slide. Thus, a fluid mountant is preferred for mounting purposes	
Microscopic and Macroscopic charcoal	To complement the palaeoenvironmental records by producing a regional and local fire history record caused by either human activity and/or climatic conditions	Counting microscopic charcoal on pollen slide has the following problems: samples are not taken continously along the core at a fine resolution, thereby missing charcoal peaks and interpreting background trends as fire events; increased charcoal fragmentation as a result of pollen preparation process, leading to a high abundance of microscopic particles which can cause misinterpretation of charcoal results; Difficulty in assessing the exact location of the fire (Whitlock and Larsen 2002)	No size differentiation was used during microcharcoal counting Multi-proxy record used to interpret charcoal record

		Possibility of increased charcoal fragmentation as a result of wet sieving (macroscopic charcoal) Difficult to attribute fire signal to either human activity or climatic event A number of different methods have been used to extract and quantify microscopic charcoal such as pollen preparation procedure and thin section analysis. This can lead to fire history records not being reliable to compare directly (Turner *et al.* 2004) The largest microcharcoal size depends on the sieve size used pollen sieving, and thus creating a size bias (Turner *et al.* 2004)	
Organic matter and bulk carbonate content	To determine organic matter content and bulk carbonate content throughout the cores that among others could indicate erosional events into the lake's catchment area		
14C dating	To create a robust chronology To address the uncertainty regarding timing and regional significance of vegetational changes and climatic events and their influence on human societies	Hard-water effect Movement of macroremains (for detailed discussion on the issues associated with radiocarbon dating see below)	Careful selection of sample depths and materials

ITRAX and magnetic susceptibility	To produce high-resolution geochemical proxy data for interpreting environmental change Allows non-destructive geochemical analysis of sediment cores unlike conventional XRF analysis (Croudace *et al.* 2006) Provides high-resolution radiographic images which can reveal sedimentary layers Carrying out magnetic susceptibility analysis to indicate the presence of terrigenous material in the lake catchment area caused by erosion due to either anthropogenic activity or environmental factors. Magnetic susceptibility will help stratigraphic correlation between cores	Loss of data during core scanning due to uneven surface or cracks on the surface sediment	Prior to analysis the surface of sediment must be cleaned with a metal scalpel to avoid contamination caused by dragging of sediment and ensure the sediment surface is as even as possible Data quality needs to be checked prior to plotting data

6.1 Practical approaches - Fieldwork

Coring at Hashilan wetland was part of the collaboration between the University of Reading and University of Tehran (Iran) and is part of the Central Zagros Archaeological Project (CZAP). Coring at Lake Ganau, on the other hand, is part of an international project funded by the German Research Foundation (Deutsche Forschungsgemeinschaft) involving teams from the Universities of Sulaymaniyah (Iraq), Heidelberg (Germany) and Munich (Germany) and the directorate of Antiquities in Sulaymaniyah under the leadership of Dr. Simone Muehl and Prof. Manfred Roesch. Cores taken from Hashilan are stored in cold storage at the University of Reading, while the cores from Lake Ganau are stored at an external cold storage facility by the Laboratory of Palaeobotany at the Landesamt fuer Denkmalplege in Gaienhofen-Hemmenhofen.

Hashilan wetland

Coring at the wetland site of Hashilan was carried out in May 2018, in collaboration with the Geography department at the University of Tehran. The coring was carried out about 20-30m inside the wetland (34°34'60.0"N 46°53'33.0"E) and a Russian corer was used, enabling the retrieval of two sets of eleven successive 50cm core sections (Figure 6-2). The two sets of cores, labelled Core 1 and Core 2, were taken at a distance of 50cm from each other. The maximum depth reached for both sets was 550cm. Both cores have been photographed in the field prior to wrapping up because after retrieving the samples the sediment is exposed to air, which causes oxidation leading to changes in sediment colour. The samples were placed into separate rigid plastic tubing, wrapped in polythene sheeting and labelled with site name, year, depth and top and bottom indications (Figure 6-2).

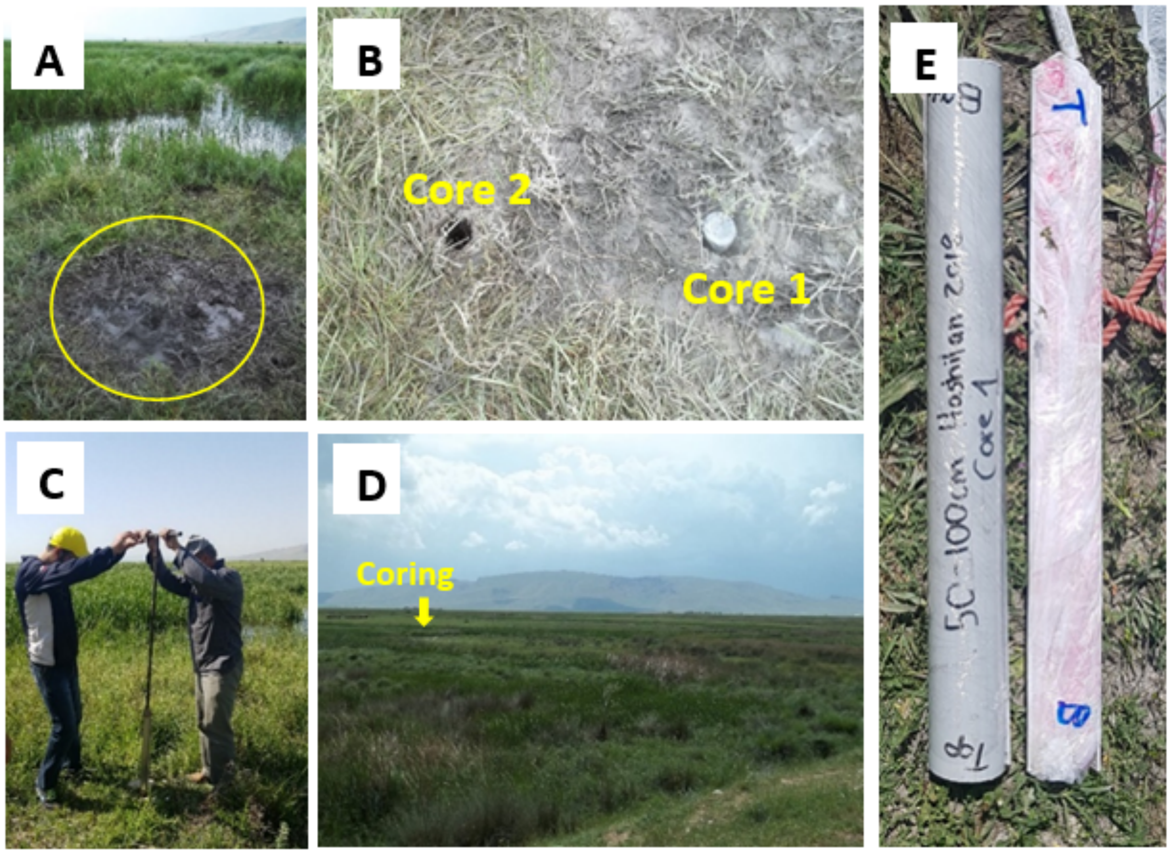

Figure 6-2 Coring at Hashilan wetland: A and B- Location of Core A and B; C- Coring using Russian corer; D- Coring site location; E- sample wrapped in polythene sheeting ready to be placed inside the plastic tubing

Lake Ganau

Coring at Lake Ganau was carried out in 2015 by an international team from the universities of Sulaymaniyah, Heidelberg and Munich and the directorate of Antiquities in Sulaymaniyah using Niederreiter/ UWITEC system. Three sets of cores were retrieved from Lake Ganau: Core A, Core B, and Core C (Figure 6-3). Core C was chosen for subsequent palaeoenvironmental analysis because of the completeness of the sediment core with no major loss of sediment. For Core C in total about 11.5m of sediment was retrieved (33-45m). Core C has been split into two halves and labelled Core C a-part and Core C b-part. Core C part-b has been chosen for palynological and LOI analysis at the University of Reading and Core C part-a has been chosen to undergo ITRAX analysis by the German colleagues at the Ludwig Maximilian University of Munich.

Figure 6-3: Coring at Lake Ganau (Muehl 2016)

6.2 Laboratory methods

Unless specified otherwise, the methods outlined below were employed on both Hashilan wetland and Lake Ganau cores in the same manner.

6.2.1 **Lithostratigraphy**

6.2.1.1 Lithology

To understand the processes involved in the formation of a site, it is vital to describe the sediment. Thus, after cleaning the core surface with a scalpel the core lithostratigraphy has been described in the laboratory using standard procedures for recording unconsolidated and organic sediments (Tröels-Smith 1955). The following conditions have been examined and recorded:

- physical properties (e.g. Munsell colour)
- sediment composition (e.g. silt, clay, herbaceous peat)
- degree of peat humification
- shrinkage of core (if any)
- presence of any inclusions (e.g. shells, roots and plant material)

- unit boundaries (e.g. sharp or diffuse)

Compression has been identified for certain parts of the 50cm core sections for Hashilan wetland (50-200cm and 450-500cm). A compression ratio, which was applied to undo the compression, was calculated in the following way:

Length of core section/ length of sediment (e.g. 50cm/47cm) = compression ratio

6.2.1.2 Chronology

Theoretical framework – Radiocarbon dating

A brief discussion will follow to identify potential factors that can lead to erroneous radiocarbon dates, impact radiocarbon reliability and precision, and lead to poor, imprecise age-depth models. These criteria were used in the identification of which radiocarbon dates should be used to produce age-depth models for Hashilan wetland and Lake Ganau.

The selection of materials to be radiocarbon dated plays an important part in producing a robust chronology, along with relevant pre-treatments that are essential to produce reliable ages (Brock *et al.* 2010). This discussion will focus on waterlogged plant material, macro-charcoal and bulk sediments as they have been used for radiocarbon dating in this research.

Lake sediments are composed of a mixture of clastic particles and organic material. Organic material used in radiocarbon dating is derived therefore from vegetation growing around the basin catchment area among other sources. Thus, it is likely that the some of the organic material found in lake sediments is derived from older organic materials eroded from the exposed lake edges, especially when periods of lower lake water level occur. In addition, other organic deposits located in the catchment area may been incorporated into the lake sediment by fluvial, colluvial or other erosional processes (Lowe and Walker 2000: 55; Butler *et al.* 2004: 404). Lowe and Walker (2000: 55) argue that bulk sediment samples consist of a variety of organic components and when dated provide an average date of all of the organic materials that made up the sample. Thus, the initial step to remove potential contamination from bulk samples involves both physical and chemical processing of the chosen sample. Physical processing involves for example removal of root material from the samples as it is an exogenous carbon and is generally younger than the surrounding deposits (Hajdas *et al.* 2021). These young roots could contaminate older sediments, explaining why older radiocarbon dates appear younger than expected based on the stratigraphy (Butler *et al.* 2004: 396). Olsson (2009: 10), however, stresses the possibility that some roots and rootlets may already have decayed contributing some younger humus material. This is especially the case in highly humified peat samples where roots have become invisible and thus caution needs to be taken when using such samples. Thus, if dating of bulk organic samples is chosen, younger dates than expected may suggest contamination of the sample by more recent material such as roots of aquatic or semi-aquatic plants.

Bulk samples can also be subject to hard water effect, which can yield older radiocarbon ages. To mitigate the impact of hard water effect, samples with low bulk carbonate and high organic matter should be chosen (including the use of Loss-on-Ignition to determine the bulk carbonate and organic matter content). To assess the extent of contamination of bulk organic samples by either old or younger carbon, preferably both the humin (alkali insoluble) and humic (alkali soluble) fraction of a sediment sample should be radiocarbon dated instead.

An age difference between these two fractions could suggest the following:

- Humic date – can be affected by introduction of younger organic material. Humic acids, that form by decomposition of organic material, can move downward into the sedimentary sequence creating a potential source of contamination that would be result in the humic date being young (Walker and Nerc 1990: 137; Walker *et al.* 2003: 505; Kaland *et al.* 1984: 254; Lowe *et al.* 2004: 155);

- Humin date – can be influenced by the incorporation of carbonaceous particles derived from older deposits (old minerogenic carbon), causing an ageing effect and resulting in the humin age being several hundred or thousands of years older than the humic date (Walker and Nerc 1990: 137; Lowe and Walker 2000: 56). An unusually younger humin age could also be caused by the downward penetration of roots (Lowe *et al.* 2004: 155; Walker *et al.* 2001: 1012; Walker *et al.* 2003: 505).

If there is no difference between those two fraction dates it suggests contamination by either older or younger carbon material is minimal (Walker *et al.* 2003: 504). Therefore, dating bulk samples as well as humic and humin fraction is subject to a variety possible sources of contamination that can be difficult to assess. In addition, some studies suggest that humin dates are more reliable than humic dates and vice versa (see Bartley and Chambers 1992; Shore *et al.* 1995), and consequently terrestrial plant material has been suggested for radiocarbon dating instead. Although it is possible that there might be no significant difference in the ages of humic and humin fractions and plant macrofossils (see Lowe *et al.* 2004).

When it comes to dating plant material, it is suggested to use terrestrial plant material instead of aquatic plants. Terrestrial plants contain direct records of atmospheric 14C present while aquatic plants take up carbonates in the lake derived from the bedrock geology in photosynthesis, leading to radiocarbon ages that are several hundred years older (Walker and Nerc 1990: 14; Kaland *et al.* 1984: 253; Hajdas *et al.* 2021: 3-4; Lowe and Walker 2000: 55-56; Olsson 2009; Turney *et al.* 2000; Godwin and Willis 1959: 214). The impact of carbonate rich waters on radiocarbon dating is known as the hard-water effect and can also affect bulk sediment samples as already mentioned. According to Kaland *et al.* (1984: 257), lakes that are going to be radiocarbon dated should be deep enough so that certain aquatic plants and algae cannot grow at the lake bottom, although this is not always possible.

Radiocarbon dating terrestrial plant material, however, is not always straightforward. Root penetration can lead to the intrusion of plant macrofossils into older sediments. Howard *et al.* (2009) investigated the contrasting ages that are attained by dating different parts of the same organic sample (humic, humin and plant macrofossils). The results showed that the humin and humic acid fraction results were statistically consistent while the plant macrofossil remains yielded in comparison younger ages potentially as a result of *Phragmites* roots that were present in the sedimentary units immediately overlying the samples, pushing plant parts through the sediment or opening up root cavities for material to fall through reaching older sediments. If the stratigraphic consistency of both data sets is examined independently, either one could be accurate. Further evidence is thus needed to decide which data set is providing the true age and is accurate. According to Howard *et al.* (2009: 2685), if the plant material ages were correct, the humin fraction (composed of organic detritus) ages would be closer in age to the plant material ages. If humin and humic fraction ages, however, are consistent this suggests that they provide the reliable age estimates. Therefore, Howard *et al.* (2009: 2687) argue that if there is evidence of *Phragmites* within sedimentary sequences, plant macrofossils should only be dated if there is evidence that they are in-situ, and unidentified plant remains, monocot and Poaceae fragments should be avoided. It is thus important to identify the plant material before radiocarbon dating. Other studies also demonstrate the importance and complexities involved in choosing the correct type of terrestrial plant material for radiocarbon dating (see Turney *et al.* 2000).

Another factor that could explain erroneous radiocarbon dates could be gaps in the depositional sequence (i.e. hiatuses) caused by either no deposition or removal of sediment by erosion (Godwin and Willis 1959: 212). Long-term and cool storage of wet macrofossil samples for more than six months can also cause erroneously young radiocarbon dating results. Fungi or micro-organisms can be easily incorporated into the sample during sample preparation leading to contamination if stored long-term in wet conditions which may cause large errors ranging from several hundred to several thousand years (Wohlfarth *et al.* 1998: 142-143). Thus it is advised to store plant macrofossils dry before submitting for analysis (Wohlfarth *et al.* 1998: 144). Alternatively, the wet macrofossil samples should be stored in constant cold temperature.

As mentioned, erosion is another factor that can lead to erroneous radiocarbon dating results of plant macrofossils. Organic detrital material can be reworked from older deposits from the surrounding catchment soils. This redeposition of plant macrofossils can yield older radiocarbon results if dated (Turney *et al.* 2000: 114; Olsson 2009: 11). Physical translocation (reworking of plant macrofossils within sediments) thus can cause erroneous dates and can be a result of, for example, bioturbation, solifluction processes, fluvial erosion (Bird *et al.* 2002: 1061; Lowe *et al.* 2004: 155).

Other factors that can impact radiocarbon dating and the results are low carbon content (which is related to sample dry weight) which can possibly give too young dates (Wohlfarth *et al.* 1998: 142). The reliability of the available radiocarbon calibration curve and the shape of the calibration curve can also add an uncertainty in the radiocarbon dating results. Plateaux in the calibration curve can impact dating precision, resulting in large calibrated errors (Blockley *et al.* 2007: 1916; Hajdas *et al.* 2021: 4).

The question then arises which material should be radiocarbon dated to produce a robust, reliable age-depth model. It entirely depends on the characteristics of a site and both terrestrial plant material and bulk sediment samples can provide true ages (Lowe and Walker 2000: 57).

Practical framework – Radiocarbon dating

Chronological control of the palaeoenvironmental sequences for both Hashilan wetland and Lake Ganau was provided through AMS ^{14}C dating.

Hashilan wetland

The initial step involved performing a visual scan of Core 1 to detect plant macrofossil for dating, with a particular focus on the organic rich peat sequences. However, due to the high degree of peat humification no dateable plant macrofossil was detected on the core surface. As a result, four bulk peat samples were selected to be radiocarbon dated (humic and humin fraction) to act as rangefinder dates. Both the humic and humin fraction were radiocarbon dated as an agreement between them offers an additional confidence in the dating results (Dunbar *et al.* 2016: 6-7). The bulk peat samples (1cm wide) were extracted using a metal scalpel and spatula. Any visible rootlets were removed from the samples using a pair of tweezers. The peat samples were wrapped in aluminium foil, bagged within labelled plastic sample bags, and sent to the radiocarbon dating laboratory of the Scottish Universities Environmental Research Centre (SUERC) in Glasgow. Based on the findings of the rangefinder radiocarbon dates, pollen and geochemical analysis, further twelve radiocarbon samples were taken focussing on constraining climatic events and transitions, as well as local event stratigraphy and potentially significant vegetation changes (Table 6-2).

Instead of dating bulk sediment samples, waterlogged plant material was chosen to be radiocarbon dated. As the Hashilan sediment is rich in carbonates (limestone geology) it can be affected by the hard-water affect which impacts on the dating results by yielding an overestimated date i.e. older date. Thus, in order to yield reliable dating results and avoid the hard-water effect, in-situ waterlogged plant materials were picked out from the sediment samples through wet sieving.

The following method was used for the extraction of plant macrofossils:

After sub-sampling 1cm wide sediment samples from the core for radiocarbon dating, using a metal scalpel and spatula, a measuring cylinder (volumetric sampler -100ml) was used to measure sample volume. The sample was gently mixed with water inside the measuring cylinder to dissolve the sediment. The sample was then poured into a 63μm sieve and water was used to gently break down clay clumps. The sample was gently wet sieved and the remaining sediment was transferred into labelled petri dishes. The sieve and measuring cylinder were thoroughly washed in between samples to avoid contamination. Non-root plant materials (ideally stems) were picked out using a feather tweezer and a Leica stereo microscope and transferred into labelled glass vials containing deionised water. The sealed glass vials were stored in in a refrigerator until the samples were sent for analysis to NERC (seven samples) and SUERC (five samples).

Table 6-2: Summary of the twelve radiocarbon dates for Hashilan wetland including sample depth, dating material and sample justification

Sample ID	Sample Depth (cm)	Material	Justification
Has-1	186	Waterlogged plant material (stems; not rootlets)	To model and constrain the predicted depth of the 8.2 cal BP (at 189/190cm) climatic event based on provisional age-depth model
Has-2	234	Waterlogged plant material (stems; not rootlets)	To model and constrain the onset of a phase of possible Neolithic human activity revealed by the pollen data (organic matter content – 7.6%)
Has-3	294	Waterlogged plant material (stems; not rootlets)	Base of an organic unit indicating the onset of a possible Late Glacial interstadial event (top of event *13,070* cal BP based on provisional age-depth model)
Has-4	319	Waterlogged plant material (stems; not rootlets)	Top of an organic unit indicating the termination of a possible Late Glacial interstadial event
Has-5	343	Waterlogged plant material (stems; not rootlets)	Base of an organic unit indicating the onset of a possible Late Glacial interstadial event
Has-6	377	Waterlogged plant material (stems; not rootlets)	Top of an organic unit indicating the termination of a possible Late Glacial interstadial event
Has-7	397	Waterlogged plant material (stems; not rootlets)	Base of an organic unit indicating the onset of a possible Late Glacial interstadial event

Has-8	50	Waterlogged plant material (stems; not rootlets)	Establish the age of the top boundary of pollen diagram
Has-12	100	Waterlogged plant material (stems; not rootlets)	Top of an organic unit
Has-14	134	Waterlogged plant material (stems; not rootlets)	Base of an organic unit
Has-15	138	Waterlogged plant material (stems; not rootlets)	Top of an organic unit
Has-18	549	Waterlogged plant material (stems; not rootlets)	To establish how far back in time the sediment goes

Upon request, prior to sending the seven samples to NERC, the samples were dried. The following steps were undertaken to dry the wet samples: The plant material was removed from the glass vials and placed onto filtered paper (funnel shaped) that was laid inside glass beakers. The glass beakers were placed inside the oven for 24 hours at 105° C. To cool the samples, they were transferred into an envelope of alluvium foil.

Figure 6-4: Plant material placed inside filtered paper to be dried in the oven prior to being sent off to NERC

The results of the radiocarbon dating from SUERC, however, indicated that the plant material dated were stratigraphically incorrect and thus a new strategy was employed for the samples sent to NERC. Based on the SUERC dates, it became clear that the plant material from silty clay units were likely not in-situ material. Based on this finding, new samples were taken at slightly different depths, located withing peat units, and sent to NERC for radiocarbon dating (Table 6-3). At the end, in total fifteen radiocarbon samples were dated for Hashilan wetland and include both plant material and humic/humin dates.

Table 6-3: Summary of the final 15 radiocarbon samples that were radiocarbon dated for Hashilan wetland

Sample ID	Sample Depth (cm)	Type of sample	Sedimentary Context
Has-12	100	Plant material	Silty clay
Hashilan C1 107-108	107	Bulk sample (humic and humin)	Peat
Hashilan C1 111-112	111	Bulk sample (humic and humin)	Peat
Has-13	116	Plant material	Peat
Hashilan C1 123-124	123	Bulk sample (humic and humin)	Peat
Has-14	134	Plant material	Silty clay
Has-16	242	Plant material	Silty clay
Hashilan C1 291-292	291	Bulk sample (humic and humin)	Peat
Has-3	294	Plant material	Peat
Has-4	321	Plant material	Peat
Has-5	343	Plant material	Peat
Has-6	379	Plant material	Peat
Has-20	393	Plant material	Peat
Has-7	397	Plant material	Sandy clay- peat transition unit
Has-18	549	Plant material	Organic rich peat?

Lake Ganau

Four rangefinder radiocarbon dates (bulk samples) had already been obtained by the Laboratory of Palaeobotany at the Landesamt fuer Denkmalplege in Gaienhofen-Hemmenhofen, Germany for the Lake Ganau sequence (Table 6-4).

Table 6-4: Rangefinder dates for Lake Ganau obtained by the Laboratory of Palaeobotany at the Landesamt fuer Denkmalplege

Sample ID	Sample Depth (m)	Material	Conventional Radiocarbon age (BP)
GAN 1c 37-39 1b	37.50	Bulk sediment	13,784 ± 58
GAN 1c 39-41 1b	39.30	Bulk sediment	15,068 ± 61
GAN 1c 41-43 1b	41.70	Bulk sediment	18,410 ± 80
GAN 1c 43-45 1b	43.70	Bulk sediment	15,941 ± 66

Locations for further radiocarbon samples were chosen based on potentially significant trends observed in the uncompleted pollen record (Table 6-5). The sub-sampling took place at the Laboratory of Palaeobotany at the Landesamt fuer Denkmalplege in Gaienhofen-Hemmenhofen, Germany.

Table 6-5: Summary of the nine radiocarbon dates for Lake Ganau including sample depth, dating material and sample justification (based on uncompleted pollen record)

Sample ID	Sample Depth (m)	Material	Justification
Gan-1	33.20	Macro-charcoal (unidentified)	Enable modelling of the predicted onset of the Early Holocene
Gan-2	33.80	Macro-charcoal (unidentified)	Enable modelling of the predicted onset of Younger Dryas suggested by the increase in *Artemisia* % (~12%) and decline in Pediastrum % (~2%)
Gan-3	35.40	Macro-charcoal (unidentified)	Establish the timing of fluctuation in *Artemisia* %
Gan-4	36.00	Macro-charcoal (unidentified)	Establish the timing of another peak in Oak woodland (~10%)
Gan-5	36.50	Macro-charcoal (unidentified)	Establish the timing of peak in Oak woodland (~12%)
Gan-6	37.00	Macro-charcoal (unidentified)	Enable modelling of the predicted onset of GI-1e (Greenland Interstadial)
Gan-7	34.60	Macro-charcoal (unidentified)	Establish the timing of the establishment of Oak woodland
Gan-8	34.90	Macro-charcoal (unidentified)	Establish the timing of the initiation of Oak woodland colonisation from very low % (~2%) which could be associated with an increase in effective moisture during Middle Holocene
Gan-9-1	33.03	Macro-charcoal (unidentified)	Establish the age of the top boundary of the pollen diagram

No waterlogged plant macrofossils were found for Lake Ganau, hence, macroscopic charcoal was selected instead for radiocarbon dating. 2cm wide sediment samples were taken using a metal scalpel and spatula and the same wet-sieving procedure as listed above for the Hashilan wetland was used to extract macroscopic charcoal (Figure 6-5)

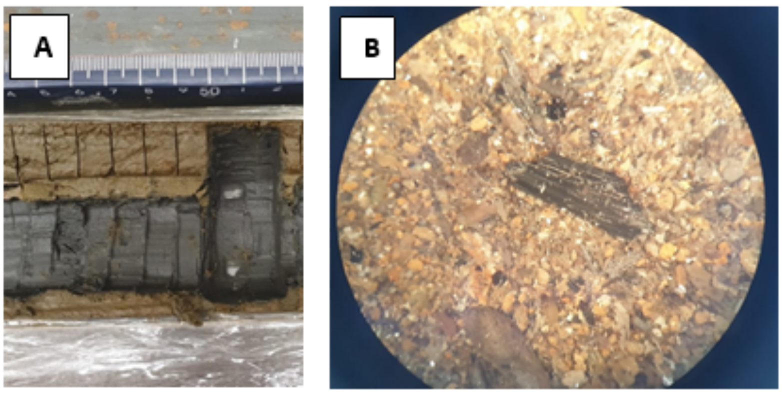

Figure 6-5: A: 2cm wide samples taken from the core; B: picking out the macroscopic charcoal after wet-sieving

The sealed glass vials were stored in in a refrigerator until the samples were sent for analysis to NERC (six samples) and SUERC (three samples). Same as for the Hashilan samples, the six samples for NERC were dried in the oven for 24 hours at 105° C (see above for detailed method). At the radiocarbon facility, prior to AMS ^{14}C dating, all samples underwent ABA pre-treatment to remove sedimentary and other contaminant carbonates, and organic acid contaminants (e.g. humic and fulvic acids) (Table 6-6). The results of the radiocarbon dating were represented as conventional radiocarbon years BP (relative to AD 1950). To produce the age-depth models for Hashilan wetland and Lake Ganau, OxCal v4.4 (Ramsey 2008; Bronk Ramsey 2009) was used alongside IntCal20 calibration curve (Reimer *et al.* 2020) with a P-sequence deposition model (Ramsey 2008).

Table 6-6: Standard radiocarbon pre-treatment methods used at the Oxford radiocarbon accelerator unit (Brock et al. 2010)

Material	Acid (HCl)	Base (NaOH)	Acid (HC1)	Bleach (NaO_2Cl)
Collagen (bone, tooth, antler, ivory)	0.5 M, RT	0.1 M, RT	0.5 M, RT	-
Skin, parchment, leather	0.5 M, 20°C	0.2 M, RT	0.5 M, 20°C	2.5-5.0%, 70°C
Hair, keratin, wool	1M, 80°C	0.1 M, RT	1 M, 80°C	-
Plant remains: wood and peat	1M, 80°C 1M, 80°C	0.2 M, 80°C 0.2 M, 80°C	1 M, 80°C 1 M, 80°C	5.0%, 80°C -
Fragile plant remains	1M, RT to 80°C	0.2 M, RT to 80°C	1 M, 80°C	2.5%, 80°C
Linen, cotton, paper	1M, RT to 80°C	0.2 M, RT to 80°C	1 M, 80°C	-
Charcoal	1M, 80°C	0.2 M, 80°C	1 M, 80°C	-
Sediment (humin and humic)	1M, RT to 80°C	0.1-0.5 M RT to 80°C	1 M, 80°C	-

6.2.1.3 Geochemical analyses

Organic matter content and bulk carbonate content

To determine organic matter content and bulk carbonate content of the sediment, samples for loss-on-ignition were taken between the depths 0-550cm at 2cm interval for Hashilan wetland (Core1) and for Lake Ganau at an interval of 4cm covering the depth 33-37.48m. 1cm^3 of sediment were sub-sampled and transferred into labelled foil dishes and then placed into a drying oven at 105° C overnight. Once samples were dried out and all the moisture was removed, they were placed in a desiccator and subsequently transferred into weighed, numbered crucibles (crucible weight) and then weighed using a 4-place balance (crucible + dry sample weight). The sub-samples were placed in a muffle furnace for two hours which allowed any organic matter to be burned off. After two hours, the muffle furnace was turned off and the tray containing the crucible samples was removed and placed back into the desiccator to cool off. Once samples were cooled off, the crucibles and ashed samples were re-weighed (crucible + ash weight) to produce the organic matter content. The samples were then put back in the muffle furnace and heated at 950° C for two hours to remove the bulk carbonate content from the sediment samples and then re-weighed (Figure 6-6)

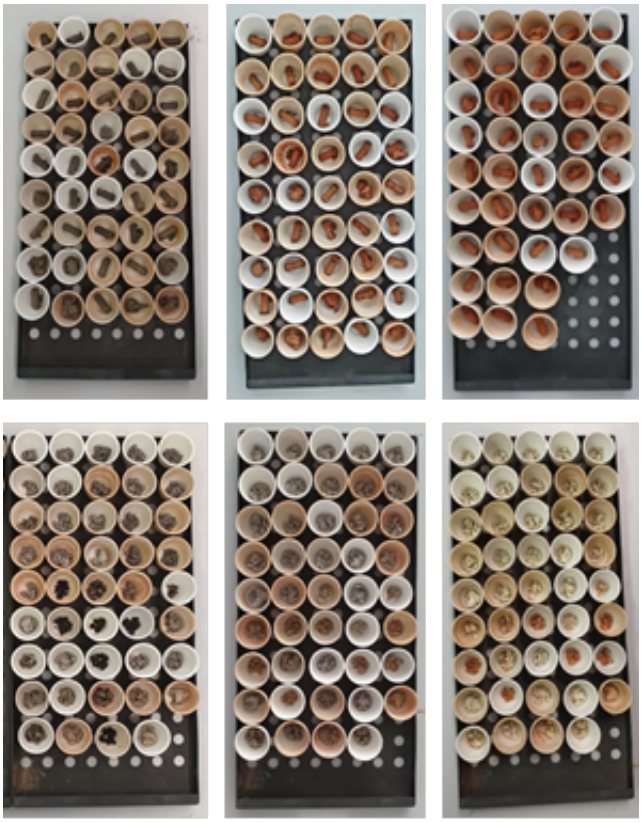

Figure 6-6: Top left to right - Lake Ganau LOI samples; Lake Ganau samples after 550°C; Lake Ganau samples after 950°C; Bottom left to right – Hashilan LOI samples; Hashilan samples after 550°C; Hashilan samples after 950°C;

At the end, the weighed results are turned into percentages using the following formulas:

Equation 1 Loss -on-ignition equation (Bengtsson and Enell 1986)

$$\%\ Organic\ Matter = \frac{(Dry - Ash)}{(Dry - Crucible)} \times 100$$

and

$$\%\ Bulk\ Calcium = \frac{(Dry - Ash)}{(Dry - Crucible)} \times 100$$

The results were calculated, and an organic matter and bulk carbonate curve was drawn in Microsoft Excel.

ITRAX core scanner

Hashilan Wetland

High-resolution measurements of the relative abundances of elements were carried out on an ITRAX uXRF Core Scanner at BOSCORF, National Oceanographic Centre, Southampton. Both Hashilan Core 1 and Core 2 were scanned at 1mm resolution (55kV, 50mA, 0ms (exposure time), molybdenum (Mo) tube used as target X-ray source). The raw XRF data was quality checked and plotted using Microsoft Excel and Adobe Illustrator. In addition, high resolution X-Ray radiograms were acquired for both cores.

Lake Ganau

The ITRAX- XRF scanning data was acquired at Austrian Core Facility, Institute of Geology, University of Innsbruck. Core Gan1-c (11.5m of sediment) was scanned at 1mm resolution (30kV, 45mA, 5s (exposure time), molybdenum (Mo) tube used as target X-ray source). High quality optical core imagery was also produced for Core Gan1-c. The raw XRF data was quality checked and plotted using Microsoft Excel and Adobe Illustrator. In addition, high resolution X-Ray radiograms were acquired. The ITRAX raw data was quality checked following the same criteria as used for Hashilan wetland.

The following criteria was used for quality checking the ITRAX data for both sites:

Validity – impacted by surface slope or gap/crack in the core section

- If validity was zero at the beginning or end of core the whole row was deleted.

Mean standard error (MSE)

- If value of MSE is higher than 10, then the elemental data was deleted.

Counts per second (cps)

- The data set was checked whether high variability was present in values.

XYZ Multi-Sensor Core Logger

The XYZ Multi-Sensor Core Logger (MSCL-XYZ) was used for continuous measurements of the magnetic susceptibility of the sediment cores of Hashilan wetland at 0.05cm intervals using Bartington MS2E point sensor.

MSCL-Core Imaging-System

High-quality core imagery of Hashilan Core 1 and Core 2, as well as RGB data were acquired using Geoscan V Colour Line-Scan Camera with Geotek Visible Light Source on the MSCL-Core Imaging-System (MSCL-CIS).

6.2.1.4 Statistical analyses

Constrained incremental sum of squares cluster analysis (CONISS)

Constrained incremental sum of squares cluster analysis (CONISS within the Tilia program) was chosen for the zonation of the pollen diagram to aid the interpretation of the pollen diagram by creating local pollen assemblage zones (Grimm 1987).

Principial component analysis (PCA)

The multivariate statistical analysis chosen to define the principal components of the sediment is principle component analysis (PCA). PCA was used on the high-resolution elemental dataset obtained with the ITRAX core scanner. The identification of the main components allows to describe the sediment and its geochemical properties. PCA was carried out using Minitab_18.

6.2.2 **Biostratigraphy**

The methods used to investigate the biostratigraphy of Hashilan wetland and Lake Ganau include pollen analysis, non-pollen palynomorph analysis, microscopic charcoal analysis, and macroscopic charcoal analysis (Hashilan only). Please see below for detailed procedures used for each method. All of the methods were performed in the labs at the University of Reading, except the sub-sampling for Lake Ganau which took place at the Laboratory of Palaeobotany at the Landesamt fuer Denkmalplege in Gaienhofen-Hemmenhofen, Germany. Unless specified otherwise, the methods outlined below were employed on both Hashilan wetland and Lake Ganau cores in the same manner.

6.2.2.1 Pollen analysis

Sub-sampling

Hashilan

Sub-samples were taken using a 1-2cm^3 volumetric sampler at regular intervals of 4cm covering the depth 50-398cm. Due to low pollen concentration at Hashilan, 2cm^3 of sediment was taken where sufficient sediment was present to sub-sample. In total 89 samples have been sub-sampled.

Lake Ganau

Sub-samples were taken using a 1cm^3 volumetric sampler at intervals between 4-20cm covering the depth 33-37.48m (Table 4). In total 81 samples have been sub-sampled.

Table 6-7: Sub-sampling resolution for Lake Ganau Core 1c

Depth (m)	Sub-sampling interval (cm)
33.00-34.00	20
34.00-35.90	5
35.90-37.50	4

The sediment samples were transferred into labelled glass beakers (50ml). Into each glass beaker, one tablet of exotic Lycopodium was added to calculate pollen concentrations, and approximately 30ml of 1% Sodium Phosphate (30ml) was added, followed by the beaker being covered with aluminium foil. The beakers containing the samples were placed onto a hotplate to simmer for one hour at around 80°C to disaggregate the sediment samples.

Sieving

Each sample was sieved through a coarse 125µm sieve which sites on top of a fine 5µm mesh sieve. The sample was poured into the upper sieve (125µm), washing out the glass beaker with distilled water. The coarser fraction was washed with distilled water until all fine particulate matter is suspended in the lower sieve. The coarse sieve was removed and washing through the fine sieve to remove some fine silts and clays was continued. After reducing the amount of water in the lower sieve, the remaining sample retained in the sieve was transferred into labelled round bottom centrifugation tubes (15ml capacity with screw cap). At the end, each tube had the same water level (15ml).

Heavy liquid separation – to dissolve calcium carbonate

Centrifuge tubes were placed into centrifuge for 5 minutes at 2500rpm (brake on), after which the supernatant was poured off. Sodium Polytungstate (specific gravity of 2.0g/cm^3) was added to the centrifuge tubes until the 6ml mark was reached, followed by agitating the samples using a vortex mixer. The centrifuge tubes were then centrifuged for 20min at 2500rpm with brake off. The organic suspension was poured off from the round bottom centrifuge tubes to labelled, conical base centrifuge tubes and topped up with deionised water until the 14ml mark was reached. The tubes were centrifuged for 5min at 2500rpm (brake on). This was followed by pouring off the supernatant to wash off the SPT from the sediment sample. The supernatant was poured off into a beaker for recycling. This step of washing off the SPT was repeated two more times.

Dehydration of sediment samples

To dehydrate the samples, each centrifuge tube was filled up with glacial acetic acid until the 6ml mark was reached. The samples were agitated using the vortex mixer and centrifuged for 5min at 3500rpm (brake on). The supernatant was poured off in the fume cupboard into running water.

Acetolysis- remove cellulose wall

Acetolysis mixture was made up using acetic anhydride and sulphuric acid (ratio 9:1) using two graduated cylinders and volumetric flask. Acetolysis mixture was added to each centrifuge tube until the 5ml mark was reached, followed by agitation of the samples and placing them in a boiling water bath (80-100° C) for 3min. The samples were then centrifuged for 5min at 3500rpm (brake on) and supernatant was then poured off into running water in fume cupboard. The centrifuge tubes were topped up with deionised water till the 10ml mark, agitated and placed back into the centrifuge for 5min at 3500rpm (brake on). This step was repeated in total three times to wash off the acetolysis mixture from the samples.

HCl and HF procedure (Hashilan wetland only)

The centrifuge tubes were centrifuged for 5min at 3500rpm, followed by pouring off the supernatant. Prior to treating the samples with HF, Hydrochloric acid (HCl) wash was needed. 2-3ml of HCl was poured into each centrifuge tube and mixed with the samples. Topping up with deionised water, agitating and centrifuging for 5min at 3500rpm (brake on) were performed. Supernatent was poured off. 5ml 40% HF was added to each centrifuge tube using calibrated bottle top dispenser. The samples were stirred using wooden sticks that were discarded in sodium carbonate to neutralise HF. The centrifuge tubes were placed in a hot waterbath (90 C) for one hour with the caps off (time depends on the silicate content in the samples). Once HF procedure is completed the caps were put on the centrifuge tubes and centrifuged for 5min at 3500rpm. The supernatant was poured off into HF waste bottle inside the fume cupboard containing sodium carbonate solution. This was followed with washing the HF from the samples with deionised water and centrifuging until the pH reached alkaline.

Mounting of slides

After the supernatant was removed, 1-2 drops of safranin were added to each centrifuge tube, topped up with deionised water till the 10ml mark, agitated and centrifuged for 5min at 3500rpm (brake on), followed by pouring off the supernatant. Deionised water was added to each conical centrifuge tube until 1.5ml mark was reached and the solution was then transferred using a pipette to labelled 1.5ml micro-centrifuge tubes. The micro-centrifuge tubes were centrifuged for 5min at 3500rpm (brake on) followed by pouring off the supernatant. Glycerol jelly was melted on a hotplate and a small amount (equal to sediment sample in micro-centrifuge tubes) was poured into each micro-centrifuge tube and then stirred using wooden sticks. Using a wooden stick, the sediment-glycerol jelly mixture was smeared onto a slide and a cover slip was placed over the jelly mixture, allowing it to spread. The slides were labelled with site code and sample depth. The slides were then allowed to dry for six hours.

Pollen counting

Pollen grains were counted using a LEICA DME light microscope with x400 and x1000 magnification. In total at least 300 pollen grains were counted per slide, excluding spores and aquatics. The pollen results were expressed as percentage of total land pollen and pollen influx. The pollen percentage and concentration were both calculated in Tilia version 2.6.1 (Grimm 2018). The 300 total land pollen count (TLP), as mentioned excluded non-pollen palynomorphs, aquatics and algae from this count, so they were calculated as percentage of their totals + TLP (e.g. % TLP + Aquatics). Identification of pollen grains was performed using the University of Reading reference collection as well as pollen keys and pollen atlases (Moore and Webb 1978; Reille 1992; Beug 2004). The preservation of the pollen grains was also noted during the scanning of the slide (broken, obscured, folded and amorphous/corroded).

6.2.2.2 Non-pollen palynomorph analysis

Non-pollen palynomorphs were counted alongside the pollen grains on the pollen slides, allowing direct correlation between them. Counting of non-pollen palynomorphs stopped when 300 pollen grain count was reached. Non-pollen palynomorphs were identified using reference papers such as Van Hoeve and Hendrikse (1998), and Gelorini *et al.* (2011).

6.2.2.3 Micro and macrocharcoal analysis

Microscopic charcoal

Microscopic charcoal was counted alongside the pollen grains on the pollen slides and are expressed as a percentage of the total land pollen sum. A large fraction of palaeoenvironmental studies uses the particle size measurement approach (e.g. Sadori and Giardini 2007) to quantify charcoal, which involves measuring the longest axis of a charcoal and placing it into different size classes. This allows inference about transport distance of the microscopic charcoal i.e. regional, extra-local and local fire event. However, as mentioned in Table 1, this method does not take into consideration the increased fragmentation of the charcoal particles that can occur depending on the extraction process used. Therefore, size differentiation for microscopic charcoal has not been implemented. The following widely used criteria (e.g. Turner *et al.* 2004) was used to identify and count microscopic charcoal: jet-black colour, angular shape and straight edges, opaque and at least 10μm in size.

Macroscopic charcoal

Macroscopic charcoal was extracted for Hashilan only because of lack of sediment available for Lake Ganau. The macroscopic charcoal samples were taken from the exact same location as the pollen samples to allow better comparison with microscopic charcoal values.

Using a volumetric sampler and spatula, $1cm^3$ of sediment were sub-sampled carefully to make sure the sediment is not pressed too much to avoid breaking of charcoal material. The samples were placed in beakers and 20ml of 1% sodium phosphate was added to disaggregate the sediment. Wooden sticks were used to help breaking down the sediment. The samples were left overnight in the lab inside sodium pyrophosphate. Once the samples were disaggregated, they were poured into a 125µm sieve and washed with abundant water. The remaining material in the sieve was transferred into labelled petri dishes with grid of lines (Figure 6-7). The petri dish was placed under a stereomicroscope and all of the charcoal was counted.

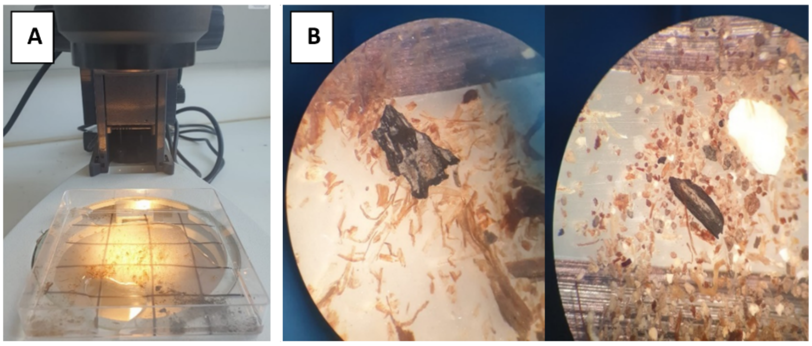

Figure 6-7: A- Petri dish with grid lines; B- Macroscopic charcoal

6.2.2.4 Mollusc and ostracod assessment

For Hashilan wetland, a brief mollusc and ostracod assessment was carried out to assess the possibility of future work and potentially help in the environmental interpretation (Figure 6-8). For the mollusc assessment, a quick scan of the core (0-400cm) was carried out by eye and a stereomicroscope was used to identify some mollusc species. The presence of ostracods was recorded using a stereomicroscope during macrocharcoal counting (0-400cm).

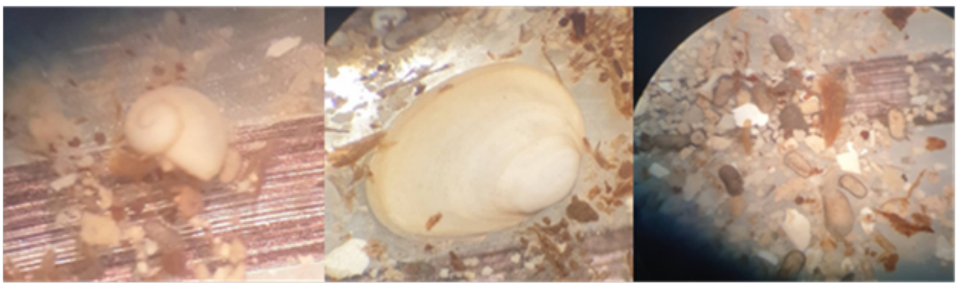

Figure 6-8: Molluscs and ostracods found during assessment of Hashilan wetland core

7 Results: Hashilan wetland

This chapter outlines the results from Hashilan wetland and is divided into two main parts which are lithostratigraphic and biostratigraphic results. The lithostratigraphic section contains the lithology, organic matter and bulk carbonate content, geochronology, principal component analysis, and ITRAX results. The biostratigraphic section contains the results of the pollen, non-pollen palynomorph, micro- and macrocharcoal analysis as well the mollusc and ostracod assessment carried out. The final part of the chapter provides the sedimentary and vegetation history of Hashilan wetland.

7.1 Lithostratigraphy

7.1.1 Lithology and Organic matter/bulk carbonate determinations

One 550cm undisturbed core was obtained from Hashilan wetland. The sedimentary description and the lithostratigraphic diagram for Core 1 can be found in Table 7-1 and Figure 7-1, which will be referred to throughout the section below. Compression of sediment occurred between 50-200cm and 450-500cm which has been corrected as outlined in the methodology chapter.

Table 7-1: Lithostratigraphic descriptions of Hashilan wetland Core 1

Depth (cm)	Depth correction (cm)	Unit	Description
0-23		37	10YR 3/2; Topsoil; As3 Ag1 Dh+; Very dark greyish brown silty clay sediment with roots present (~20%); gradual and smooth boundary
23-84	23- 86	36	10YR 4/1 changes gradually to 10YR 5/1; As3 Ag1 Dh+ Molluscs+; Dark grey silty clay that changes to grey silty clay with slightly higher silt content towards the end of the unit (As2 Ag2); <2% roots, large root between 20-24cm, and <1% Molluscs; clear and smooth boundary
84-89	86- 91	35	2.5Y 3/1; As3 Ag1 Sh+ Dh+ Molluscs+; Very dark grey organic silty clay; <1% roots and <1% molluscs; presence of fragments of herbaceous plants; abrupt and smooth boundary.
89-107	91- 107	34	10YR 4/1; As3 Ag1 Dh+ Molluscs+; Dark grey silty clay; <5% roots, <5% molluscs fragments and mollusc shells at 88 and 95cm; Abrupt and irregular boundary
107-126	107-127	33	10YR 2/1; Sh3 Ag1 As+ Th+ Ld+ Molluscs+; Black silty herbaceous peat (organic rich) with 15% roots and <1% molluscs fragments; Sharp and smooth boundary

126-180	127-184	32	10YR 4/1, colour change to 10YR 3/1; As3 Ag1 Dh+ Molluscs+; Dark grey which changes to very dark grey silty clay with <1% roots and <2% shell fragments; Diffuse and smooth boundary
180-285	184-285	31	7.5YR 3/1 changes to 10YR 3/1; As2 Ag2 Dh+ Molluscs+; Very dark grey which changes to very dark grey silty clay with <1% roots, <1% mollusc fragments, CaCo3?; More shells and CaCo3 at the lower half from around 273cm onwards; more silty and compact than unit 31; Abrupt and irregular boundary
285-288		30	10YR 4/1 with patches of 10YR 5/2 sediment; As3 Ga1 Ag+ Dh+ Molluscs+; Dark grey sandy clay with greyish brown sediment in it; <1%mollusc fragments, <1% roots, CaCo3?; compact unit; Abrupt and smooth boundary
288-296		29	10YR 2/1; Sh3 Ag1 Th+ Molluscs+ As+ Ld+; Black silty herbaceous peat with <2% roots and <1% shell fragments; highly humified (organic rich); compact unit; Sharp and wavy boundary
296-299		28	10YR 5/2 with 10YR 3/1 sediment in it; As4 Dh+ Molluscs+; Greyish brown clay with very dark grey sediment in it; <1% roots and <1% molluscs fragments; Sharp and wavy boundary
299-302		27	10YR 3/2; As4 Ag+ Dh+ Molluscs+; Very dark greyish brown clay with <1% roots and <1% molluscs fragments; Sharp and smooth boundary; Transitional unit from marl to peat
302-319		26	2.5Y 6/3; As2 Lc2 Dh+ Molluscs+; Light yellowish brown organic clay marl with <1% roots and <1% molluscs fragments; compact unit; Sharp and smooth boundary; not 100% marl in composition
319-344		25	10YR 2/1; Sh3 Ag1 As+ Th+ Ld+ Molluscs+; Black silty peat with <5% roots <1% molluscs fragments; highly humified peat (in-situ plant); Sharp and smooth boundary
344-350		24	2.5Y 4/3; As2 Lc1 Ga1 Dh+ Molluscs+; Olive brown sandy clay marl with <1% roots and <2% mollusc fragments; compact unit; calcite rich; Sharp and smooth boundary
350-354		23	10YR 2/1; As3 Ag1 Dh+ Molluscs+ Ld+; Black silty clay with <1% roots and <1% molluscs fragments; mixing of sediment; Sharp and smooth boundary. Contaminated unit?
354-378		22	2.5Y 5/3; As2 Lc1 Ga1 Dh+Molluscs+; Light olive brown sandy clay marl with <2% roots, 5-10% shell fragments and CaCo3; calcium-rich sediment; More molluscs and darker in colour from around 364cm onwards; Abrupt and smooth boundary
378-383		21	7.5YR 3/1; Sh3 Ag1 As+ Th+ Ld+ Molluscs+; Very dark grey silty peat with <2% roots and <1% shell fragments; Sharp and smooth boundary
383-384		20	7.5YR 3/2; As3 Ag1 Dh+; Dark brown silty clay (light coloured band) with <1% roots; Sharp and smooth boundary

384-387		19	7.5YR 2.5/1; As3 Ag1 Dh+Ld+ Molluscs+ Sh+; Black silty clay with <1% roots, <1% molluscs and a large root at 387cm; Sharp and smooth boundary
387-388		18	7.5YR 2.5/1; Sh3 Ag1 Ld+; Black silty peat (dark coloured band) sediment; Sharp and wavy boundary
388-397		17	10YR 2/1; Sh3 Ag1 Th+ As+ Ld+ Molluscs+; Black silty peat with <1% roots and <1% shell fragments; Sharp and smooth boundary
397-400		16	10YR 5/3; As3 Ga1 Ld+ molluscs+; Brown sandy clay with <1% molluscs and CaCo3?; Sharp and smooth boundary; mixing of sediment before peat formation; transitional unit from marl to peat?; organic rich
400-406		15	7.5YR 3/2; As3 Ag1 Th+ Sh+; Dark brown silty clay with <1% roots; Abrupt and wavy boundary
406-408		14	10YR 4/1; As2 Ag2 Dh+ Molluscs+; Dark grey silty clay with <1% roots, <1% molluscs and a large root between 405-407cm; Sharp and smooth boundary; mixing of units?
408-412		13	10YR 2/1; Sh3 Ag1 Th+ As+ Ld+; Black silty organic rich peat with <1% roots; Sharp and smooth boundary; highly humified peat (in-situ plants)
412-423		12	2.5Y 5/4; As2 Lc1 Ga1 Dh+; Light olive brown sandy clay marl with <1% roots, <1% CaCo3?; calcium rich; Abrupt and wavy boundary
423-435		11	2.5Y 3/3; As3 Ga1 Dh+ Ld+ Mollusc+; Dark olive brown organic rich sandy clay
435-439		10	10YR 3/1; As3 Ag1 Dh+ Ld+ Molluscs+; Very dark grey silty clay with <1% roots, <1% shell fragments and CaCo3; organic rich sediment; Sharp and irregular boundary
439-444		9	10YR 3/1; As3 Ag1 Sh+ Ld+; Very dark grey silty clay; Organic rich; Sharp and smooth
444-468	444-469	8	5Y 5/2; As2 Ag2 molluscs+; Olive grey silty clay with <1% shell fragments; Between 454-455cm and 456-457cm dark band (7.5YR 4/1 - Dark grey); Sharp and wavy boundary; less calcium rich then unit 6 (472-504cm)
468-471	469-472	7	10YR 3/2; As3 Ag1; Very dark greyish brown silty clay; Abrupt and wavy boundary; mixing up of sediment, smearing?
471-504	472-504	6	2.5Y 5/3; As2 Lc1 Ga1 Molluscs+; Light olive brown sandy clay marl with <1% shell fragments and CaCo3; Calcite rich unit (but not 100% marl in composition); Sharp and smooth boundary
504-508		5	10YR 3/2; As3 Ga1 Dh+ Ld+ Molluscs+; Very dark greyish brown sandy clay with <1% roots and <1% molluscs; organic rich?; Sharp and smooth boundary

508--512	4	2.5Y 6/4; As2 Lc1 Ga1 Dh+ Molluscs+; Light yellowish brown sandy clay marl with <1% roots and <1% molluscs; Sharp and smooth boundary?
512-521	3	10YR 3/2; As3 Ga1 Ag+ Ld+ Molluscs+; Very dark greyish brown sandy clay with <1% shell fragments and CaCo3; organic unit; Abrupt and irregular boundary
521-542	2	2.5Y 5/3; As3 Lc1 Ga+ Molluscs+; Light olive brown clay marl with <1% shell fragments, shell at 542cm, Charcoal? and CaCo3; Sharp and smooth boundary
542-550	1	10YR 2/1; Sh3 Ag1 Th+ molluscs+ As+ Ld+; Black silty peat with <1% roots and <1% shell fragments

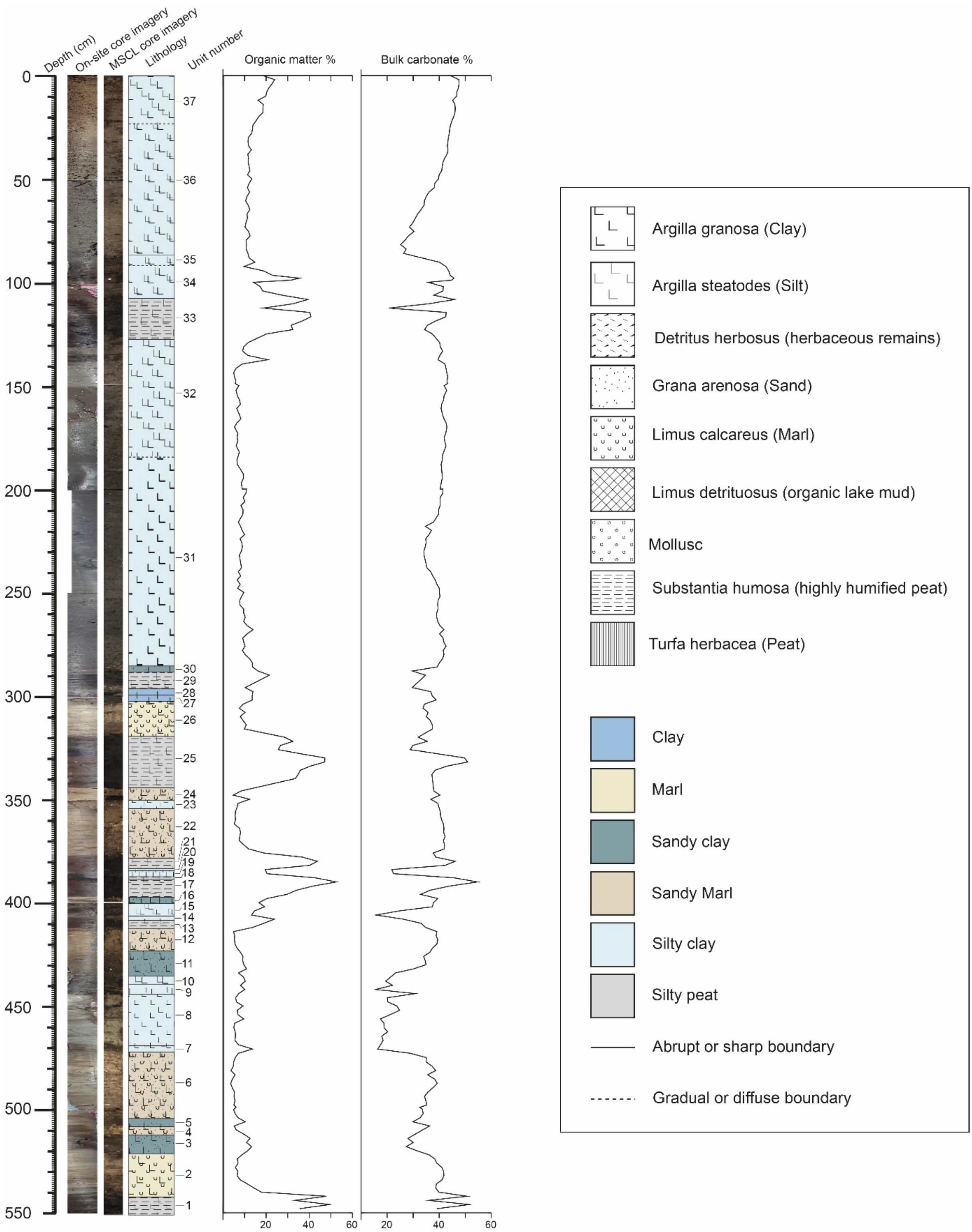

Figure 7-1: Lithology, organic matter content (%) and bulk carbonate content (%) for Hashilan wetland core 1

The basal sediments at 550cm (Unit 1) consist of black organic rich silty peat. The organic matter (max.50% min.34%) and bulk carbonate content (max.50% min.34%) are both high in the silty peat unit. At 542cm, the peat transitions into a light olive brown clay (Unit 2) which has a bulk carbonate percentage of ~42% while the organic matter content experiences a sharp decrease to ~ 8%. The calcium rich clay unit transitions into a very dark greyish brown sandy clay at 521cm (Unit 3) in which the bulk carbonate content declines to ~27% while the organic matter content slightly increases to ~13%. The very dark greyish brown sandy clay changes to light yellowish brown sandy clay at 512cm (Unit 4) with organic matter content experiencing a decline to ~5% while bulk carbonate content increases to ~35%. This sedimentary unit changes to very dark greyish brown sandy clay between 508-504cm (Unit 5) with a peak in organic matter content (~10%) and decline in bulk carbonate (~29%) content that is followed by the deposition of light olive brown sandy clay between 504-472cm (Unit 6), which resembles Marl. The organic matter content remains low in this Marl sedimentary unit (~7%) while the bulk carbonate content increases and remains high (min.33%, max.39%) (Unit 6).

The Marl like sediment is overlain by very dark greyish brown silty clay at 472cm (Unit 7) with a peak in organic matter content (~14%) and declining bulk carbonate content (min.16%), followed by olive grey silty clay between 469-444cm (Unit 8) that contains two dark bands between 454-455cm and 456-457cm (organic matter content: max.8% and max.10%, respectively). The bulk carbonate content in this sedimentary until fluctuates but generally is increasing over time (min.17%, max.28%).

From 439-444cm (Unit 9), organic rich clay deposit occurs which changes into very dark grey silty clay (Unit 10) that continues until 435cm with bulk carbonate increasing and organic matter content decreasing slightly. A small peak in organic matter content (~10%) occurs at 442cm while bulk carbonate content declines from ~31% to 15%. The silty clay sediment is followed by the deposition of dark olive brown, organic-rich sandy clay (435-423cm) (Unit 11), which sees an increase in bulk carbonate content (max.34%), and then calcium-rich light olive brown sandy clay (423-412cm) (Unit 12). The bulk carbonate content remains high (~39%) in the sandy clay unit while organic matter content starts increasing towards the end of the sedimentary unit.

Highly humified black silty peat overlays the calcium-rich sandy clay between 412-408cm (Unit 13). The organic matter content continues to rise and peaks (max.23%) as bulk carbonate content starts to decline. At 408cm (Unit 14), the sediment switches to dark grey silty clay followed by dark brown silty clay between 406-400cm (Unit 15). The bulk carbonate content starts to increase reaching 38% at 400cm while on the other hand the organic matter content declines (min.13% and max.19%). Brown sandy clay deposition occurs between 400-397cm (Unit 16) that transitions into black silty peat (Unit 17 and 18) that continues until 387cm. Black silty clay (Unit 19) overlays the peat that transitions into dark brown silty clay at 384cm (Unit 20). A return to very dark grey silty peat occurs between 383-378cm (Unit 21). Peaks in organic matter content can be identified at 390cm (~52%) and 380cm (~44%) with organic matter content generally remaining very high except between 386-384cm (~11%). Similarly, bulk carbonate content is high and peaks at 390cm and 380cm with ~55% and 46%, respectively. A decline in bulk carbonate content occurs between 386-384 (~22%).

Above the peat, light olive brown sandy clay deposition (Unit 22) occurs that continues until 354cm containing 5-10% of shell fragments with the sediments being darker in colour and higher quantity of molluscs between 378-364cm. A black silty clay deposition occurs between 352-350cm (Unit 23) that is followed by a compact layer of calcite-rich olive brown clay (Unit 24) that stops at 344cm. The organic matter content remains low between 384-344cm (~9%) with a small peak at 350cm (~12%). The bulk carbonate content for this depth interval remains high (~40%). A highly humified black silty peat forms on top of the calcite-rich clay sediments at 344cm (Unit 25). In this peat unit organic matter content increases reaching ~47% at 331cm after which it declines as it enters the next sedimentary unit. Bulk carbonate content also peaks in the peat unit to ~50% at 332cm after which it also starts decreasing.

At 319cm (Unit 26), the sediment changes to light yellowish brown organic clay. From 302cm (Unit 27) onwards, very dark greyish brown clay deposition is followed by greyish brown clay at 299cm (Unit 28). In these clay deposits, the organic matter content generally remains low with minor fluctuations (~10%) and the bulk carbonate remains high (~34%) with minor fluctuations. A return to black silty herbaceous peat occurs at 296cm (Unit 29) that is overlain by a compact dark grey sandy clay sedimentary unit (Unit 30) until 285cm. The bulk carbonate content declines slightly in the peat unit while the organic matter content increases with a peak of ~16% at 288cm. Between 288-285cm, dark grey sandy clay deposits are present (Unit 30) in which bulk carbonate content starts increasing (max.39%).

From 285- 184cm (Unit 31), very dark grey silty clay deposition occurs that becomes less compact and silty from 273cm onwards. Organic matter content and bulk carbonate content, both remain stable with no major spikes in percentage in this sedimentary unit. Organic matter content remains low (~10%) while bulk carbonate content remains high (~35%). A small decline in bulk carbonate content occurs between 244-224cm to ~ 33%. This sedimentary unit is followed by the deposition of dark grey silty clay between 184-127cm (Unit 32) that gradually changes into to a very dark grey colour. A peak in organic matter content occurs in this silty clay deposit at 137cm to ~20% after which it declines back to ~11%.

Black silty highly humified herbaceous peat overlays the very dark grey silty clay from 127-107cm (Unit 33) that contains about 15% root material. Both the organic matter content and bulk carbonate content are high in the peat deposit max.41 and max.43%, respectively. A decline in organic matter content and bulk carbonate content occurs at 112cm to ~19 and 21%, respectively, but increases again after the decline. From 107-91cm (Unit 34), the sediment deposited changes back to dark grey silty black. The bulk carbonate content for this sedimentary unit remains high (~44%) while the organic matter content declines between 107-100cm to ~9%, only to peak again afterwards reaching ~36% at 98cm.

Between 91-86cm (Unit 35), very dark grey organic silty clay deposit occurs that has fragments of herbaceous plants, an organic matter content of ~13% and a decline of bulk carbonate content from ~40% to 26%. This is followed by a transition into dark grey silty clay (Unit 36) that changes to grey silty clay between 86-23cm, with the silt content slightly decreasing over time. This sedimentary deposit is overlain by topsoil (Unit 37) that is very dark greyish brown in colour and has ~20% root content. From 91cm towards the surface (0cm) the organic matter content remains constant (~12%) with no major spikes and a gradual increase towards the surface (max.24%). The bulk carbonate content (~25%), on the other hand, experiences a gradual increase from 91cm onwards until it reaches ~48% towards the surface.

Throughout the core, broken or complete mollusc shells are present in different quantities (see mollusc and ostracod assessment section).

7.1.2 Geochronology

Based on the results of the radiocarbon dating, it appears that a number of dates are not in stratigraphic order (Table 7-2 and Figure 7-2). A number of factors can affect radiocarbon dating as discussed in the 'Methodology' chapter. In order to determine which radiocarbon dates are reliable and stratigraphically correct, several age-depth models were created. In addition, the pollen record of Hashilan wetland acted as a stratigraphic marker to verify the chronology. The pollen assemblage of Hashilan wetland suggests that the pollen sequence covers both the Lateglacial and Holocene period.

Prior to discussing the age-depth models produced, it is important to discuss the humic and humin dates, and which fraction should be used to produce age-depth models for Hashilan wetland.

Table 7-2: Radiocarbon dates for Hashilan wetland. Abbreviation: Plant material (P), humic (HC), humin (HN)

Sample ID	Conventional Radiocarbon Age (BP)	Depth (cm)	Type of sample	Sedimentary Context	Calibrated Age BP (95.4%)	$\delta^{13}C$ relative to VPDB	Laboratory Code
Has-12	202 ± 26	100	P	Silty clay	302	-26.90	SUERC-96806 (GU57241)
Hashilan C1 107-108	2821 ± 30	107	HC	Peat	3055-2848	-25.40	SUERC-87397 (GU51694)
Hashilan C1 107-108	2892 ± 30	107	HN	Peat	2934-3154	-26.1 ‰	SUERC-87398 (GU51695)
Hashilan C1 111-112	3117 ± 30	111	HC	Peat	3397-3239	-25.40	SUERC-87399 (GU51696)
Hashilan C1 111-112	3222 ± 30	111	HN	Peat	3376-3483	25.9 ‰	SUERC-87400 (GU51697)
Has-13	2390 ± 26	116	P	Peat	2663-2346	-26.60	SUERC-96810 (GU57269)
Hashilan C1 123-124	4273 ± 30	123	HC	Peat	4953-4728	-25.50	SUERC-87401 (GU51698)
Hashilan C1 123-124	4369 ± 30	123	HN	Peat	4855-5039	-27.8 ‰	SUERC-87402 (GU51699)
Has-14	941 ± 26	134	P	Silty clay	918-788	-24.70	SUERC-96807 (GU57242)
Has-16	1182 ± 26	242	P	Silty clay	1179-1001	-24.90	SUERC-96811 (GU57270)
Hashilan C1 291-292	11,013 ± 32	291	HC	Peat	13,067-12,838	-26.90	SUERC-87403 (GU51700)
Hashilan C1 291-292	11,680 ± 30	291	HN	Peat	13,476-13,597	-26.1 ‰	SUERC-87407 (GU51701)
Has-3	9493 ± 26	294	P	Peat	11,066-10,597	-26.85	OxA-41152
Has-4	5678 ± 21	321	P	Peat	6527-6398	-26.24	OxA-41687

Has-5	7459 ± 22	343	P	Peat	8346-8192	-26.08	OxA-41153
Has-6	8371 ± 25	379	P	Peat	9475-9298	-27.29	OxA-41688
Has-20	10,359 ± 29	393	P	Peat	12,467-12,000	-26.71	OxA-41689
Has-7	2935 ± 18	397	P	Sandy clay-peat	3163-3003	-25.38	OxA-41154
Has-18	16,388 ± 53	549	P	Peat	19,916-19,576	-26.20	SUERC-96805 (GU57240)

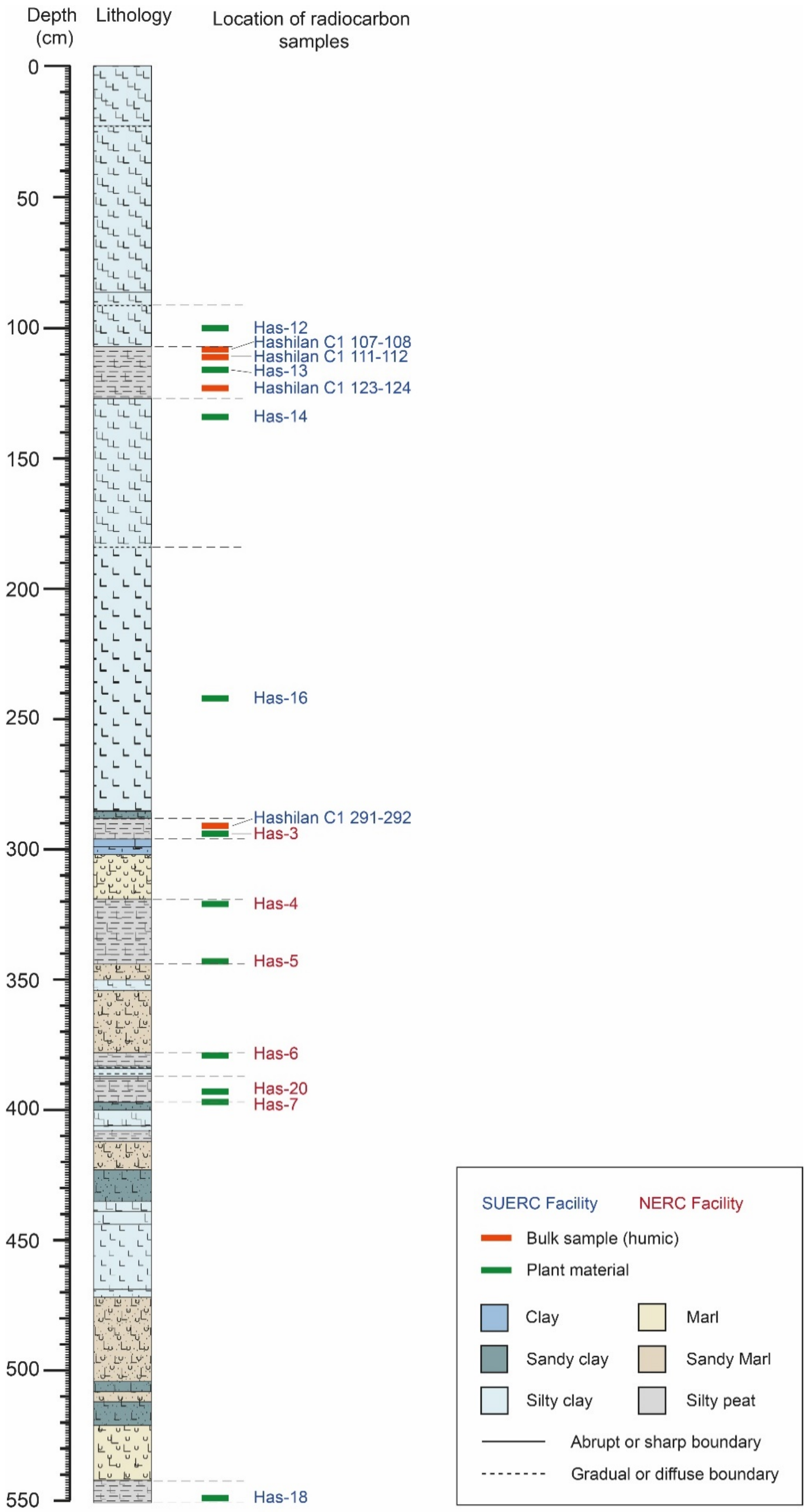

Figure 7-2: The location of radiocarbon dates and the type of material dated for Hashilan wetland

7.1.2.1 Humic vs humin date

Based on the results of the radiocarbon dating (Table 7-3), the un-calibrated humic dates are only slightly younger than the humin dates (~70-105 yrs), except for 'Hashilan C1 291-292' where there is a larger difference of ~670 years between the humic and humin date. As discussed in the Methodology chapter, a number of factors can control the humic and humin date results such as the movement of humic acid down the profile as water level drops leading to a younger humic date. Alternatively, the inclusion of mineral fractions such as clay particles or in-wash of older plant material resulting in a humin date older than expected.

Table 7-3: Humic and humin dates for Hashilan wetland

Sample ID	**Material**	**Conventional Radiocarbon Age (BP)**	**Calibrated Age BP (95.4%)**	**$\delta^{13}C$ relative to VPDB**
Hashilan C1 107-108	Bulk peat: Humic acid	2821 ± 30	2848-3055	-25.4 ‰
Hashilan C1 107-108	Bulk peat: Humin fraction	2892 ± 30	2934-3154	-26.1 ‰
Hashilan C1 111-112	Bulk peat: Humic acid	3117 ± 30	3239-3397	-25.4 ‰
Hashilan C1 111-112	Bulk peat: Humin fraction	3222 ± 30	3376-3483	-25.9 ‰
Hashilan C1 123-124	Bulk peat: Humic acid	4273 ± 30	4728-4953	-25.5 ‰
Hashilan C1 123-124	Bulk peat: Humin fraction	4369 ± 30	4855-5039	-27.8 ‰
Hashilan C1 291-292	Bulk peat: Humic acid	11,013 ± 32	12,838-13,067	-26.9 ‰
Hashilan C1 291-292	Bulk peat: Humin fraction	11,680 ± 30	13,476-13,597	-26.1 ‰

As it is difficult to determine which fraction is more reliable, two age-depth models were created, one that provides a minimum age-depth model and one that provides a maximum age-depth model. Both age-depth models were mapped onto the pollen diagram and lithology to determine the better fit with the vegetation and sedimentary history (see appendix). Since the Holocene humic and humin dates were only slightly different from each other in age, changes in vegetation during the Holocene period were occurring at roughly the same time based on the two age-depth models. The Lateglacial humic and humin date ('Hashilan C1 291-292'), in contrast, indicated a larger difference in age. Based on this approach of mapping the vegetation and lithology with both age-depth models, the Lateglacial vegetation and sedimentary sequence slightly fitted better with the humic age-depth model. Therefore, any subsequent age-depth model created for the Hashilan sequence includes the humic fraction dates.

7.1.2.2 Age-depth models

In total nine age-depth models were created using OxCal, using a combination of plant and humic dates, as well as humic-only and plant-only dates (Table 7-4). Plant material retrieved from silty clay units (Has-12, Has-14, Has-16 and Has-7) were excluded from every age-depth model because stratigraphically they were too young in date and likely are not in-situ plant material.

Table 7-4: Summary of the radiocarbon dates selected for producing each age-depth model

Age-depth model	Radiocarbon dates selected
Has-1	Hashilan C1 107-108, Hashilan C1 111-112, Hashilan C1 123-124, Has-4, Has-5, Has-6, Has-20, Has-18
Has-2	Hashilan C1 107-108, Hashilan C1 111-112, Hashilan C1 123-124, Hashilan C1 291-292
Has-3	Has-13, Has-3, Has-20, Has-18
Has-4	Has-13, Has-4, Has-5, Has-6, Has-20, Has-18
Has-5	Has-13, Hashilan C1 123-124, Has-4, Has-5, Has-6, Has-20, Has-18
Has-6	Has-13, Hashilan C1 123-124, Has-3, Has-20, Has-1
Has-7	Has-13, Hashilan C1 123-124, Hashilan C1 291-292, Has-18
Has-8	Hashilan C1 107-108, Hashilan C1 111-112, Hashilan C1 123-124, Has-3, Has-20, Has-18
Has-9	Hashilan C1 107-108, Hashilan C1 111-112, Hashilan C1 291-292, Has-18

The age-depth models Has-1, Has-3, Has-4, Has-5, Has-6, Has-7, and Has-8 have been rejected after comparing them with the pollen record of Hashilan wetland (see appendix for age-depth models). Based on the chronology of these rejected age-depth models, the Holocene period is characterised by high and increasing values of *Artemisia* and Amaranthaceae values, 15% and 45% respectively. Such high percentages of *Artemisia* and Amaranthaceae are typical for the Lateglacial period rather than the Early Holocene, which is supported by the nearby Lake Zeribar pollen record (Van Zeist and Bottema 1977). This leads to the conclusion that all of the plant material dated are erroneous i.e. too young in date in comparison to the humic dates, which is also the reason for rejecting the age-depth model Has-9 as it contains one plant material date. Several factors could have been responsible for yielding erroneous plant dates (see Methodology chapter). Root penetration of plants, such as *Phragmites australis* that grows nowadays at the wetland (Karami *et al.* 2001), into the underlying sediments could have led to intrusion of plant material into older sediments. Furthermore, as the plant materials were not identified prior to sample submission to the laboratory for radiocarbon dating, there is a possibility that the material dated contained *Phragmites* root material, monocot or Poaceae fragments that should have been avoided (Howard *et al.* 2009). Due to this uncertainty and the likely presence of *Phragmites* at the wetland in the past, the radiocarbon dates derived from plant material are rejected. The age-depth model Has-2, which is based on four humic-dates only (Table 7-5), is thus chosen to be reliable as it also agrees with the changes in the pollen stratigraphy. Based on the age-depth model created the base of the sequence dates to ~24,500 yrs BP (Figure 7-3).

As discussed in the research context, previous pollen studies of this region used bulk samples to create age-depth models for their study sites and thus are likely to be subject to hardwater-effect if their surrounding geology is limestone rich, resulting in older radiocarbon dates. For Hashilan wetland both humic and humin dates, rather than bulk dates, were obtained to help in the identification of any hard water effect on the samples. Since the humin and humic dates for Hashilan wetland were relatively close to each other in age and taken from organic-rich units, there is a possibility that the hard-water effect is minimal. The age-depth models created using plant material only (Has-3 and Has-4) as expected yielded an age-depth model that is younger in age than the humic-based age-depth model. However, as mentioned, the age-depth models based on plant material only do not agree with the vegetation changes identified. Therefore, the humic-based age-depth model has been chosen as the final model to be used in this study.

Table 7-5: Age-depth model Has-2: Radiocarbon dates highlighted in green have been rejected and only four humic dates were chosen for the final age-depth model for Hashilan wetland

Sample ID	Conventional Radiocarbon Age (BP)	Depth (cm)	Sedimentary context	$\delta^{13}C$ relative to VPDB	Reason for excluding
Has-12	202 ± 26	100	Silty clay	-26.90	Plant material
Hashilan C1 107-108	2821 ± 30	107	Bulk peat	-25.40	
Hashilan C1 111-112	3117 ± 30	111	Bulk peat	-25.40	
Has-13	2390 ± 26	116	Peat	-26.60	Plant material
Hashilan C1 123-124	4273 ± 30	123	Bulk peat	-25.50	
Has-14	941 ± 26	134	Silty clay	-24.70	Plant material
Has-16	1182 ± 26	242	Silty clay	-24.90	Plant material
Hashilan C1 291-292	11,013 ± 32	291	Bulk peat	-26.90	
Has-3	9493 ± 26	294	Peat	-26.85	Plant material

Has-4	5678 ± 21	321	Peat	-26.24	Plant material
Has-5	7459 ± 22	343	Peat	-26.08	Plant material
Has-6	8371 ± 25	379	Peat	-27.29	Plant material
Has-20	10,359 ± 29	393	Peat	-26.71	Plant material
Has-7	2935 ± 18	397	sandy clay / peat unit	-25.38	Plant material
Has-18	16,388 ± 53	549	Peat	-26.20	Plant material

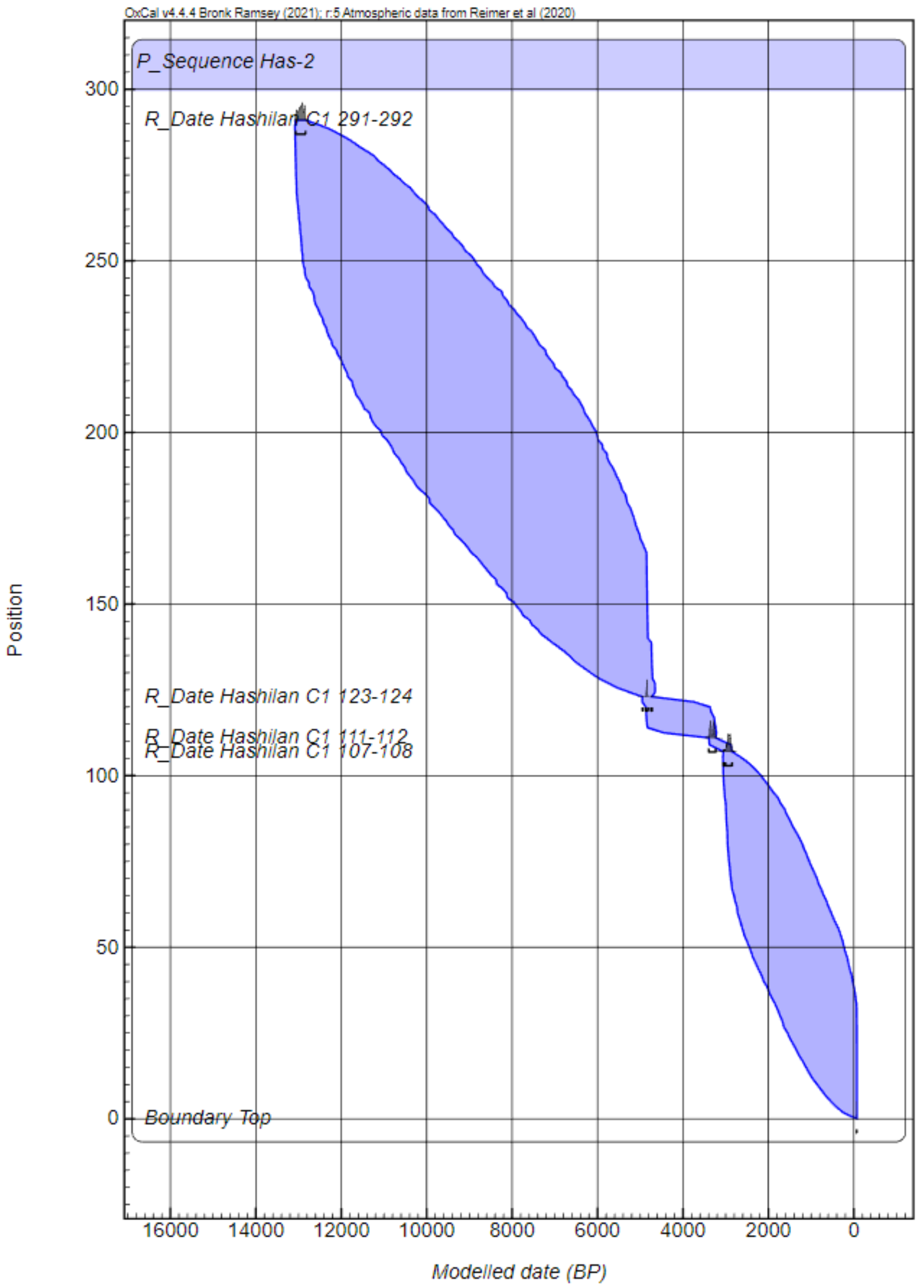

Figure 7-3: OxCal model for Hashilan wetland (0-291cm)

7.1.3 Geochemical data and Principal Component Analysis (PCA)

Prior to describing and interpreting the ITRAX data, principial component analyses was performed on the ITRAX data to determine the variability and relationship between the elements, as well as characterise the sediments and geochemical properties of the core. The presence and abundance of these elements can be influenced by a number of factors including the local bedrock composition and erosion of surrounding soil into the lake (Aliff *et al.* 2020: 8). PCA allows the identification of distinct geochemical clusters such as organic material, carbonates, and lithogenic/clastic material. An increase in lithogenic elements such as Ti (titanium), K (potassium), Fe (iron), Zr (zirconium) and Rb (rubidium) can suggest detrital input into the system by either surface water runoff or by wind. Carbonates are either derived from detrital material washed in as a result of erosion and weathering of the limestone or form because of precipitation of Ca (calcium) from the lake by evaporation or changes in the pH value. By performing PCA on Hashilan wetland, it will enable us to shed more light onto the correlation between the sediment type and the measured elements.

Principal component analysis was performed on all of the elements for Hashilan wetland to see overall relationship of elements (Figure 7-4). The ITRAX core scanner provided counts for 36 elements in total. All 36 elements were grouped according to their affinity with different geochemical fractions. PCA identified three main elemental fractions; carbonate material; organic material, and clastic detrital material (Figure 7-4). PCA was performed again but only using selected elements, with elements lower than 300 counts excluded (Figure 7-5). The results of the PCA also identify the three main elemental fractions: carbonates (Ca, Sr), organic material, and clastic material (Fe, Ti, Si, K). The score plot created for the selected elements has been divided into 50cm depth intervals to identify the relationship between depth and the elements (Figure 7-6).

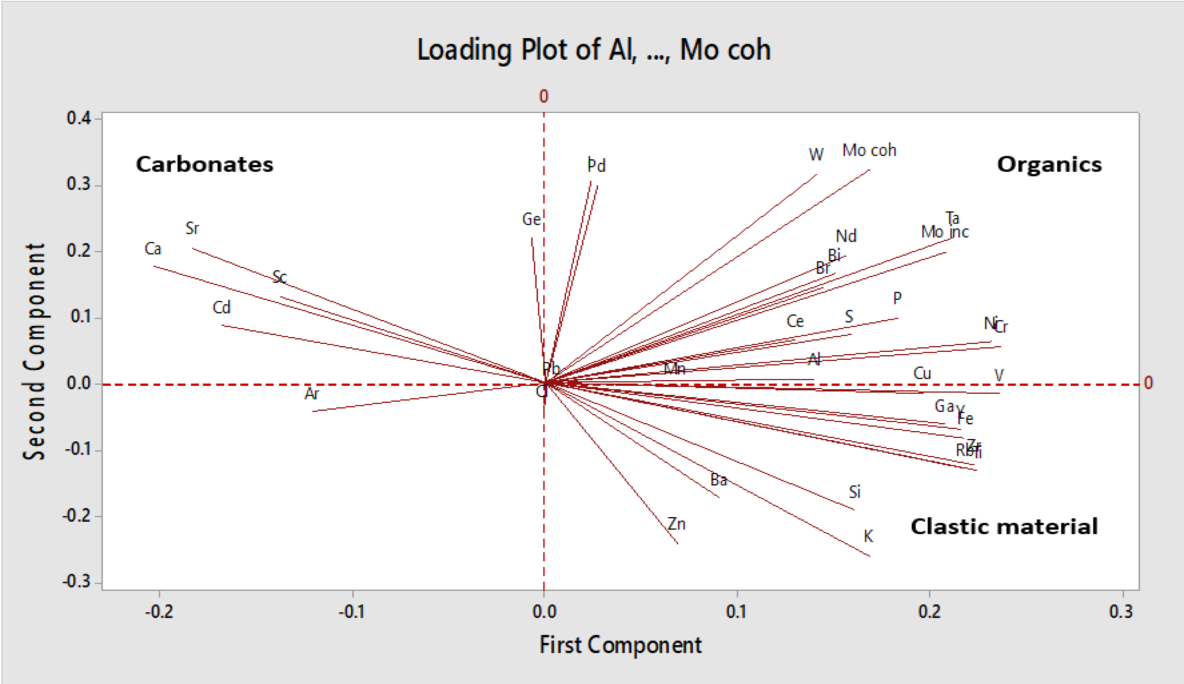

Figure 7-4: Loading plot for Hashilan wetland elemental abundance with main groups elemental fractions identified

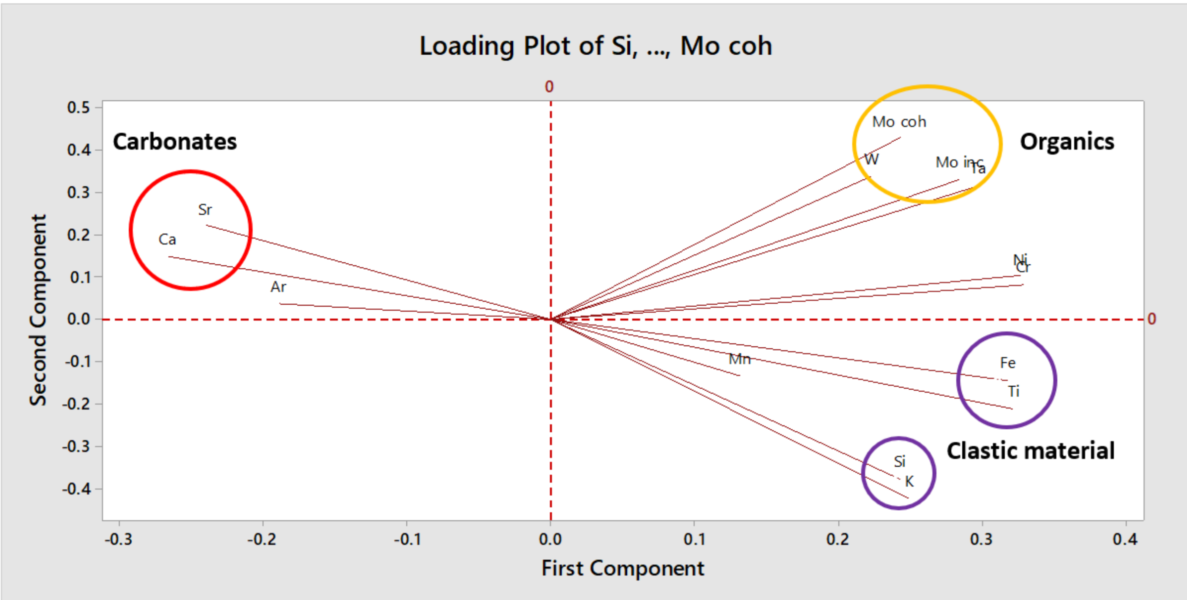

Figure 7-5: Loading plot for Hashilan wetland for selected elemental abundance with main groups elemental fractions identified

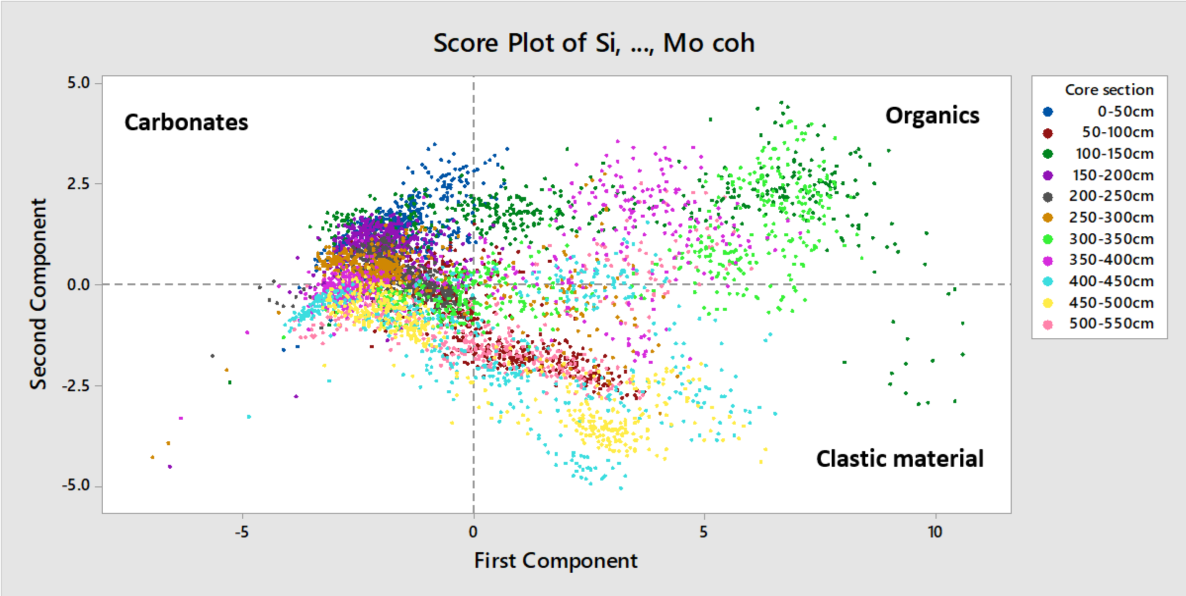

Figure 7-6: Score plot of Hashilan wetland divided into 50cm intervals and main controlling grouping identified for each quadrant

Based on the score plot, the sediments of Hashilan wetland are controlled largely by carbonates which can be explained by the carbonate rich geology of the region, except between 300-450cm (~13,350-20,100 yrs BP) which is controlled by all three elemental fractions, emphasising the variability in the make-up of the sediments for this specific depth interval.

7.1.4 ITRAX – geochemical data

The results of the ITRAX data and magnetic susceptibility are described in Table 7-6. The geochemical record has been divided into five zones using visual inspection (Figure 7-7). The following elements have been used to infer dust input: Si, K, Ti and Fe (Sharifi et al. 2015; Vaezi et al. 2019). An increase in these elements has been interpreted as an increase in dust input i.e. dry climate. Changes in Ca can be used to identify periods of increased authigenic carbonate production within the wetland, while Mn/Fe has been used to infer fluctuations in water level. Inc/Coh follows the organic matter % curve and thus is being used as an indicator for organic matter providing a much higher resolution than the organic matter % data. Magnetic susceptibility has been used to infer terrigenous input (soil erosion) from the surrounding catchment area into the basin.

Table 7-6: Description of elemental ratios and cps data derived from ITRAX core scanner for Hashilan wetland

Depth (cm)	Zone	Time period (yrs BP)
0-55	**HW-5**	**~1500-present**
Zone HW-5 is marked by gradually declining values of Si/cps, K/cps, Ti/cps and Fe/cps. Ca/cps increases at the beginning of the zone, followed by a gradual decline from ~48cm onwards. Mn/Fe ratio is high at the beginning of the zone, declines slightly and increases again towards the end of the zone. Inc/Coh ratio remains low, increasing slightly towards the end of the zone. Magnetic susceptibility declines and remains low throughout the zone.		
55-144	**HW-4**	**~6200-1500**
Zone HW-4 experiences a major increase in Si/cps, K/cps, Ti/cps and Fe/cps between 133-104cm, and 88-64cm, while Ca/cps and Mn/Fe ratio decline in values. At the start of the zone both Ca/cps and Mn/Fe ratio decline in values, only to increase again between 107-88cm. Towards the end of the zone Si/cps, K/cps, Ti/cps, Fe/cps decline, and Ca/cps and Mn/Fe ratio increase. Inc/Coh slightly increases in values with one major peak between 133-107cm, and two small peaks between 140-136cm and 100-92cm. Magnetic susceptibility increases gradually over time.		
144-284	**HW-3**	**~12,400-6200**
Zone HW-3 is characterised by generally low and less fluctuating values of Si/cps, K/cps, Ti/cps and Fe/cps. A small peak in these elements occurs at ~234cm. Ca/cps and Mn/Fe ratio follow a similar trend with high values between 284-246cm, followed by a small decline in values, after which they increase again with numerous fluctuations. Inc/Coh ratio declines in values and remains fairly low in this zone. Magnetic susceptibility continues to increase gradually starting to decline steadily from 234cm onwards.		
284-416	**HW-2**	**~18,500-12,400**
Zone HW-2 is characterised by continued large-scale fluctuations with high values of Si/cps, K/cps, Ti/cps, Fe/cps and low values of Ca/cps, Mn/Fe ratio occurring between 413-377cm, 344-317cm, and 297-286cm. During the remaining depth intervals, low Si/cps, K/cps, Ti/cps, Fe/cps values and high Ca/cps and Mn/Fe ratio occur. Inc/Coh ratio also fluctuates with two major peaks between 413-377cm and 344-317cm, and one minor peak between 297-286cm. Magnetic susceptibility declines gradually from the start of the zone reaching the lowest values at 348cm after which it starts to increase gradually.		
416-550	**HW-1**	**~24,500-18,500**
Zone HW-1 starts with Si/cps, K/cps, Ti/cps and Fe/cps being high in values, while Ca/cps and Mn/Fe ratio are low between 550-541cm. Inc/Coh ratio is also high during this depth interval, after which it declines and remains reactively low with minor fluctuations and peaks. Between 541-524cm, Si/cps, K/cps, Ti/cps and Fe/cps decline in values and remain low, and Ca/cps and Mn/Fe ratio increase. Other depth intervals with low Si/cps, K/cps, Ti/cps, Fe/cps and high Ca/cps and Mn/Fe ratio occur at 511-508cm, 501-474cm, and 431-413cm. Between 524-511cm, 508-501cm, and 473-431cm, Si/cps, K/cps, Ti/cps and Fe/cps are high in value		

while Ca/cps and Mn/Fe ratio are low. An increase in Mn/Fe and Ca/cps occurs toward the end of the zone. Magnetic susceptibility fluctuates, peaking at 521cm and 466cm with the latter one being the highest peak in the record. From 444cm, magnetic susceptibility starts to increase gradually.

HW-1 550-416cm ~24,500-18,500 yrs BP

Zone HW-1 (24,500-18,500 yrs BP; ~6000 yrs) is characterised by major fluctuations in dust input and water level. Four dust events have been identified between ~24,500-24,100 yrs BP, 23,400-22,800 yrs BP, 22,300-22,700 yrs BP, 21,100-19,200 yrs BP (high Si/cps, K/cps, Ti/cps and Fe/cps) (see Figure 7-7 no.1-4). Mn/Fe, used here as an indicator of water level fluctuations, indicates low water levels between 24,500-24,100 yrs BP, 23,400-22,800 yrs BP, 22,700-22,300 yrs BP, and 21,100-19,200 yrs BP. High water level as indicated by an increase in Mn/Fe occur at ~24,100-23,400 yrs BP, 22,800-22,700 yrs BP, 22,300-21,100 yrs BP, and 19,200-18,400 yrs BP. Low water levels occur during times of organic rich and peat sediment units. Inc/Coh ratio increases during organic-rich and peat units. Since Ca/cps is not increasing with the other elements, it suggests that majority of Ca/cps abundance is not coming from detrital material but has an authigenic origin.

HW-2 416-284cm ~18,500-12,400 yrs BP

Zone HW-2 (~18,500-12,400 yrs BP; ~6100 yrs) as well is characterised by major fluctuations in dust input and water level. Three dust events have been identified between ~18,400-16,800 yrs BP, 15,300-14,200 yrs BP, and 13,200-12,700 yrs BP based on high S/cps, K/cps, Ti/cps and Fe/cps. These dust events coincide with periods of low water level suggesting dry climatic conditions. High water levels occur between ~16,700-15,300 yrs BP, and 14,100-13,200 yrs BP (see Figure 7-7 no.5-7).

HW-3 284-144cm ~12,400-6200 yrs BP

Zone HW-3 (~12,400-6200 yrs BP; ~6200 yrs) unlike the previous two zones (HW-2 and HW-1), experiences less variability with the dust signal generally being low, slightly increasing until at ~10,200 yrs BP after which it starts declining again. The water level in this zone also experiences less fluctuations. The increase of Mn/Fe between 12,400-11,700 yrs BP suggests the presence of higher water levels, followed by a decline in water levels. Water levels only start to increase again gradually from ~9150 yrs BP onwards.

HW-4 144-55cm ~6200-1500 yrs BP

In Zone HW-4 (~6200-1500 yrs BP; ~4900 yrs BP), according to the Mn/Fe ratio water level starts declining from ~6300 yrs BP which corresponds to an increase in the dust input suggesting the onset of drier climatic conditions that increase at ~5300 yrs BP and last until ~3000 yrs BP with the highest peak in dust occurring at ~3900 yrs BP (see Figure 7-7 no.8). A small decline in water level occurs between ~2600-2400 yrs BP. However, no increase in dust input occurs during this short time interval. This time interval is followed by dusty conditions until ~1700 yrs BP (see Figure 7-7 no.9).

HW-5 55-0cm ~ 1500 – to present yrs BP

Zone 5 (~1500 yrs to present; ~1500 yrs) is characterised by an overall increase in water level and low dust input, with authigenic calcium production declining over time.

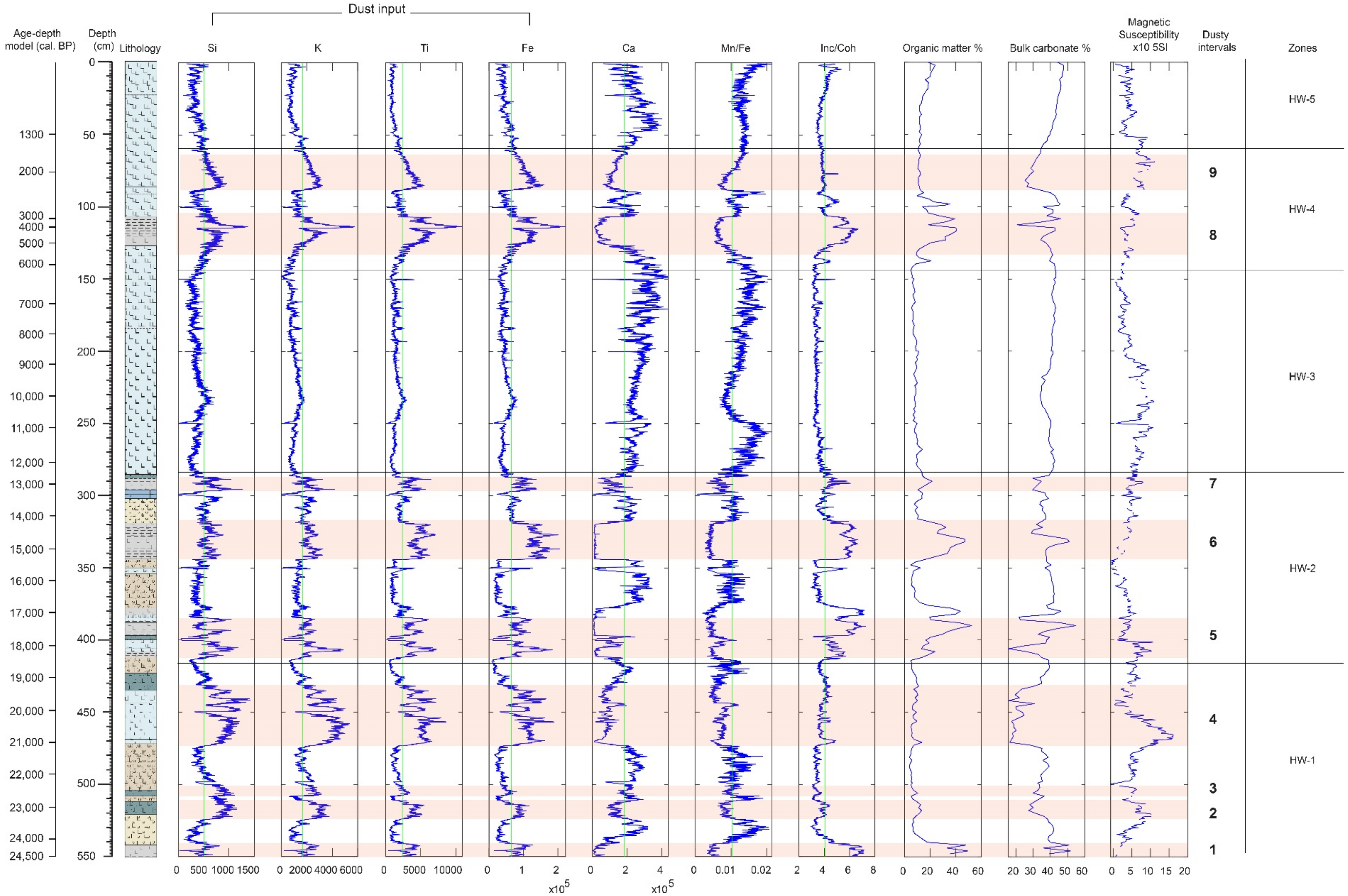

Figure 7-7: Geochemical data of Hashilan wetland mapped against age (cal. BP) and lithology. Pink highlighted boxes indicate periods of low lake levels and increased dust input

7.2 Biostratigraphy

7.2.1 Pollen, non-pollen palynomorph, microcharcoal and macrocharcoal

The results of the pollen, non-pollen palynomorphs, microcharcoal and macrocharcoal are described in Table 7-7. The pollen, non-pollen palynomorph and microcharcoal results are expressed as a percentage of total land pollen (trees, shrubs and herbs), and the macrocharcoal as total count/cm^2. Pollen concentration and influx are expressed as grains/cm^2 and grains/cm^2/year, respectively.

The pollen percentage, influx and pollen ratio diagrams (Figure 7-8; Figure 7-9; Figure 7-10) have been divided into six local pollen assemblage zones using visual and statistical (constrained cluster analysis) methods. The full pollen, non-pollen palynomorph, macrocharcoal and microcharcoal counts can be found in the Appendix.

Table 7-7: Description of pollen zones for Hashilan wetland

<table>
<tr><th>Depth (cm)</th><th>Zone</th><th>Main taxa</th><th>Time period</th></tr>
<tr><td>398-319</td><td>HW-1</td><td>Amaranthaceae – Artemisia – Poaceae</td><td>~17,700-14,200</td></tr>
<tr><td colspan="4">HW-1 is characterised by high values of herbs, and low values of trees and shrubs. Low amount of algae and npps are present throughout the zone while aquatics values are higher. Microcharcoal increases overtime from ~15% to ~80% towards the end of the zone, with three peaks at 387cm (~86%), 338cm (~64%), and 326cm (~79%). Macrocharcoal values remain low with two peaks at 387cm and 326cm (2700 particles and 2044 particles, respectively) that coincide with sharp peaks in the microcharcoal values.

This zone is dominated by Amaranthaceae (~45%) and Artemisia (~10%), both of which increase over time to reach ~60% and ~20%, respectively. Poaceae values are also high but decline from ~45% to 25%. Other herbs include Apiaceae (~5%), Asteraceae (~3%), and Thalictrum (~2%), along with very low values of Caryophyllaceae, Cousinia, Fabaceae, Galium, Matricaria-type, Plantaginaceae, Polygonaceae (all ~1%). The tree taxa is dominated by very low values of Salix and Tamarix (~1-2%). The Aquatic taxa is dominated by fluctuating levels of Cyperaceae (~10%), and low values of Pediastrum (~2%) are present between 382-342cm. Npps include Zygnema-type (~2%) and low, fluctuating values of Glomus (~2%).

Pollen concentration is fluctuating in this zone with the highest concentration at 398cm (31768 grains/cm^2) followed by a decline to 3008 grains/cm^2 at 362cm, after which it peaks reaching max. concentration of 18614 grains/cm^2 at 342cm. Pollen influx of Quercus (values between 0-1 grain/cm^2/year), Artemisia (values between 5-91 grains/cm^2/year), Poaceae (values between 20-222 grains/cm^2/year), Poaceae >40micron (values between 0-33 grains/cm^2/year), and microcharcoal (values between 3-673 particles/cm^2/year) fluctuate and match the trend identified in the percentage diagram. The pollen influx for Amaranthaceae differs from its percentage data, starting with a decline from 229 grains/cm^2/year to 29 grains/cm^2/year at 362cm, followed by a peak at 342cm to 195 grain/cm^2/year. The total land pollen influx reflects the Poaceae and Amaranthaceae influx values.</td></tr>
</table>

Amaranthaceae/*Artemisia*, Poaceae/*Artemisia* and Poaceae/Amaranthaceae are low in values. (*Artemisia*+Amaranthaceae)/Poaceae values slightly increase over time starting at 351cm.

319-285	**HW-2**	**Amaranthaceae – *Artemisia* – Poaceae**	**~14,200-12,400**

Zone HW-2 is still characterised by high values of herbs, and very low values of trees and shrubs. Aquatics values decline and npp values increase. Microcharcoal declines to ~18% after which it peaks at 298cm (~80%), followed by a decline to ~40%. Macrocharcoal values remain low with a peak between 298-295cm (368 particles/cm^2).

Salix and *Tamarix* percentages decline to lower than 1% and completely disappear towards the top of the zone. The herbaceous taxa is still dominated by fluctuating values of Amaranthaceae (~45%) with peaks occurring at 310cm (~60%) and 295cm (~62%). *Artemisia* is declining from ~15% to ~8%, while Poaceae, which is also fluctuating, increases from ~25% to ~50%. Apiaceae drops to less than 1% at the start of the zone, while Asteraceae experiences an increase from ~2% to ~10% (average ~5%). Other herbaceous taxa present in low percentages are Caryophyllaceae, *Centaurea undiff.*, *Cirsium*, *Cousinia*, *Filipendula*, *Senecio-/Filago-type* and *Thalictrum* (all ~1-2%). Cyperaceae declines as the zone starts from ~15% to ~4%, and *Potamogeton* (less than 1%) and *Sparganium-type* (~2%) are present, with *Sparganium-type* appearing towards the end of the zone. *Glomus* values fluctuate but generally increase in this zone (max. ~30%).

Pollen concentration increases over time reaching max. concentration of 28742 grains/cm^2 at 290cm after which the concentration declines. Pollen influx of *Quercus* (values between 0-1 grain/cm^2/year), Poaceae (values between 15-203 grains/cm^2/year), Poaceae >40micron (values between 0-12 grains/cm^2/year) and microcharcoal (values between 17-562 particles/cm^2/year) follow a similar identified in the percentage diagram. The total land pollen influx increases over time from 144 grains/cm^2/year to 428 grains/cm^2/year. Amaranthaceae influx values are low at the beginning of the zone (72 grains/cm^2/year) but increase and peak towards the end of the reaching 204 grains/cm^2/year at 295cm after which it declines sharply. *Artemisia* pollen influx follows a similar trend to its percentage values, starting the zone with a decline from 24 grain/cm^2/grain to 4 grains/cm^2/year, followed by an increase from 306cm onwards to 33 grains/cm^2/year at 290cm. From 290cm onwards *Artemisia* pollen influx declines to 10 grains/cm^2/year.

Amaranthaceae/*Artemisia* and Poaceae/Amaranthaceae remain low. (*Artemisia*+Amaranthaceae)/Poaceae values remain high until the end of the zone after which it declines. Poaceae/*Artemisia* values remain low until 299cm after which it starts increasing.

285-212	**HW-3**	**Poaceae - Amaranthaceae – Asteraceae – Cichoriaceae**	**~12,400-9100**

Zone HW-3 is characterised by high values of herbs, very low values of shrubs and declining, low values of trees. Aquatics and npps values increase. Microcharcoal values fluctuate in the first half the zone followed by an increase from 262cm onwards reaching up to ~75%. Macrocharcoal values are gradually declining to very low values (less than 30 particles/cm^2) with a peak at 274cm (195 particles/cm^2).

The herbaceous taxa is characterised by high, increasing values of Poaceae (~40%), and declining values of Amaranthaceae (~35%) and *Artemisia* (~4%). Asteraceae declines from ~12% to ~3% followed by a gradual increase from 242cm to ~18%. Caryophyllaceae experiences a peak between 266-235cm (~10%). Cichoriaceae increases (~6%), and low values of Brassicaceae (~1%), *Centaurea undiff.* (~2%), *Cirsium-type* (2%), Fabaceae (~1%), *Filipendula* (~1%), *Matricaria-type* (~2%), *Senecio-/Filago-type* (~4%), and *Thalictrum* (~2%) are present. The aquatic taxa is characterised by the low presence of *Potamogeton* (less than 1%), low values of

Cyperaceae (~5%), and increasing values of *Sparganium-type* (min.5% to max.10%). Npp taxa is characterised by *HdV-181/182* (~2%) and fluctuating *Glomus* values (average ~10%).

Pollen concentration is gradually declining (min. concentration of 1812 grain/cm^2 at 242cm), increasing slightly towards the end of the zone (max. concentration of 4391 grain/cm^2 at 218cm). Pollen influx of *Artemisia* (values between 1-10 grains/cm^2/year), Poaceae >40micron (values between 0-2 grains/cm^2/year) and microcharcoal (values between 17-214 grains/cm^2/year) follow a similar trend to their percentage data. Amaranthaceae pollen influx data also follows a declining value trend, similar to its percentage data, with values between 14-51 grains/cm^2/year. Poaceae pollen influx values unlike the percentage data are low only slightly increasing towards the end of the zone (values between 14-41 grain/cm^2/year. The total land pollen influx is low and gradually declines (values between 38-119 grains/cm^2/year.

Poaceae/Amaranthaceae slightly increases and (*Artemisia*+Amaranthaceae)/Poaceae value declines. Both Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* start to increase over time to very high values. The highest peaks in Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* occur at 218cm.

212-148	**HW-4**	**Poaceae – Asteraceae – Cichoriaceae**	**~9100-6300**

Zone HW-4 is characterised by a slight increase in trees and high values of herbs. Aquatics values remain fairly constant with some fluctuations and npps increase. Microcharcoal values increase further reaching up to ~86%. Towards the end of the zone microcharcoal percentage declines to ~60%. Macrocharcoal values, in contrast, slightly increase reaching 76 particles/cm^2 at 194cm after which it declines to very low values (less than 30 particles/cm^2.

The tree taxa is dominated by low values of *Fraxinus*, *Pinus*, *Quercus*, and *Salix* (all less than 1%). Amaranthaceae values further decline to ~20%, while Poaceae values increase to ~53%. Other herbs characterising this zone include Asteraceae (~8%), Cichoriaceae (~10%), *Centaurea undiff.* (~4%), Caryophyllaceae (~2%), *Centaurea solstitialis-type* (~1%), *Centaurea scabiosa-type* (~1%), *Cirsium-type* (~3%), Malvaceae (~3%), *Matricaria-type* (~2%), Poaceae >40 micron (~1%), *Senecio-/Filago-type* (~4%), *Thalictrum* (~2%). Cyperaceae increases from 190cm onwards to ~18% (average ~13%), while *Sparganium-type* declines from the start of the zone to ~4%. *Glomus* increases (average ~12%), and low peaks of *Sporormiella-type*, *Sordaria-type*, *HdV-143* (all lower than 1%) are present. *HdV-181/182* values increase rapidly and remain high (~15%).

Pollen concentration further declines from 200cm onwards with max. concentration of 1273 grain/cm^2. The lowest pollen influx occurs in this zone which is reflected in the total land pollen values (values between 13-89 grains/cm^2/year). Microcharcoal influx values also decline from 384 grains/cm^2/year at 206cm to 41 grains/cm^2/year at 150cm.

(*Artemisia*+Amaranthaceae)/Poaceae declines to very low values, while Poaceae/Amaranthaceae increases. Both Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* increase further and fluctuate, portraying a similar trend. Two peaks can be identified in the Amaranthaceae/*Artemisia* ratio between 206-188cm and 166-152cm. The two peaks in the Poaceae/*Artemisia* ratio occur between 208-186cm and 170-152cm.

148-103	**HW-5**	***Quercus*- Poaceae >40micron – *Artemisia* - *Apiaceae***	**~6300-2700**

Zone HW-5 is characterised by an increase in trees and slight decline in herbs. Aquatics increase, npps decline, and algae's experience an increase. Microcharcoal values decline slightly towards the start of the zone but still remain relatively high, followed by an increase to ~77%. Macrocharcoal increases from very low counts from 126cm onwards reaching a maximum 228 particles/cm^2.

The tree taxa is dominated by *Quercus* (max.7%) that starts to increase from 138cm onwards, and the sporadic presence *Fraxinus* (~2%). From 118cm, *Quercus* values start to decline to ~2%. The herbaceous taxa is still dominated by Poaceae (~50%). Asteraceae and Cichoriaceae decline from 134cm onwards to ~5% and 7%, respectively, while Poaceae >40micron (~10%), *Artemisia* (~4%) and Apiaceae (~4%) increase. Amaranthaceae further declines to ~12%. Other herbaceous taxa present include Caryophyllaceae (~2%), *Centaurea undiff.* (4%), *Cirsium-type* (~2%), Fabaceae (ca1%), *Filipendula* (~2%), *Matricaria-type* (~3%), *Mentha-type* (~1%), Plantaginaceae (~2%), *Plantago lanceolata-type* (less than 1%), *Polygonum aviculare-type* (~1%), *Senecio-/Filago-type* (~4%) and *Thalictrum* (~2%). Cyperaceae is highly fluctuating but generally increasing (max.50%, min.2%). *Sparganium-type* increases over time (~8%) with a peak at 118cm (~30%) after which it declines to ~5%. *Pediastrum* appears between 130-103cm (max.12%, min.1%). *Glomus* slightly declines and fluctuates (average ~10%), and *HdV-181/182* declines over time to ~2%. A small peak of *Sordaria-type* at 126cm occurs (less than 1%).

Pollen concentration increases gradually in this zone with max. concentration of 18800 grain/cm^2 towards the end of the zone. Pollen influx values start increasing as indicated by the total land pollen values increasing from 65 to 257 grains/cm^2/year. Pollen influx of *Quercus* (values between 0-13 grains/cm^2/year), *Artemisia* (values between 0-5 grains/cm^2/year), and Poaceae >40micron (values between 1-24 grains/cm^2/year) follow similar trend as their percentage data. Poaceae influx values are increasing over time from 36 to 110 grains/cm^2/year. Amaranthaceae influx values increase but generally are low (maximum 28 grain/cm^2/year. Microcharcoal influx values also increase (values between 47-713 grains/cm^2/year).

(*Artemisia*+Amaranthaceae)/Poaceae declines further and Poaceae/Amaranthaceae slightly increases over time (starting to increase from 128cm onwards). Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* fluctuate but generally decline. One peak in both Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* occurs at ~138cm.

103-50	**HW-6**	**Amaranthaceae – *Centaurea undiff.* - Poaceae**	**~2700-to 1300**

Zone HW-6 is characterised by low values of trees and high values of herbs. Both aquatics and npps increase in value over time. Microcharcoal slightly fluctuates at the beginning of the zone but remains high (max.75%), while macrocharcoal counts decline with a peak at 86cm (111 particles/cm^2).

The tree taxa is still dominated by *Quercus* (~4%) which declines over time, followed by *Fraxinus* (~2%). *Salix* and *Pinus* are present sporadically (less than 1%). The herbaceous taxa is dominated by Poaceae which has increased to ~58%. Other herbaceous taxa include Poaceae >40micron (~8%), Apiaceae (~2%), *Artemisia* (~2%), *Asteraceae* (~4%), Caryophyllaceae (~2%), Cichoriaceae (~7%), *Cirsium* (~1%), Fabaceae (less than 1%), *Galium* (~2%), Malvaceae (~1%), *Matricaria-type* (~2%), *Mentha-type* (less than 1%), Plantaginaceae (~2%), *Plantago lanceolata-type* (less than 1%), *Polygonum aviculare-type* (less than 1%), *Senecio-/Filago-type* (~2%) and *Thalictrum* (~2%). *Centaurea undiff.* increases over time from ~3% to ~6%, and Amaranthaceae also increases from ~9% to 14%. Cyperaceae experiences a decline to ~7% between 90-93cm after which it increases to ~30%. *Sparganium-type* increase to ~18% between 86-82cm, followed by a decline to ~5%. *Glomus* increases from 86cm onwards to ~25% and remains high. Other npps include *HdV-181/182* that increases to ~8%, *HdV-143* (between 78-50cm), and one small peak of less than 1% of *Sporormiella-type* and *Sordaria-type*.

Pollen concentration declines in this zone towards the end of the zone from 17097 grains/cm^2 at 98cm to 5638 grains/cm^2 at 50cm. Pollen influx values are the highest in this zone. Total land pollen influx is high but gradually declines from 499 grains/cm^2/year at 98cm to 200 grains/cm^2/year at 50cm. *Quercus* influx values decline over time with the highest peak occurring at 98cm (23 grains/cm^2/year). *Artemisia* influx values also decline in this zone (values between 0-13 grains/cm^2/year). Amaranthaceae influx increases and remains fairly constant (values between 12-39 grains/cm^2/year). Poaceae and Poaceae >40micron reach the highest influx values ranging between 52-304 grains/cm^2/year and 5-32 grains/cm^2/year, respectively. Microcharcoal influx data follows a similar trend to its percentage data except that it declines towards the end of the zone (values between 116-573 grains/cm^2/year).

(*Artemisia*+Amaranthaceae)/Poaceae remains very low, and Poaceae/Amaranthaceae also remains low.

Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* follow a similar trend of increasing towards the end of the zone, with Poaceae/*Artemisia* having higher values.

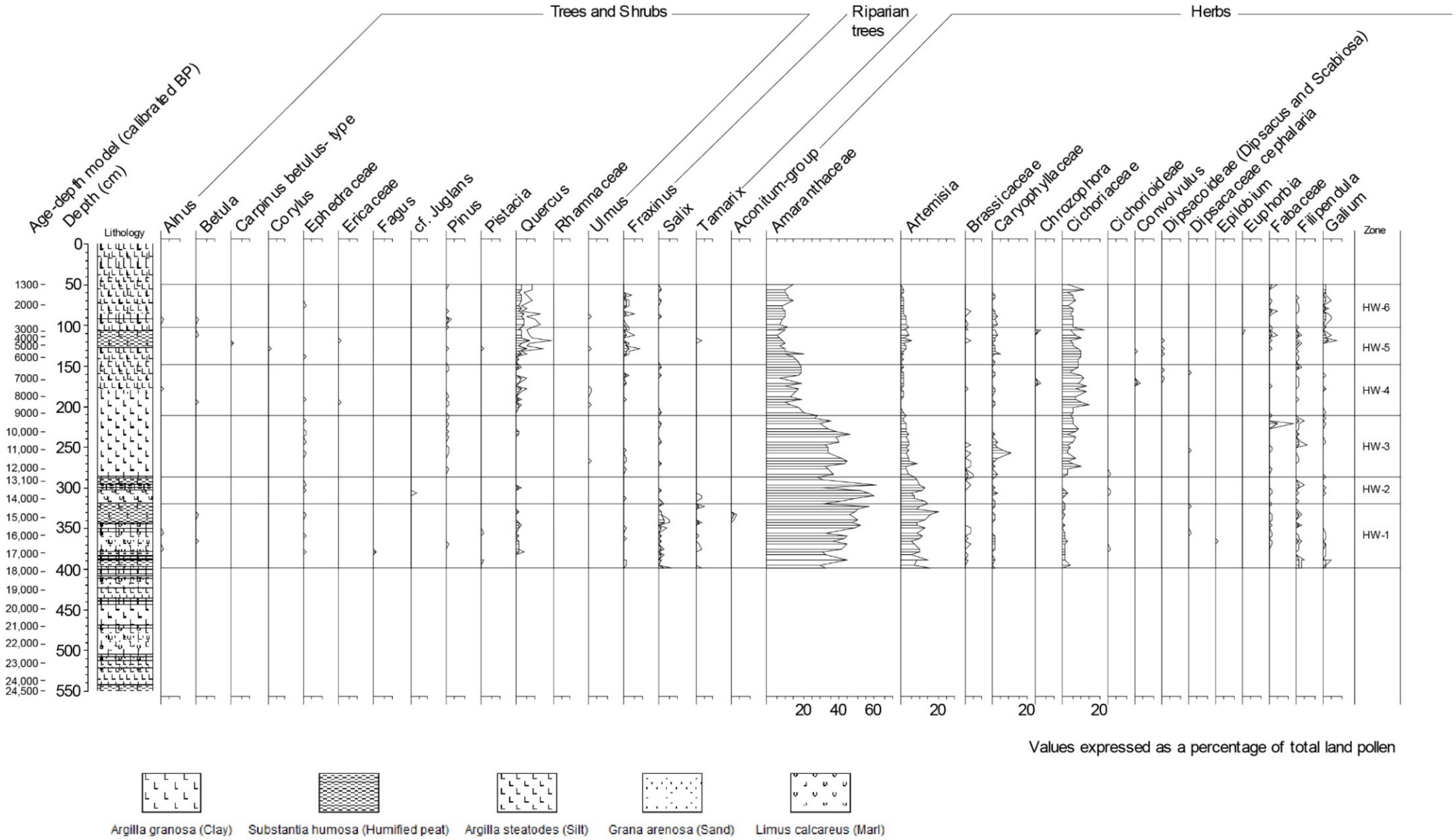

Figure 7-8: Pollen percentage diagram of Hashilan wetland with selected taxa exaggerated by factor 3 (Part 1)

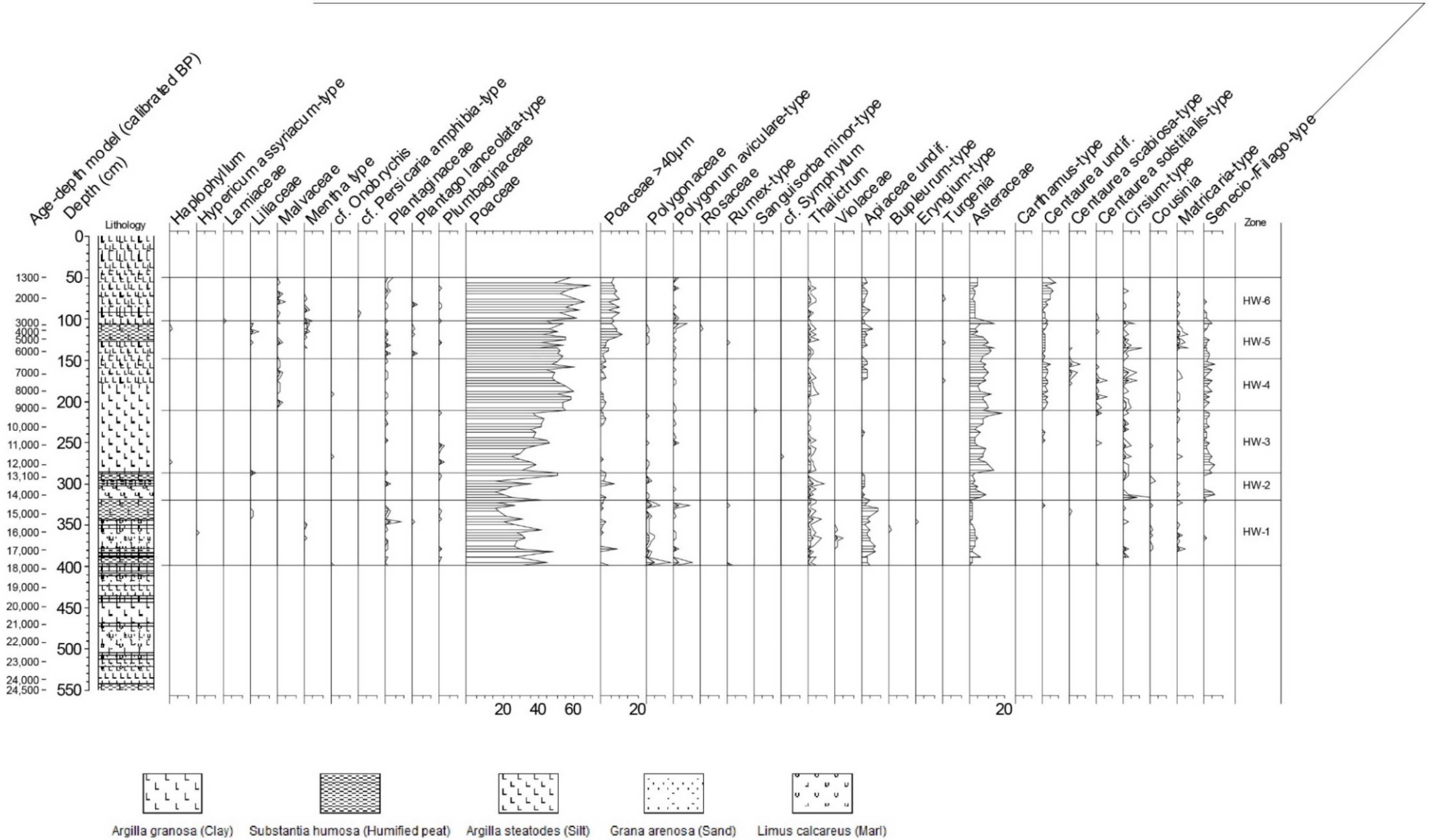

Figure 7-8: Pollen percentage diagram of Hashilan wetland (Part 2)

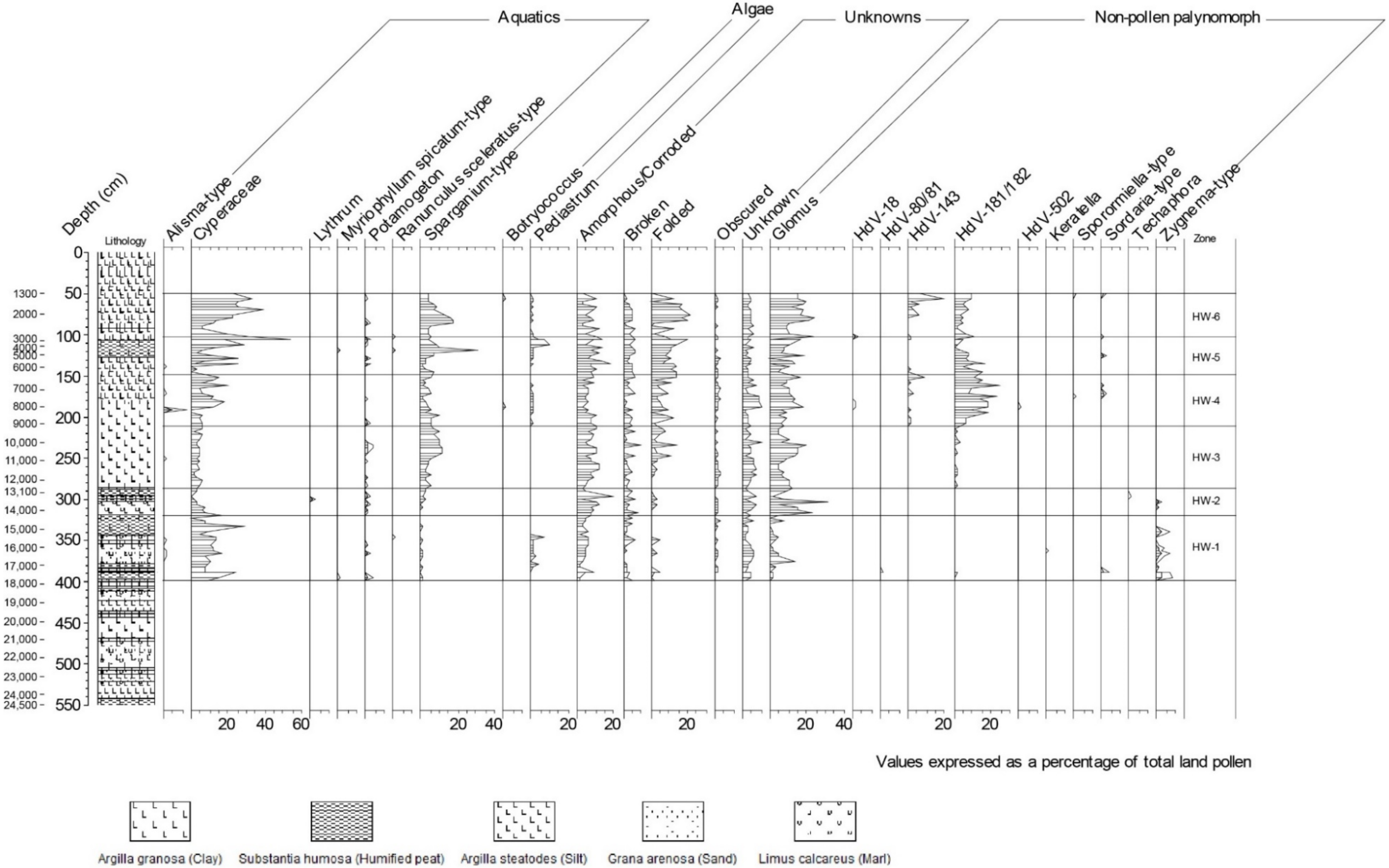

Figure 7-8: Pollen percentage diagram of Hashilan wetland (Part 3)

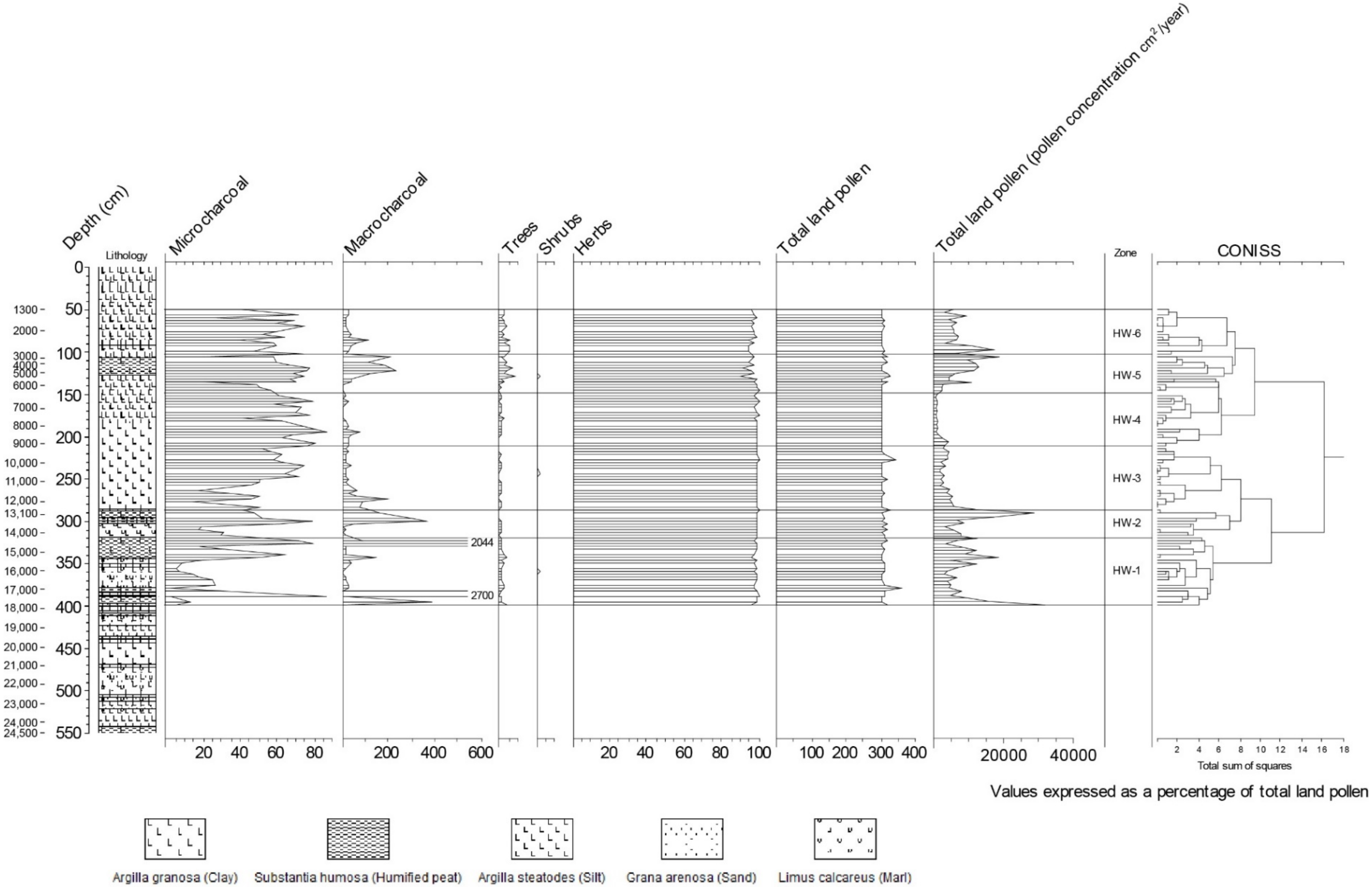

Figure 7-8: Pollen percentage diagram of Hashilan wetland (Part 4)

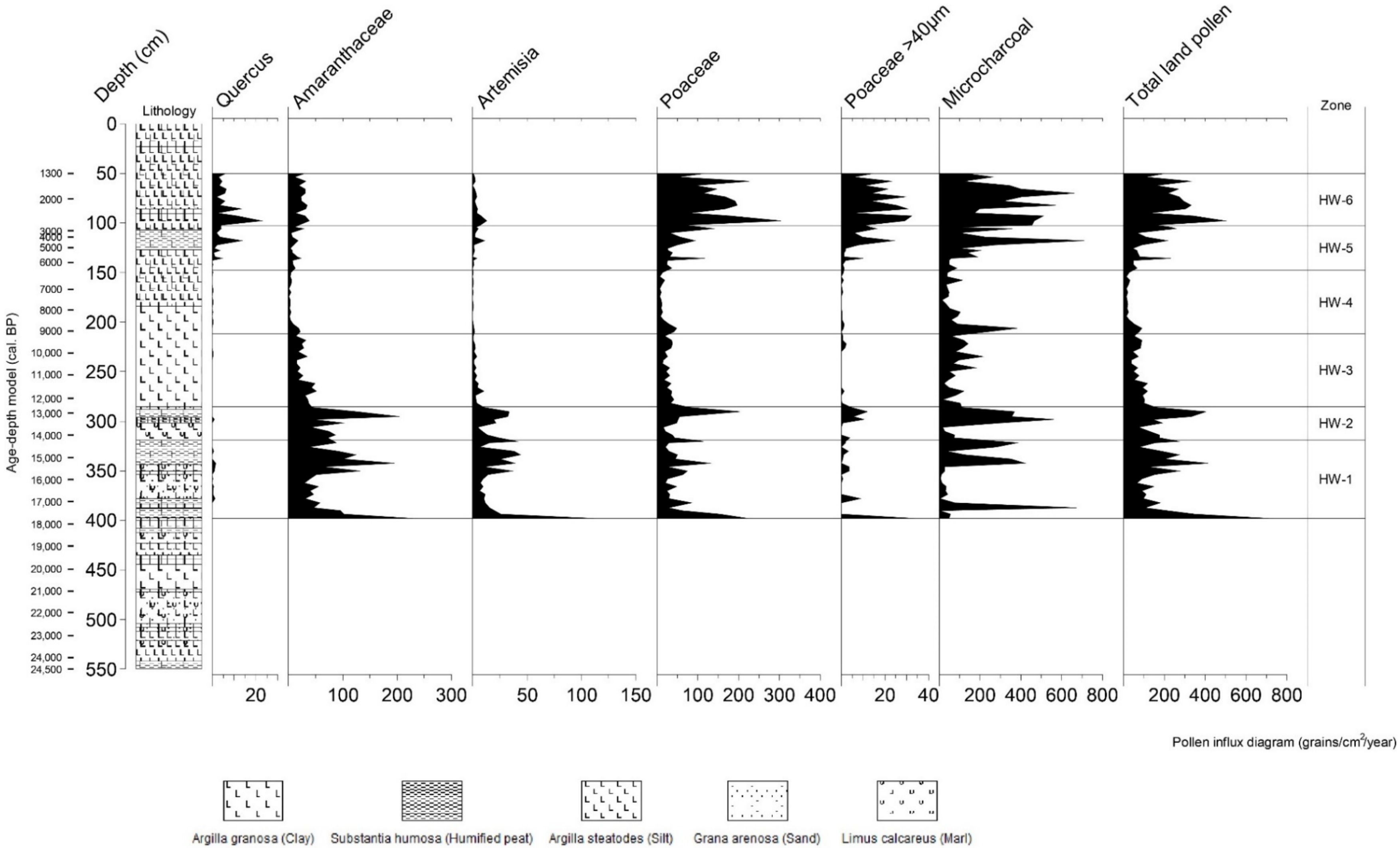

Figure 7-9: Pollen influx diagram of Hashilan wetland of selected taxa and microcharcoal

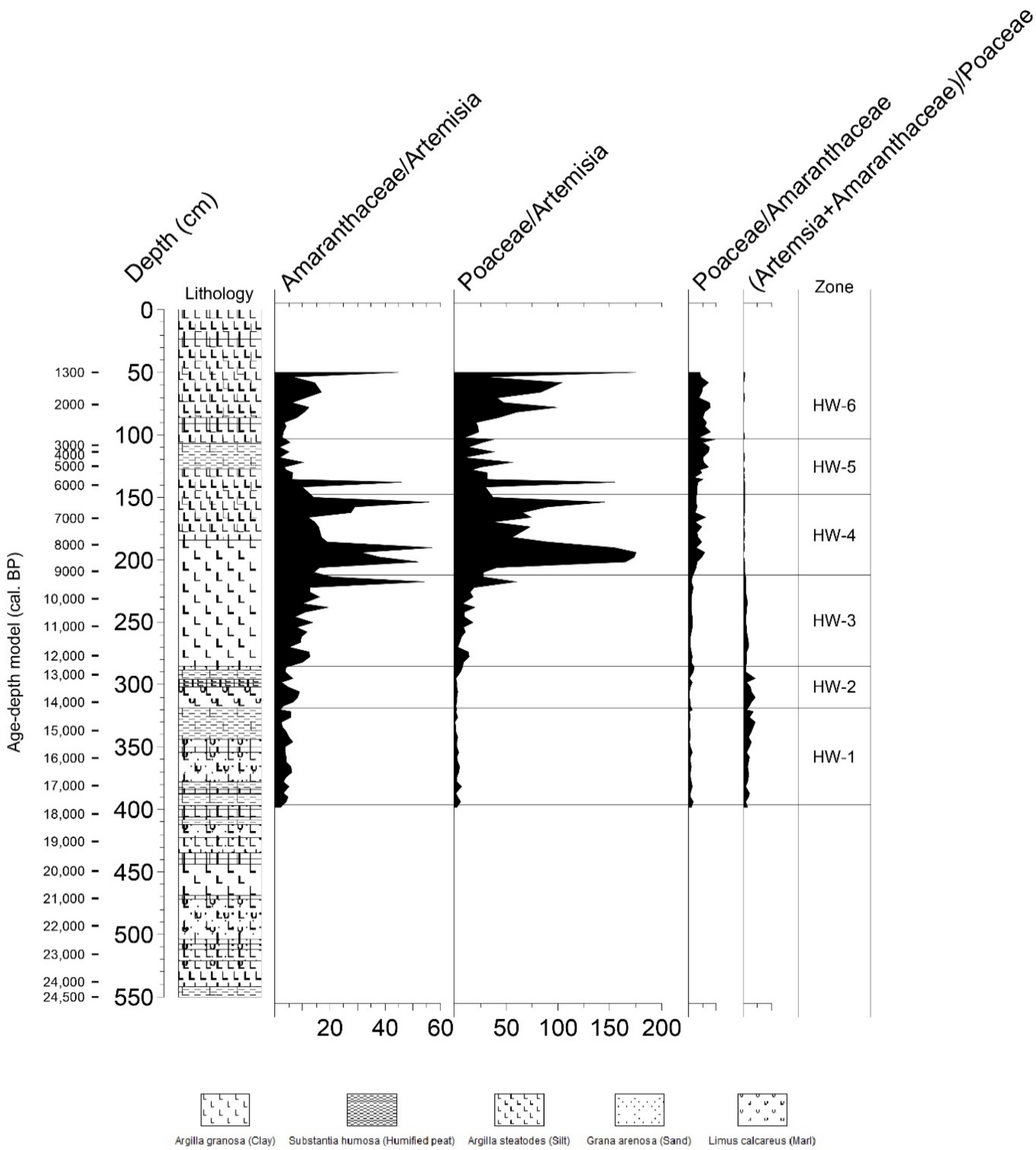

Figure 7-10: Pollen ratio of Hashilan wetland

7.2.2 Mollusc and ostracod assessment

Molluscs are well represented in the core and are mostly freshwater or terrestrial (Table 7-8). Among the molluscs, Planorbis family and *Bithynia* were present which have been identified in the Lake Zeribar mollusc assemblage (Alexandrowicz 2008) and the following ecology is given:

- *Planorbis planorbis* – A hard water snail usually found in small and shallow water bodies with muddy sediments and rich vegetation. It can tolerate water salinity of up to 4‰ and is resistant to drying up (Alexandrowicz 2008: 261).

- *Bithynia badiella* – Lives in rivers, lakes and small water bodies between water plants and on sandy or muddy sediments (Alexandrowicz 2008: 260).

Ostracods were present between 346-374cm, with the highest concentration found between 358-370cm (Table 7-8).

Table 7-8: Mollusc and ostracod assessment results for the depth 0-400cm

Depth (cm)	Molluscs (visual inspection)	Depth (cm)	Ostracods (wet sieving)
50-100	Mostly terrestrial Some freshwater	346	Low numbers
100-150	Some molluscs fragments	350	Low numbers
150-200	No molluscs	354	Low numbers
200-250	Freshwater and land snails Planorbis family	358	High numbers
250-300	Terrestrial Planorbis family	362	High numbers
300-350	No mollusc	366	High numbers
350-400	Fragments of freshwater bivalves cf. *Bithynia* (frequent in freshwater deposit)	370	High numbers
-	-	374	Low numbers

7.2.3 Sedimentary history

Prior to providing the sedimentary history of Hashilan wetland, it is important to highlight the complexity associated with the site. Hashilan wetland, which is fed by karstic carbonate springs, has three main sub-environments namely areas of peat, aerially exposed areas (calcrete island), and deep open water environments (ponds). The channels and springs within this environment are constantly moving, creating a dynamic wetland environment. Such wetlands have been termed 'anastomising wetlands' (Djamali *et al.* 2018). The lithological changes identified at Hashilan wetland, thus, reflect the internal dynamics of this environment, specifically horizontal changes in the sub-environments at the coring point (Figure 7-11).

HW-1 550-416cm ~24,500-18,500 yrs BP

Zone HW-1 (24,500-18,500 yrs BP; ~6000 yrs) starts with the presence of peat at ~24,500 yrs BP (550cm) that is rich in organic matter and bulk carbonate. The low Mn/Fe values along with an increase in dust input (high Si/cps, K/cps, Ti/cps and Fe/cps), potentially, suggest drier climatic conditions and low water levels during the peat deposition between 24,500-24,200 yrs BP (550-542cm). The peat transitions into marl between ~24,200-23,200 yrs BP (542-521cm) with low organic matter and Inc/Coh, high bulk carbonate content, low dust signal, and high Ca/cps. Magnetic susceptibility starts rising as well suggesting increased erosion into the basin from the surrounding catchment area. The marl is being formed by the precipitation of calcium from the water, which could be due to increase in evaporation (higher summer temperatures) or changes in the pH levels.

Marl formation is followed by the deposition of sandy clay between ~23,200-22,500 yrs BP (521-504cm) which is interrupted by marl deposition between ~22,900-22,700 yrs BP (512-508cm). The dust input and magnetic susceptibility, as well as organic matter content and Inc/Coh increase during the sandy clay deposition suggesting increased erosion into the basin and a potential change in climate. In contrast, Ca/cps, bulk carbonate content and Mn/Fe decline in values. The marl deposition between 22,900-22,700 yrs BP, in contrast to the sandy clay unit, experiences the opposite trend which is the same as the marl unit that follows the sandy clay unit between ~22,500-21,050 yrs BP (504-472cm); low dust input, high Ca/cps and Mn/Fe, low Inc/Coh, organic matter and magnetic susceptibility and high bulk carbonate content. The marl deposition is followed by silty clay depositions between 21,050-19,400 yrs BP (472-435cm) that is changing from calcium-rich to being organic- rich sediment. These silty-clay depositions suggest the presence of slow moving, low energy water in which mineral sediments are being deposited from suspension within

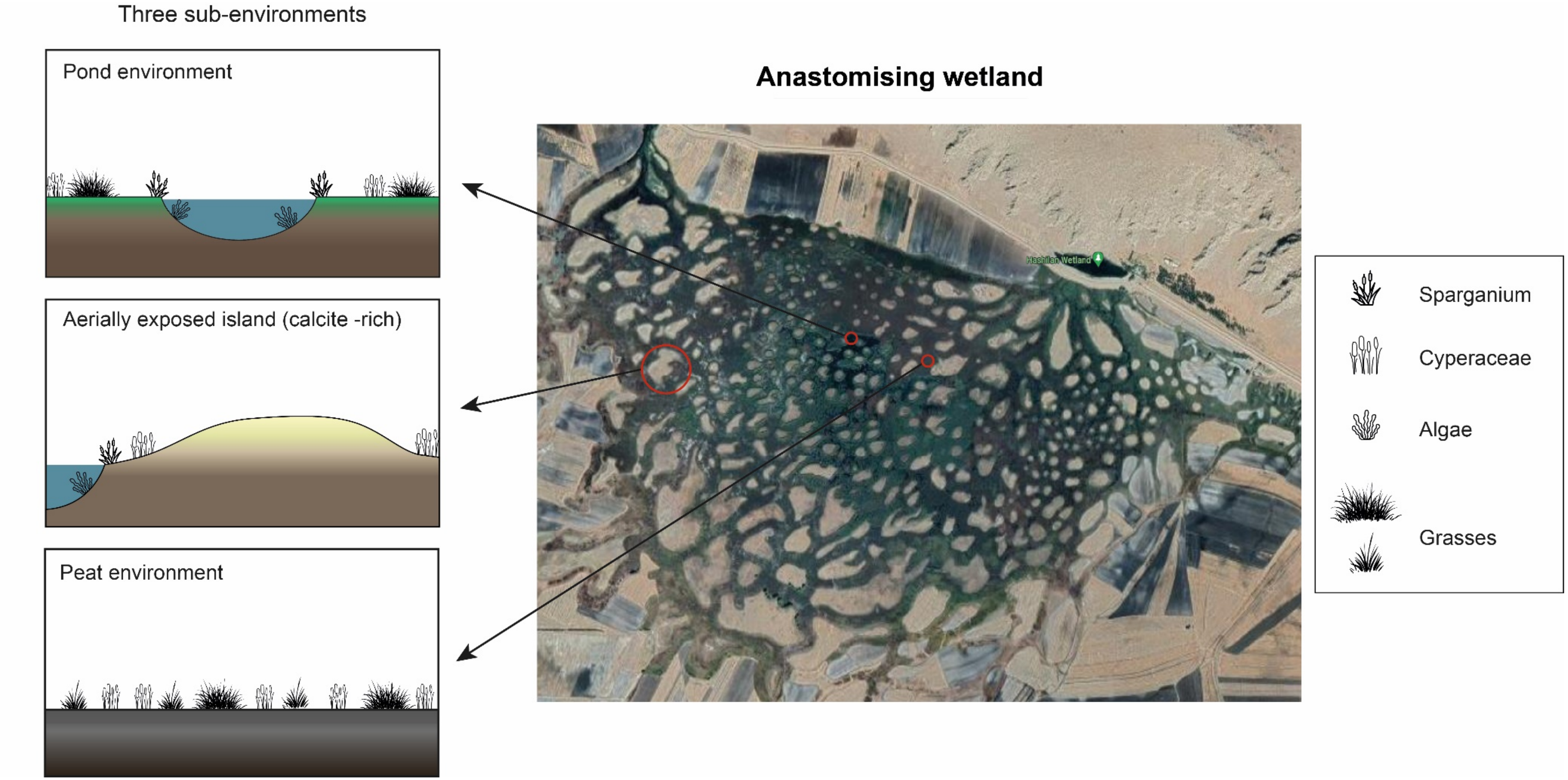

Figure 7-11: Illustration of the three sub-environments found at Hashilan wetland and the vegetation type characterising these sub-environments (author's own)

the water, potentially leading to the formation of calcretic aerially exposed islands. Water level is low at the beginning increasing gradually, only to drop again from ~19,800 yrs BP onwards. The dust input fluctuates but stays generally high with Ca/cps increasing over time from low values. Inc/Coh, organic matter and bulk carbonate remain low, while magnetic susceptibility increases reaching its highest values in the record followed by a gradual decline.

Silty clay deposition transitions into sandy clay at ~19,400 yrs BP (435cm) with magnetic susceptibility increasing, suggesting increased erosion into the basin. Bulk carbonate increases while organic matter and Inc/Coh decline slightly. The dust input declines while Ca/cps and Mn/Fe increase. The sandy clay transitions into marl at ~18,900 yrs BP (423cm) which experiences continued decline in dust input, increase in Ca/cps and Mn/Fe, decline in organic matter and Inc/Coh, and increase in bulk carbonate and magnetic susceptibility.

HW-2 416-284cm ~18,500-12,400 yrs BP

Zone HW-2 (~18,500-12,400 yrs BP; ~6100 yrs BP) continues with the marl deposition that transitions into peat accumulation between ~18,400-18,200 yrs BP, suggesting a change in the depositional environment potentially linked to either climate change or the internal dynamics of the wetland. Between 18,400-16,800 yrs BP, the wetland undergoes multiple short phases of changes in the sub-environment which includes peat formation between 18,400-18,200 yrs BP (412-408cm), silty clay deposition between ~18,200-17,800 yrs BP (408-400cm), organic rich sandy clay deposition between ~17,800-17,700 yrs BP (400-397cm), peat accumulation between 17,700-17,250 yrs BP (397-387cm), silty clay deposition between 17,250-17,070 yrs BP (387-383cm), and peat accumulation between ~17,070-16,800 yrs BP (383-378cm). These short intervals of changing depositional environment could be related to unstable climatic conditions impacting on the water level and surrounding vegetation and/or to intra-basinal changes. These unstable conditions are reflected by the high variability in the dust input signal which generally remains high but declines gradually. Between 18,400-16,800 yrs BP, both Ca/cps and Mn/Fe decline over time except between ~18,100-17,700 yrs BP. Inc/Coh and organic matter are high during this time interval corresponding to the peat units. Magnetic susceptibility is high until ~17,800 yrs BP after which it declines suggesting a decline in erosion from the surrounding catchment. Bulk carbonate content generally remains high with declines occurring during times of silty clay deposition.

Between 17,600-15,100 yrs BP, the presence of *Zygema-type* spore indicates the presence of stagnant, shallow and mesotrophic freshwater. The presence of *Pediastrum* and sporadic appearance of *Potamogeton* also suggest the presence of open water environment (pond), while the high values of Cyperaceae (sedge) were growing on the peatlands. Riparian trees *Fraxinus*, *Salix* and *Tamarix* were growing along the edge of Hashilan wetland or along streams. The presence of Myriophyllum spicatum-type as well as Pediastrum suggest that a pond environment was present at the coring location at ~17,600 and between 17,000-15,400 yrs BP. The increase in (*Artemisia*+Amaranthaceae)/Poaceae ratio, an index of soil salinity and development of halophytic species, between ~15,600-12,900 yrs BP suggests slightly brackish to saline environment, which would suggest the presence of more halophytic vegetation.

A prolong period of marl deposition occurs between ~16,800-15,300 yrs BP (378-344cm), which is interrupted between ~15,800-15,600 yrs BP (354-350cm) by silty clay deposition. The dust input, Inc/Coh, and organic matter remain generally low in the marl deposition interval, only increasing slightly during the silty clay deposition. In contrast, Ca/cps, Mn/Fe and bulk carbonate content increase in the marl unit, declining in the silty clay unit possibly indicating changes in water level. Magnetic susceptibility is dropping over time indicating a decline in erosion. The marl transitions into a period of peat formation lasting between ~15,300-14,200 yrs BP (344-319cm), suggesting a lowering of the water table (low Mn/Fe and Ca/cps). Dust input along with Inc/Coh and organic matter content increase during this time interval, while bulk carbonate slightly declines. Magnetic susceptibility increases over time, remaining high for the remaining part of the zone. Marl forms again between ~14,200-13,400 yrs BP (319-302cm) with the dust signal declining during this interval, along with increase in Mn/Fe, Ca/cps and high bulk carbonate content. In contrast, organic matter content and Inc/Coh are low. Between ~13,400-13,200 yrs BP (302-296cm) clay deposition occurs, prior to the formation of peat, with dust input, Ca/cps, Mn/Fe and bulk carbonate declining and organic matter content and Inc/Coh slightly increasing. *Sparganium-type* starts to increase, which suggests it was growing on the marginal parts of nearby pond areas. Alternatively, it could suggest that the coring location was undergoing a change into a pond environment. The low presence of *Potamogeton* also indicates an open water body. The clay deposition transitions into peat that lasts until ~12,600 yrs BP. This peat formation suggests low water levels which, however, are slightly higher than previous low water stands as indicated by the slightly higher Mn/Fe and Ca/cps values. Organic matter and Inc/Coh slightly increase. The increase in dust input is linked to a change in climate. The peat transition into a sandy clay unit between ~12,600-12,400 yrs BP (288-285cm), suggesting the presence of high-energy water or erosion of detrital material from the surrounding catchment area into the wetland. Ca/cps and bulk carbonate content also increase slightly while the dust input declines along with organic matter content and Inc/Coh.

HW-3 284-144cm ~12,400-6200 yrs BP

Zone HW-3 (~12,400-6200 yrs BP; ~6200 yrs) is characterised by the continuous deposition of silty clay between ~12,400-5200 yrs BP (285-127cm) with the ratio of silt to clay changing from ~7800 yrs BP onwards. This continuous deposition of mineral sediments suggests the presence of a standing body of water with slow moving water. Mn/Fe and Ca/cps remain high except between ~10,700-9400 yrs BP where the dust signal slightly increases, suggesting a change in the environment. Organic matter content and Inc/Coh remain low throughout this depositional environmental while bulk carbonate remains high. The magnetic susceptibility is high until ~10,200 yrs BP after which it declines, suggesting an increase in erosion into the basin from the surrounding catchment area followed by a decline in erosion possibly suggesting an increase in landscape stability. The peak in magnetic susceptibility at ~10,200 yrs BP coincides with a small peak in dust input. *Sparganium-type* further increases from ~11,300 yrs BP onwards suggesting an increase in their presence around the pond areas within the wetland with aquatic *Potamogeton* found inside these open water bodies. The low presence of Cyperaceae from 12,050 yrs BP could be indicative that the coring location was changing into a sub-aerially exposed island. The increase in grass pollen could also have been originated to some extent from the wetland vegetation although majority of the pollen grains likely had an upland origin. *Alisma-type* and *Thalictrum* were also part of the wetland vegetation. The area around the wetland hat scattered trees of *Salix*, *Fraxinus*, and *Tamarix* present. From ~8100 yrs BP onwards, an increase in Cyperaceae at the expense of *Sparganium-type* occurs. The very low values of *Pediastrum* and spore *HdV-181/182* suggest areas of stagnant open shallow water during this time interval.

HW-4 144-55cm ~6200-1500 yrs BP

Zone HW-4 (~6200-1500 yrs BP; ~4700 yrs) continues to experience silty clay deposition until ~5100 yrs BP when water level declines (low Mn/Fe and Ca/cps) leading to peat formation between ~5100-2950 yrs BP (126-107cm). Organic matter and Inc/Coh increase along with dust input and magnetic susceptibility. The depositional environment changes back to silty clay deposition between ~2950-1500 yrs BP (107-55cm), suggesting the presence of standing water with low-energy water with slightly higher water level (high Mn/Fe) and a reduction in dust input. A slight increase in water level between 2950-2300 yrs BP occurs along with a decline in dust input. This time interval is followed by higher dust input and slightly lower water levels until ~1700 yrs BP.

The wetland vegetation also experiences changes including fluctuating but increasing values of Cyperaceae growing on the peaty areas and the highest peak in *Sparganium-type* at ~4100 yrs BP. The peak in *Sparganium-type* suggests the potential presence of a pond environment around which *Sparganium-type* was growing. Due to the open water conditions, *Pediastrum*, *Myriophyllum* spicatum-type and *Potamogeton* were able to grow in this environment with Cyperaceae growing in the peat surrounding the pond. Between 6200-2700 yrs BP, taxonomic diversification of the aquatic vegetation is visible (Cyperaceae, *Sparganium-type*, *Alisma-type*, *Myriophyllum spicatum-type*, *Potamogeton*, and *Ranunculus sceleartus-type*). The presence of *Ranunculus sceleartus-type* suggests the presence of shallow water*.* *Mentha* also starts growing on the wetland among other taxa such as grasses, *Thalictrum*, Brassicacea and Asteraceae.

HW-5 55-0cm ~ 1500 – to present yrs BP

Silty clay deposition continues into zone HW-5 (~1500-present yrs BP; 1300 years) which indicates sediment deposition from suspension within a slow moving waterbody. Dust input gradually declines while water levels are increasing over time along with organic matter and bulk carbonate content. Magnetic susceptibility declines and remains low throughout the zone suggesting relatively stable conditions.

7.2.4 Vegetation history

The vegetation history of Hashilan wetland is outlined below and a summary of the non-pollen palynomorphs identified at Hashilan wetland (and Lake Ganau) are listed in Table 7-9 including their palaeoenvironmental indication.

Table 7-9: A summary of the ecological information of NPPs identified at Hashilan wetland and Lake Ganau using the 'Non-Pollen Palynomorph Image Database' (Shumilovskikh et al. 2016b) and the 'Non-Pollen Palynomorphs Database' (Wieckowska-Lüth et al. 2020) unless stated otherwise in the table

Non-pollen palynomorph	Ecological information
Glomus	Indicative of soil erosion
Sporormiella (HdV-113)	Coprophilous spore - Presence for large herbivore populations
Sordaria/ Sordariaceae	Coprophilous (Morandi 2020: 3)
HdV-143	Eutrophic to mesotrophic conditions
HdV-181/182	Stagnant shallow open water
HdV-18	Wet depositional environment
Bryophyte spore	Non-vascular land plant: liverworts, hornworts and mosses
Zygnema-type	Indicative of stagnant, shallow and mesotrophic fresh water
Keratella	*Keratella* species occur in lakes, ponds and swamps
HdV-502	Can be found on the wood and bark of deciduous trees
Thecaphora	Indicative of presence of higher herbs
Arnium-type	Mostly occur on herbivore dung but can also be found on rotting herbaceous stems and wood
Cercophora-type	Indicative of presence for animal dung in the vicinity but can also occur on decaying wood

Chaetomium	Occurs on plant remains and dung
Coniochaeta	Common on dung and wood
Delitschia	Mostly coprophilous
HdV- 55b	Dung indicator (Cugny *et al.* 2010: 392)
HdV- 55b-2	No information
Neurospora	No information
Podospora inequalis	Mostly coprophilous (Morandi 2020: 3)
Rosellinia-type	Grows either on herbaceous or woody substrates
Trichocladium	No information
Trichodelitschia	Possible dung indicator (Cugny *et al.* 2010: 397)
Type 1081	No information (Gelorini *et al.* 2011: 147)
Type 1150	No information (Gelorini *et al.* 2011: 154)
Xylariaceae	Known as saprotrophic wood-rotting fungi, as inhabitants of dung and pathogens of a range of plants

HW-1 396-319m ~ 17,700-14,200 yrs BP

Zone HW-1 (17,650-14,200 yrs BP; ~3450 yrs) is dominated by high and increasing pollen values of Amaranthaceae and *Artemisia*, with Apiaceae and Poaceae also playing an important part in the vegetation composition. This interval, thus, can be characterised as an open Irano-Turanian mountain steppe. Other taxa that were constituents of the upland steppe vegetation included Caryophyllaceae, Plantaginaceae, Fabaceae, Polygonaceae, Chichoriaceae, and a variety of Asteraceae species (including *Centaurea undif*., *Cirsium*, *Cousinia*, *Matricaria-type*, and *Senecio-/Filago-type*). The presence of *Cousinia*, a cold-adapted plant common in the environment, suggests temperatures were not optimal for tree growth and expansion. The rather low pollen values of drought tolerant Ephedraceae suggests that it played a minor role in the steppe environment. Trees stands were rare with the very low *Quercus* pollen values (less than 1%) suggesting a regional signal rather than local presence of *Quercus* in the landscape, likely brought in from the western Zagros Mountains region. *Pistacia*, an underrepresented plant in the modern pollen rain, is also present in very low values (less than 1%) which suggests it might have been present scarcely in the landscape and was able to survive the harsh climatic conditions in sheltered places with higher moisture availability. Low Poaceae/*Artemisia* ratio values suggest low moisture availability between ~17,650-14,200 yrs BP.

The very low and rare appearance of arboreal pollen grains of *Alnus*, *Betula*, *Fagus*, *Juglans* and *Pinus* are indicative of wind transport of these grains from great distances such as from the south of the Black Sea, Hycranian forest (south of the Caspian Sea) or Elburz mountains.

A change in vegetation composition, as well as lithology, occurred sometime between ~15,200-14,700 yrs BP with *Salix*, Plantaginaceae, Cichoriaceae, and Asteraceae declining in pollen percentages. Poaceae started to increase from ~14,700 yrs BP onwards, while *Artemisia* and Apiaceae started declining. In the Irano-Turanian region, Amaranthaceae can both be halophytic, growing in saline areas near lakes, and xerophytic growing on the dry slopes of the upland area. Thus, its interpretation in the pollen record needs to be carried out carefully. Fluctuations in Amaranthaceae values could be associated with changes in water levels.

The pollen influx data suggests increased pollen influx between ~17,650-17,500 yrs BP and 15,800-14,250 yrs BP which overlaps with organic-rich /peat units, suggesting higher level of overall vegetation cover. Thus, higher pollen influx could be related to lithostratigraphic changes that are a response to either climatic change or intra-basinal changes. The microcharcoal values increase over time with peaks coinciding roughly with macrocharcoal peaks at ~17,600 yrs BP (small peak), ~17,250 yrs BP (large peak), ~15,200 yrs BP (small peak), and ~14,500 yrs BP (large peak), indicating localised fire events.

HW-2 319-285m ~ 14,200-12,400 yrs BP

In zone HW-2 (~14,200-12,400 yrs BP; ~1800 yrs) the landscape remains an open steppe vegetation dominated by Chenopodiaceae, *Artemisia* and Poaceae. Poaceae experiences an increase over time while *Artemisia* declines, suggesting Poaceae was starting to become an increasingly important part of the steppe environment.

The continued absence of trees suggest that climate was still unsuitable for tree expansion around the Hashilan wetland area with arboreal vegetation (low and sporadic values of *Salix* and *Tamarix*) constricted to the edge of the lake, disappearing completely between 13,400-12,400 yrs BP. A change in the vegetation composition of the steppe vegetation occurs in this zone with Apiaceae no longer being an important constituent of the upland vegetation. In contrast, Asteraceae starts to form a more important constituent and includes *Centaurea undiff.*, *Cirsium-type*, *Cousinia*, *Matricaria-type* and *Senecio-/Filago-type*.

Glomus spores increase significantly and remain high between 14,400-13,400 yrs BP, suggesting high soil erosion during this time interval. Microcharcoal values remain high and peak between ~13,500-12,400 yrs BP which coincides with a macrocharcoal peak between 13,500-12,650 yrs BP.

The increased (*Artemisia*+Amaranthaceae)/Poaceae ratio suggests continued slightly brackish/saline conditions until ~13,100 yrs BP, while the low Poaceae/*Artemisia* ratio suggests low moisture availability, i.e. dry climatic conditions. An increase in pollen influx occurs between ~13,300-12,700 yrs BP, potentially related to peat formation and associated vegetation cover.

HW-3 285-212m ~12,400-9100 yrs BP

Zone HW-3 (~12,400-9100 yrs; ~3300 yrs) continues to be characterised by an open steppe environment dominated by Amaranthaceae, *Artemisia* and Poaceae, with Asteraceae and Cichoriaceae becoming an increasingly significant part of the steppe. The increase in Asteraceae and Cichoriaceae at ~12,500 yrs BP could suggest extreme soil degradation, or desiccation of the water body. *Artemisia* starts declining from 11,700 yrs BP onwards suggesting a change from an open *Artemisia*- Amaranthaceae dominated steppe environment to an open Poaceae dominated steppe environment suggesting moister conditions which is confirmed by the slight increase in Poaceae/*Artemisia* ratio. From ~12,000-11,500 yrs BP, Poaceae declines while Amaranthaceae increases, which suggests moisture levels were lower during this interval, after which Poaceae increases again. This increase in grasses could suggest a change in seasonality of climate i.e. increase in spring/summer precipitation (Van Zeist 2008: 85). Amaranthaceae although lower in values than in the previous zones, remains relatively high after 11,500 yrs BP but declines over time. The high Amaranthaceae values could be a signal of local expansion of halophytic Amaranthaceae on exposed saline areas rather than Amaranthaceae's contribution to the upland vegetation.

Despite slightly moister conditions at ~11,500 yrs BP, trees are restricted to the edge of the wetland with scattered trees of *Fraxinus*, *Salix* and *Tamarix* present. Rare appearance of *Quercus* pollen grains in the Early Holocene sequence of the pollen record suggests that it was still potentially too dry climatically which is confirmed by the low Poaceae/*Artemisia* ratio indicating relatively low moisture availability. The presence of *Pinus* and *Betula* during the Early Holocene suggests transport of their pollen grains from great distances.

A small peak in macrocharcoal occurs at ~11,850 yrs BP but overall, the macrocharcoal values decline over time, suggesting a decline in local biomass burning. The peak in macrocharcoal coincides with a peak in microcharcoal percentage, which in contrast starts to increase from ~11,350 yrs BP onwards.

HW-4 212-148m ~ 9100-6300 yrs BP

Zone HW-4 (~9100-6300 yrs BP; ~2800 yrs) is characterised by an open Poaceae dominated steppe environment which is confirmed by the low (*Artemisia*+Amaranthaceae)/Poaceae ratio indicating a wet mountain steppe. Amaranthaceae has decreased in value, likely growing in the steppe upland and in saline habitats near the wetland. Other herbs that play an important part in the composition of the upland as well as are present locally include Cichoriaceae, Asteraceae undif. (including *Centaurea* *undif*., *Centaurea scabiosa-type*, *Centaurea solstitiales-types*, *Cirsium-type*, *Matricaria-type* and *Senecio-/Filago-type*), Apiaceae undif., and Caryophyllaceae. The low and nearly, continuous presence of Poaceae >40micron suggests the presence of wild cereal grasses in the vicinity of the wetland but could also be a signal of grasses growing locally on the wetland. An increase in *Centaurea undif*. (~9000 yrs BP) as well as *Centaurea scabiosa-type* (~7700 yrs BP), and *Centaurea solstitiales-types* (~9400 yrs BP) could potentially be a human activity signal. Poaceae/*Artemisia* values increase and remain high suggesting high moisture availability, especially between ~9200-8300 yrs BP and 7150-6500 yrs BP. The low presence of *Quercus* (likely to be *Quercus brantii* Lindl.) from ~8600 yrs BP potentially suggests a change in the environment from an open Poaceae dominated steppe environment to the formation of a very open forest steppe environment dominated by *Quercus* and a grass- dominated steppe ground vegetation. Whether *Quercus* was indeed present in the vicinity of Hashilan wetland will be discussed further in the discussion chapter. The area around Hashilan wetland was still open in nature with very scattered trees of *Fraxinus* and *Salix* present. Pollen grains of *Ulmus*, *Pinus*, *Betula* and *Alnus* indicate transport over large distances.

From ~7300 yrs BP, coprophilous spore *Sordaria-type* sporadically appears suggesting the presence of herbivores in the area. The lowest pollen influx and concentration values occur between ~8300-6500 yrs BP. Microcharcoal percentage is high while the macrocharcoal count declines over time with a small peak at ~8300 yrs BP.

HW-5 148-103m ~ 6300-2700 yrs BP

Zone HW-5 (~6300-2700 yrs BP; ~3400 yrs) is characterised by potentially an open *Quercus*-Poaceae steppe environment with *Quercus* starting to increase from ~5900 yrs BP onwards. At around the same time *Artemisia* starts increasing along with *Fraxinus*, Apiaceae, Poaceae >40micron, while Asteraceae declines. *Quercus* woodland continues to expand reaching its densest form at ~4100 yrs BP after which it experiences a decline. The presence of one *Pistacia* pollen grain at ~5300 yrs BP suggests that *Pistacia* was also present in the open woodland. Since *Pistacia* is poor in pollen dispersal, it was likely an important tree in the composition of the *Quercus* woodland. The very low pollen percentage of *Quercus* (less than 5%) throughout the record suggests that *Quercus* woodland likely did not reach the Hashilan area which remained a relatively open landscape throughout the Holocene. Pollen influx and concentration increases from ~6400 yrs BP onwards, while Poaceae/*Artemisia* ratio is declining in this zone suggesting an overall decline in moisture availability with a peak in moisture between ~6100-5900 yrs BP. Poaceae/*Artemisia* ratio indicates a decline in moisture between 4500-4100 yrs BP and 4035-3220 yrs BP.

This zone starts seeing indicators of anthropogenic activity including grazing activities as indicated by the sporadic presence of *Plantago lanceolata* from ~6000 yrs BP onwards as well as general increase in Plantaginaceae. An increase in *Artemisia* could also point to increased human activity from ~ 5800 yrs BP onwards (Van Zeist 2008: 91) with a peak in *Polygonum aviculare-type* also signalling anthropogenic disturbances (i.e. livestock grazing, and overgrazing). Two pollen grains of *Rumex* at ~5300 yrs BP along with Plantaginaceae could suggest pastoralism. The presence of *Euphorbia* at ~2900 yrs BP also indicates grazing activities taking place in the vicinity.

Macrocharcoal values are high between ~5100-2900 yrs BP, suggesting local burning events potentially linked to human activity. The microcharcoal percentage is high and the influx and concentration data indicates an increase from ~5800yrs BP onwards. Poaceae/Artemisia is high between 3200-2780 yrs BP, which declines slightly between 2780-2690 yrs BP.

HW-6 103-50m ~ 2700-1300 yrs BP

Zone HW-6 (~2700-1300 yrs BP; ~1400 yrs BP) is characterised by a decline in the open *Quercus* woodland with Poaceae and Amaranthaceae increasing and Asteraceae declining. Scattered trees of *Fraxinus* and *Salix* continued to form part of the hydrophilous vegetation along the edge of the wetland. The presence of one pollen grain of *Juglans* at ~1900 yrs BP could be a signal of tree arboriculture happening in the area. Other indicators of human activity include *Galium*, *Plantago-lanceolata-type*, Poaceae >40 micron, *Polygonum aviculare-type*, and *Centaurea undif*.

Poaceae/*Artemisia* ratio peaks at ~2000, 1800 and 1300 yrs BP, suggesting increase in moisture availability. Microcharcoal percentage values remain high, while macrocharcoal values increase between ~2700-2200 yrs BP. The microcharcoal influx data suggests that overall there is a decline which suggests a decline in local fire events. Pollen influx and concentration start declining from ~2500 yrs BP onwards.

8 Results: Lake Ganau

This chapter outlines the results from Lake Ganau and is also divided into two main parts which are lithostratigraphic and biostratigraphic results.

8.1 Lithostratigraphy

8.1.1 Lithology and organic matter/bulk carbonate determinations

The total depth retrieved for core Gan-1c was 11.5m (33-45m) with 33m representing the actual surface of the lake sediments. Due to the system used by the German coring team for labelling the cores, it was decided not to change the depth for easier cross-reference for future work. During the coring of the Lake Ganau sequence, sediment losses occurred which have been summarised in Table 8-1. The focal part of this research, however, focusses only on the depth between 33-37.48m. The sedimentary description for core Gan-1c can be found in Table 8-2 (Figure 8-1).

Table 8-1: Table summarising sediment loss that occurred for Gan-1c during coring operation

Depth (m)	Sediment loss (cm)	Sediment loss occurred at this depth (m)
36-37	10	36-36.90
38-39	8	38-38.92
40-41	50	40-40.50
42-43	16	42-42.84
44-45	20	44-44.80

Table 8-2: Lithostratigraphic descriptions of core Gan-1c

Depth (m)	Unit	Description
33-37.48	1	2.5Y 4/1 – 2.5Y 4/2, As2 Ag2; Dark grey- dark greyish brown silty clay

The sediment for the chosen depth (33-37.48m) is silty clay in nature with no variation in colour and texture. The bulk carbonate content remains fairly constant throughout the core sequence (~10%) with minor fluctuations and a peak occurring at 35.38m to 22% (Figure 8-1).

The organic matter content increases from 37.50m onwards from ~5% to 8% until 35.80m, after which it starts to decline reaching its lowest value at 34.60m (~4%). The highest peak in organic matter occurs at 35.38m to 20%. From 34.60m onwards organic matter values start increasing again to ~6%, followed by a decline to ~4.5% at 34.09m. This is followed by a small peak to ~7.2% at 33.98m after which values start declining to ~5%.

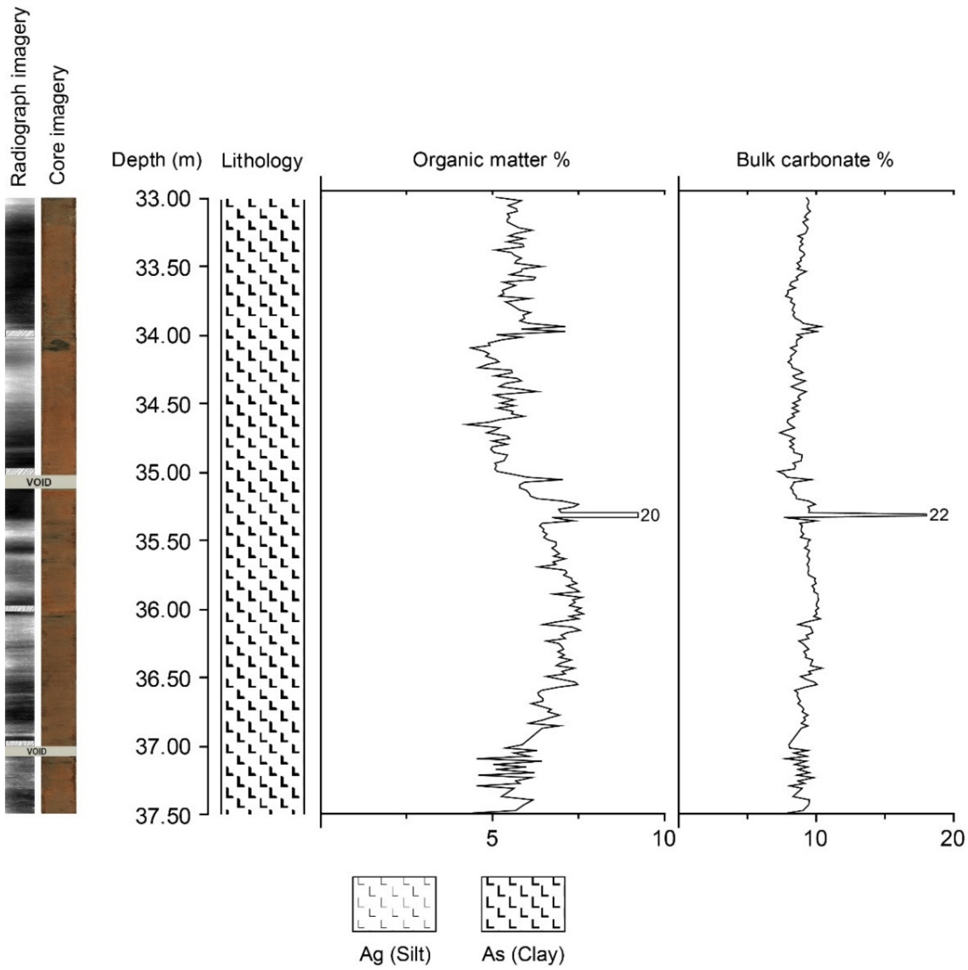

Figure 8-1: Lithology, radiograph imagery, organic matter content (%) and bulk carbonate content (%) for core Gan-1c for the depth 33-37.48m

8.1.2 Geochronology

Four bulk samples were radiocarbon dated in Germany and nine macrocharcoal samples were radiocarbon dated at the NERC facility at Oxford and Glasgow (Figure 8-2). The results of the radiocarbon dating are summarised in (Table 8-3). The Lake Ganau sequence also suffers from radiocarbon dating issues with the dates not being in stratigraphic order. Therefore, several age-depth models were created to identify reliable radiocarbon dates. Based on the pollen assemblage (characterised by Amaranthaceae, *Artemisia* and Apiaceae), which acts as a stratigraphic marker, the Lake Ganau pollen record appears to only covers the Pleniglacial and Lateglacial periods. According to the pollen assemblage and radiocarbon dating, the Holocene sequence has not been captured during the coring of the lake. Either the sediment sequence covering the Holocene period has been lost during the coring operation, or there is a possibility that the coring has been carried out close to a spring resurgence point which would allow no sedimentation build and erode any Holocene sediments nearby (non-depositional environment). Carrying out the coring in the littoral zone might have allowed the capturing of both the Holocene and Lateglacial sediments (see Djamali *et al.* 2021).

The reason why the macrocharcoal dates are stratigraphically incorrect is probably due to the movement of macrocharcoal across the sediment. The presence of an active spring at the bottom of the lake could cause mixing of sediment and particles. It is also a possibility that charcoal particles were washed into the basin and became incorporated into sediments of young age. Since the area is susceptible to seismic activity, it can lead to displacement of sediment layers and movement of large amount of sediment over a slope into the lake.

Table 8-3: Radiocarbon dates for Lake Ganau. Abbreviation: Charcoal (C), Sediment (S)

Sample ID	**German Sample ID**	**Conventional Radiocarbon Age (BP)**	**Depth (m)**	**Type of sample**	**Calibrated Age BP (95.4%)**	**$\delta^{13}C$ relative to VPDB**	**Lab code**
Gan-9.1	-	15,530 ± 29	33.03	C	18,884-18,768	-25.20	SUERC-99167 (GU58646)
Gan-1	-	3772 ± 18	33.20	C	4235-4085	-26.65	OxA-41155
Gan-2	-	11,922 ± 32	33.80	C	14,009-13,608	-26.24	OxA-41308
Gan-7	-	11,294 ± 49	34.60	C	13,299-13,101	-25.00	SUERC-96148 (GU56826)
Gan-8	-	6606 ± 24	34.90	C	7566-7431	-26.70	SUERC-96152 (GU56827)
Gan-3	-	11,611 ± 28	35.40	C	13,580-13,365	-26.56	OxA-41156
Gan-4	-	11,611 ± 38	36.00	C	13,580-13,365	-27.45	OxA-41102
Gan-5	-	11,799 ± 31	36.50	C	13,760-13,522	-26.64	OxA-41103
Gan-6	-	7785 ± 48	37.00	C	8645-8423	-25.95	OxA-X-3117-35
Gan-10	GAN 1c 37-39 1b	13,784 ± 58	37.50	S	16,965-16,502	-	-
44	GAN 1c 39-41 1b	15,068 ± 61	39.30	S	18,643-18,220	-	-
43	GAN 1c 41-43 1b	18,410 ± 80	41.70	S	22,480-22,176	-	-
42	GAN 1c 43-45 1b	15,941 ± 66	43.70	S	19,457-19,061	-	-

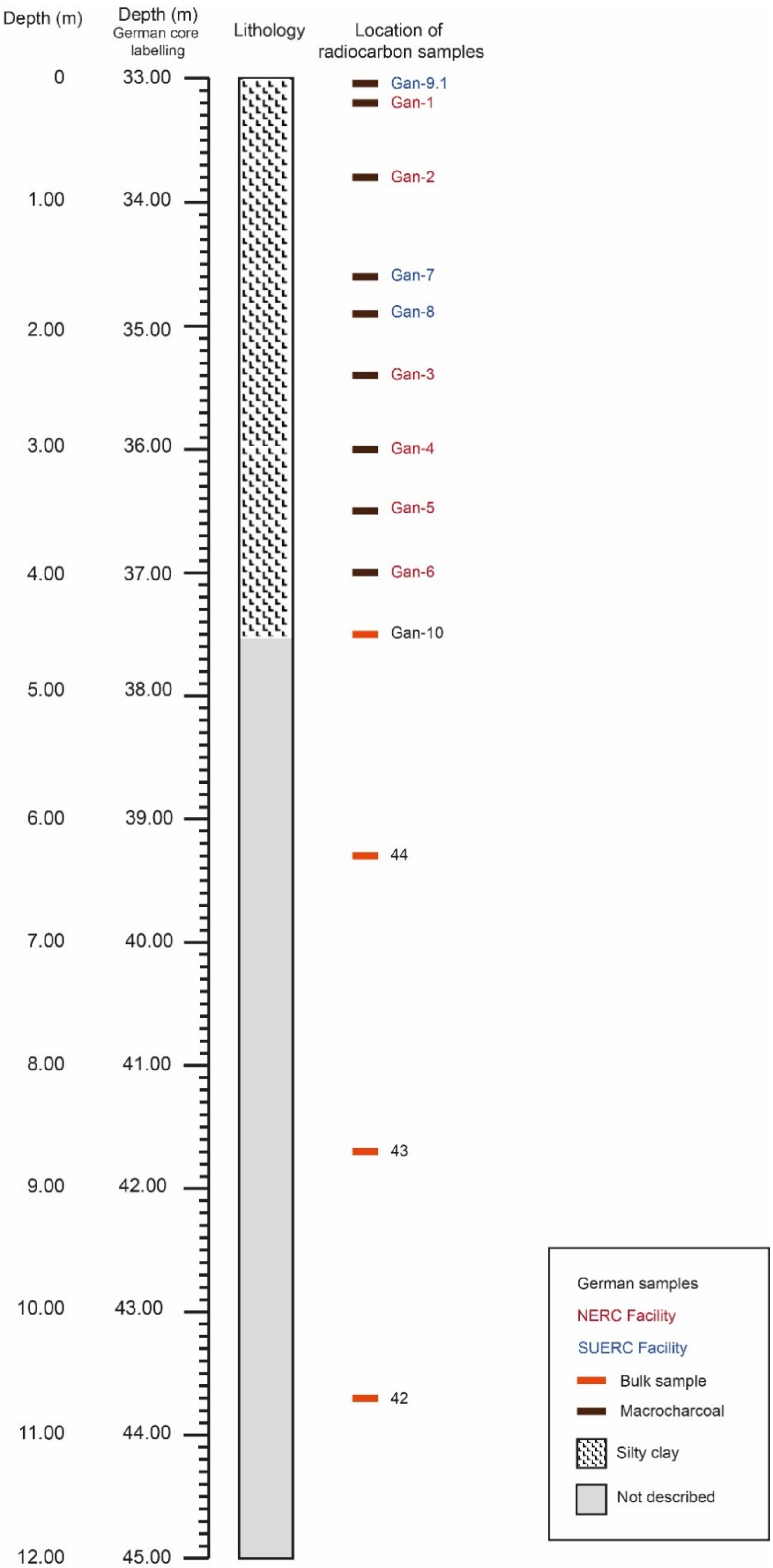

Figure 8-2: The location of radiocarbon dates and the type of material dated for Lake Ganau

To identify which radiocarbon dates are reliable, 15 age-depth models have been created using OxCal, using a combination of macrocharcoal and bulk sediment dates (Table 8-4). Furthermore, to establish the most reliable age-depth model, the pollen stratigraphy and comparison with the Greenland ice core record and Lake Zeribar record were used as a criteria.

Table 8-4: Summary of the radiocarbon dates selected for producing each age-depth model

Age-depth model	Radiocarbon dates selected
Gan-1	Gan-9.1, Gan-1, Gan-2, Gan-7, Gan-8, Gan-3, Gan-4, Gan-5, Gan-6, GAN-10, 44, 43, 42
Gan-2	Gan-9.1, Gan-2, Gan-7, Gan-3, Gan-4, Gan-5, GAN-10, 44, 43, 42
Gan3	Gan-7, Gan-3, Gan-4, Gan-5, Gan-10, 44, 42
Gan3 vs2	Gan-7, 42
Gan3 vs3	Gan-7, Gan-10, 42
Gan3 vs4	Gan-7, 43
Gan4	Gan-7, Gan-3, Gan-4, Gan-5, Gan-10, 44, 43
Gan4 vs2	Gan-7, Gan-10, 44, 43
Gan4 vs3	Gan-4, 43
Gan4 vs4	Gan-7, Gan-10, 43
Gan5	Gan-2, Gan-10, 44, 43
Gan5 vs2	Gan-2, Gan-10, 42
Gan5 vs3	Gan-2, Gan-10, 43
Gan5 vs4	Gan-2, 43
Gan5 vs5	Gan-2, 42

OxCal was unable to produce age-depth models for Gan-1 and Gan-2, due to multiple issues related stratigraphic order and the program not able to produce a distribution, which is why both model have been rejected. Out of the remaining 13 age-depth models (see appendix for all age-depth models), Gan-3 vs4, Gan4, Gan4 vs2, Gan4 vs3 and Gan4 vs4 were rejected as according to their chronology the pollen sequence covers the Early Holocene period (Table 8-5). Based, however, on the pollen assemblage for Lake Ganau the pollen record does not cover the Early Holocene period. Age-depth models Gan3 vs2, Gan5 vs4 and Gan5 vs5, were also rejected because they are only constrained by two radiocarbon dates, which produces a greater uncertainty.

To identify which of the remaining five age-depth models is a suitable fit for the pollen record, the pollen record was examined closely to identify stratigraphic markers for major Lateglacial climate change, for example Lateglacial Stadial and Lateglacial Interstadial, and to evaluate their relationship with periods of climate change identified in the Greenland ice core records and Lake Zeribar (interstadial: GI-1= 14,700 yrs BP; Lake Zeribar= 15,000 yrs BP; stadial: GS-1= 12,900 yrs BP; Lake Zeribar= 12,600 yrs BP) (Wasylikowa *et al.* 2008; Rasmussen *et al.* 2014). The pollen record for Lake Ganau does not indicate any distinctive changes over time, making it challenging to identify any stratigraphic markers. Based on the pollen record, a change in hydrology and plant diversity occurs at approximately 34m along with a slight increase in Amaranthaceae percentage and decrease in Poaceae percentage, possibly suggesting drier climatic conditions which will be discussed in detail in the pollen data results. This change in hydrology and pollen taxa could thus correspond to the start of the Lateglacial Stadial-1 (Younger Dryas) at 34m. Furthermore, a small change in pollen taxa (increase in Poaceae >40 micro and Pistacia) is noticeable at approximately 37m which suggests a slightly moister time period that could correspond to the climate amelioration that starts at the beginning of the start of the Lateglacial Interstadial. Based on the changes in the pollen record, the Lateglacial Interstadial possibly starts at approximately 37m (interstadial: GI-1= 14,700 yrs BP; Lake Zeribar= 15,000 yrs BP) and the Lateglacial Stadial starts at roughly 34m (stadial: GS-1= 12,900 yrs BP; Lake Zeribar= 12,600 yrs BP). This is supported by the data from the Greenland ice core record and Lake Zeribar record (Wasylikowa *et al.* 2008; Rasmussen *et al.* 2014).

Besides the pollen data acting as a stratigraphic marker, the organic matter content (%) and ITRAX data, which will be discussed in detail later, also suggest changes happening at approximately 34m.

Therefore, based on this, Gan5, Gan5 vs2 and Gan5 vs3 have been rejected as they suggest a date between 14,400-14,000 yrs BP for the depth 34m, and 16,200-16,300 yrs BP for the depth 37m (Table 8-5). Out of the remaining two age-depth models (Gan3 and Gan3 vs3), Gan3, which is based on four marcocharcoal and three bulk radiocarbon dates, has been chosen to be a better fit as it agrees with the changes in the pollen stratigraphy (Table 8-6 and Figure 8-3). Based on the age-depth model created the sediment sequence covers ~12,100 -20,100 yrs BP.

The shape of the age-depth curve for Gan3 is not linear (i.e. distribution of radiocarbon dates is not linear), indicating an abrupt change between 37.5-36.5m (radiocarbon samples Gan-10-Gan-5) (Figure 8-3).

Table 8-5: All age-depth models and the corresponding ages to the depths 34m and 37m that might be related to the start of the stadial and interstadial periods

Age-depth models	Change in pollen assemblage (37m) - age yrs BP	Change in hydrology and pollen assemblage (34m) - age yrs BP	Top of pollen record (33m) – age yrs BP
Gan3	15,200	12,800	12,100
Gan3 vs2	14,800	12,800	12.100
Gan3 vs3	15,900	12,800	12,100
Gan3 vs4	16,300	12,400	11,100
Gan4	15,200	12,400	11,100
Gan4 vs2	16,100	12,400	11,100
Gan4 vs3	15,000	10,400	8800
Gan4 vs4	16,200	12,400	11,100
Gan5	16,300	14,400	12,900
Gan5 vs2	16,200	14,000	13,400
Gan5 vs3	16,300	14,000	12,900
Gan5 vs4	17,200	14,000	12,900
Gan5 vs5	15,600	13,900	13,400

Table 8-6: Age-depth model Gan3: Radiocarbon dates highlighted in green have been rejected and the final age-depth model for Lake Ganau consists of seven radiocarbon dates

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Type of sample	d13C (‰)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Macro-charcoal	-25.20	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.20	Macro-charcoal	-26.65	Holocene date
Gan-2	11,922 ± 32	33.80	Macro-charcoal	-26.24	Stratigraphically too old
Gan-7	11,294 ± 49	34.60	Macro-charcoal	-25.00	
Gan-8	6606 ± 24	34.90	Macro-charcoal	-26.70	Holocene date
Gan-3	11,611 ± 28	35.40	Macro-charcoal	-26.56	
Gan-4	11,611 ± 38	36.00	Macro-charcoal	-27.45	
Gan-5	11,799 ± 31	36.50	Macro-charcoal	-26.64	

Gan-6	7785 ± 48	37.00	Macro-charcoal	-25.95	Holocene date
Gan-10	13,784 ± 58	37.50	Bulk sediment	-	
44	15,068 ± 61	39.30	Bulk sediment	-	
43	18,410 ± 80	41.70	Bulk sediment	-	Stratigraphically too old
42	15,941 ± 66	43.70	Bulk sediment	-	

This either suggests the presence of hiatuses, i.e. break in the sediment record caused by the removal of sediment by erosion, or very slow sediment accumulation rate. Based on the pollen record, there is no indications for a hiatus or movement of sediments. Therefore, this stepped appearance of the curve suggests very low sedimentation accumulation rate, with one metre of sediment being deposited within approximately 3100 yrs. The slow accumulation rate between 37.5-36.5m could be explained by dry, cooler conditions that correspond to Greenland Stadial 2 (22,900-14,700 yrs BP). From 36.5m onwards, sedimentation rate increases which could be associated with the climate amelioration of the Greenland Interstadial 1 (14,700-12,900 yrs BP). The rate of sediment accumulation could thus be equated to different climate states i.e. rapid sedimentation rate during a period that corresponds to Greenland Stadial 2 (GS-2), slow sedimentation rate during the Greenland Interstadial (GI-1) and faster sedimentation rate during the Greenland Stadial 1 (GS-1). The evidence from the age-depth model suggests that sediment accumulation increased from 36.5m (sample Gan-5) onwards, but it may have already started earlier. The duration of the slow accumulation rate is difficult to establish because the model is not very well chronologically constrained between sample Gan-5 and Gan-10. Nevertheless, based on the age-depth model and pollen data it is possible that sedimentation accumulation might have increased at approximately 37m which is when slight climate amelioration is taking place based on the pollen data and increase in organic matter content. To refine the chronology and identify when the sedimentation accumulation rate changed between 37.5-36.5m, further radiocarbon dates are needed for this depth interval.

Regarding the bulk samples, it is possible that they are subject to hard-water effect since the lake is situated in a carbonate-rich area. It is, however, difficult to determine the extent of the hard-water effect on the bulk samples. Based on the low bulk carbonate content it can be argued that the hard-water effect is minimal.

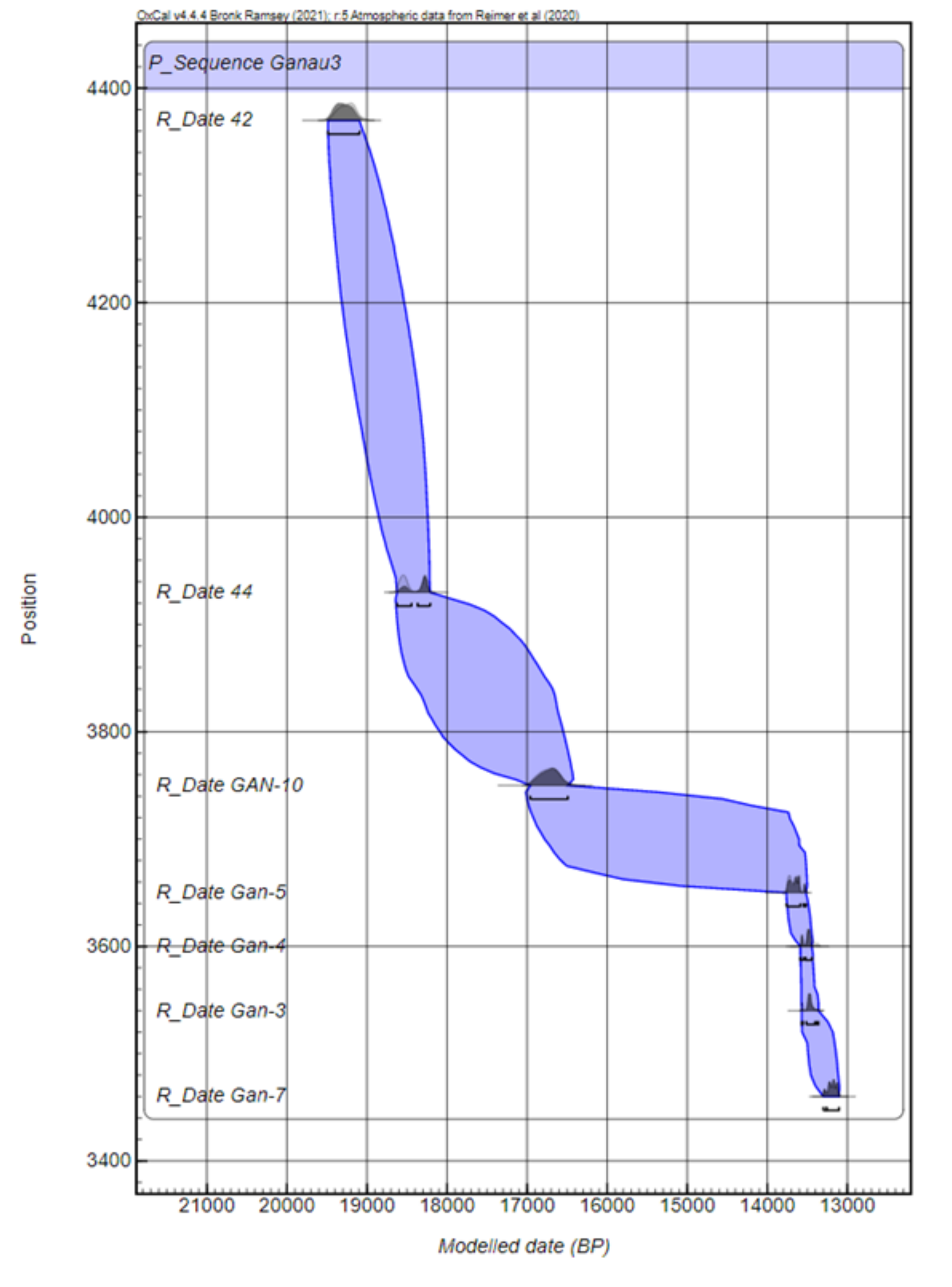

Figure 8-3: OxCal model for Lake Ganau (34.6-43.7m)

8.1.3 Geochemical data and Principal Component Analysis (PCA)

The ITRAX core scanner provided counts for 39 elements in total, however, 19 elements were used for principial component analysis. Elements that had counts lower than 300 were not used in the principal component analysis. Using Principal component analysis, three groupings have been identified: Iron (Fe) and arsenic (As), clastic sediment (e.g. titanium (Ti), silica (Si), potassium (K)), and carbonates (Calcium (Ca) and sulphur (S)) (Figure 8-4) The iron and arsenic are likely originating from the same source, with the bituminous nature of the underlying Jurassic rocks most likely being the source of the iron and arsenic abundance. Calcium abundance can be explained by the local bedrock geology which is dominated by carbonates. Clastic elements, in contrast, are brought into the lake body by either water run-off or aeolian transport.

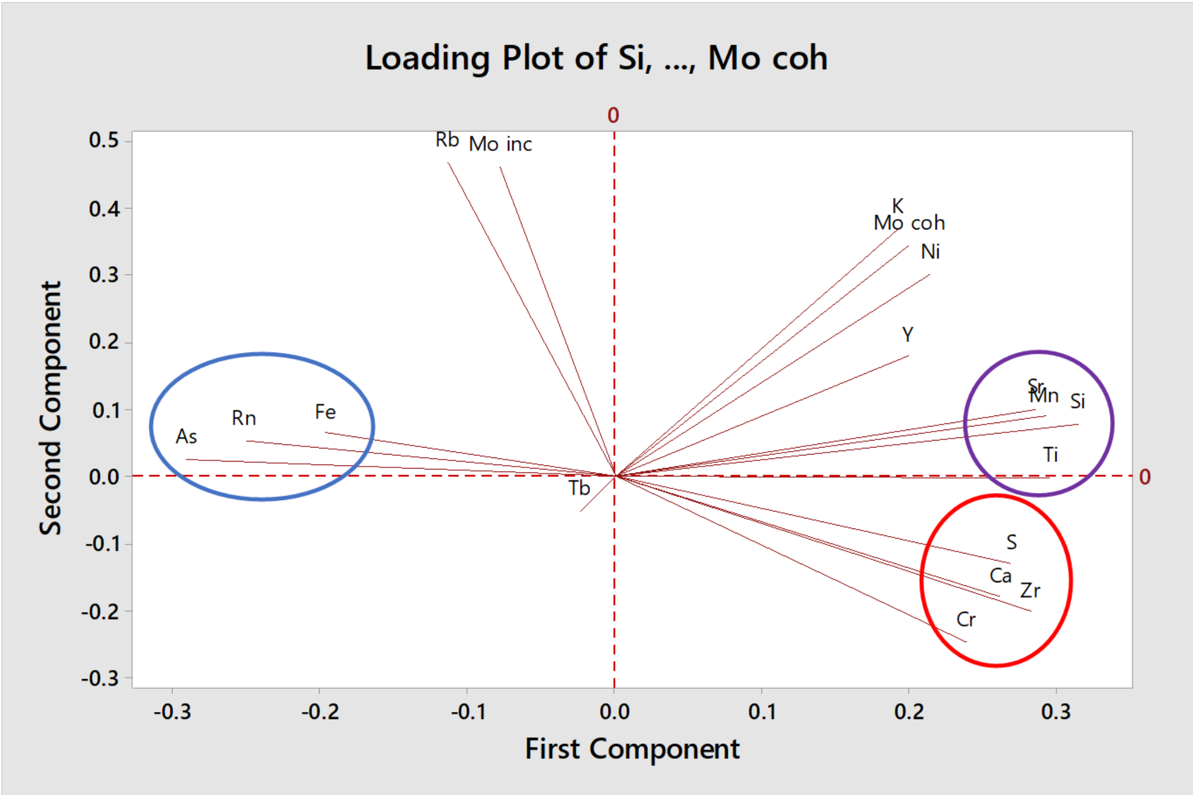

Figure 8-4: Loading plot for Lake Ganau elemental abundance with main groups of elements circled

A score plot has also been produced which has been divided into one metre depth intervals to identify which depth intervals of the core are being controlled by which elements (Figure 8-5). The lower part of the core (44.8m-41m) is controlled slightly more by carbonates, while the upper part of the core (40.5-33m) is controlled and dominated largely by iron and arsenic. This highlights the significant contribution of the lake's groundwater and local bedrock geology to the elemental abundance.

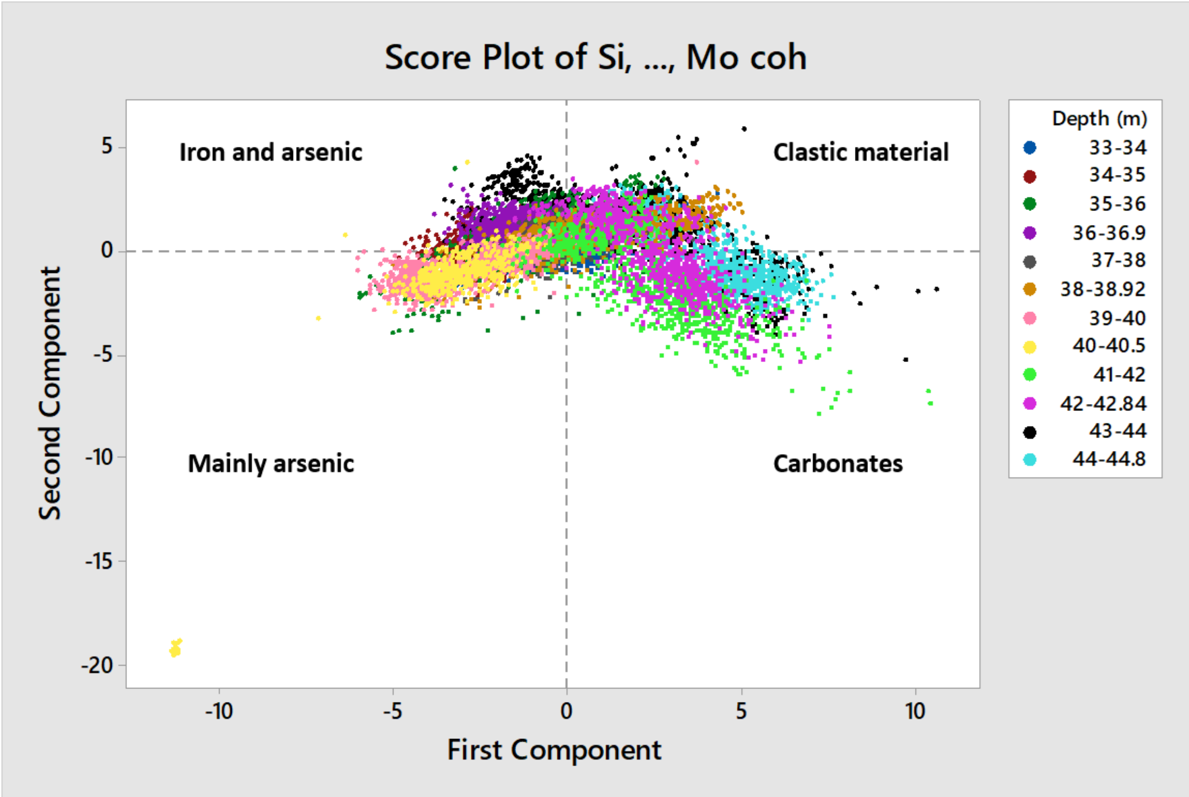

Figure 8-5: Score plot of Lake Ganau divided into one metre intervals and main controlling grouping identified for each quadrant

8.1.4 ITRAX – geochemical data

The results of the ITRAX data are described in Table 8-7. The geochemical record has been divided into six zones using visual inspection. Due to no gypsum crystals or layers visible in the core sequence, the changes in sulphur (S) are likely not related to gypsum formation which is indicative of dry climatic conditions. Sulphur and Mn/Fe ratio are generally related to redox conditions which can be affected by changes in a lake's water level (Algeo and Maynard 2004; Martinez-Ruiz *et al.* 2015; Alinezhad *et al.* 2021). As both sulphur and Mn/Fe ratio follow a similar trend, they are likely indicative of lake water fluctuations (Figure 8-6). This is further confirmed by the Rb/K ratio. Rb/K is a proxy for riverine input. High Rb/K ratio has been interpreted as lower riverine input during drier climatic condition. As the Rb/K ratio shows an opposing trend to S/cps and Mn/Fe peaks, changes in these ratios and element can be used as a lake water level fluctuation indicators (Figure 8-6; and Table 8-7; Figure 8-8).

Fe/cps, As/cps and Ca/caps were plotted to show their high contribution to the sediments composition which are likely controlled by the underlying geology (Figure 8-7). Fe/cps and As/cps follow a similar highly fluctuating trend possibly suggesting same source of origin. Ca/cps, in contrast, shows an opposite trend to Fe/cps and As/cps, i.e. Ca/cps values shift to higher values when Fe/cps and As/cps values shift to lower values. The main trend observed, which is confirmed by the PCA analysis, shows that Ca/cps is higher in values between 45-41.20m, and the remaining depth interval (41.20-33.00m) is dominated by high values of Fe/cps and As/cps.

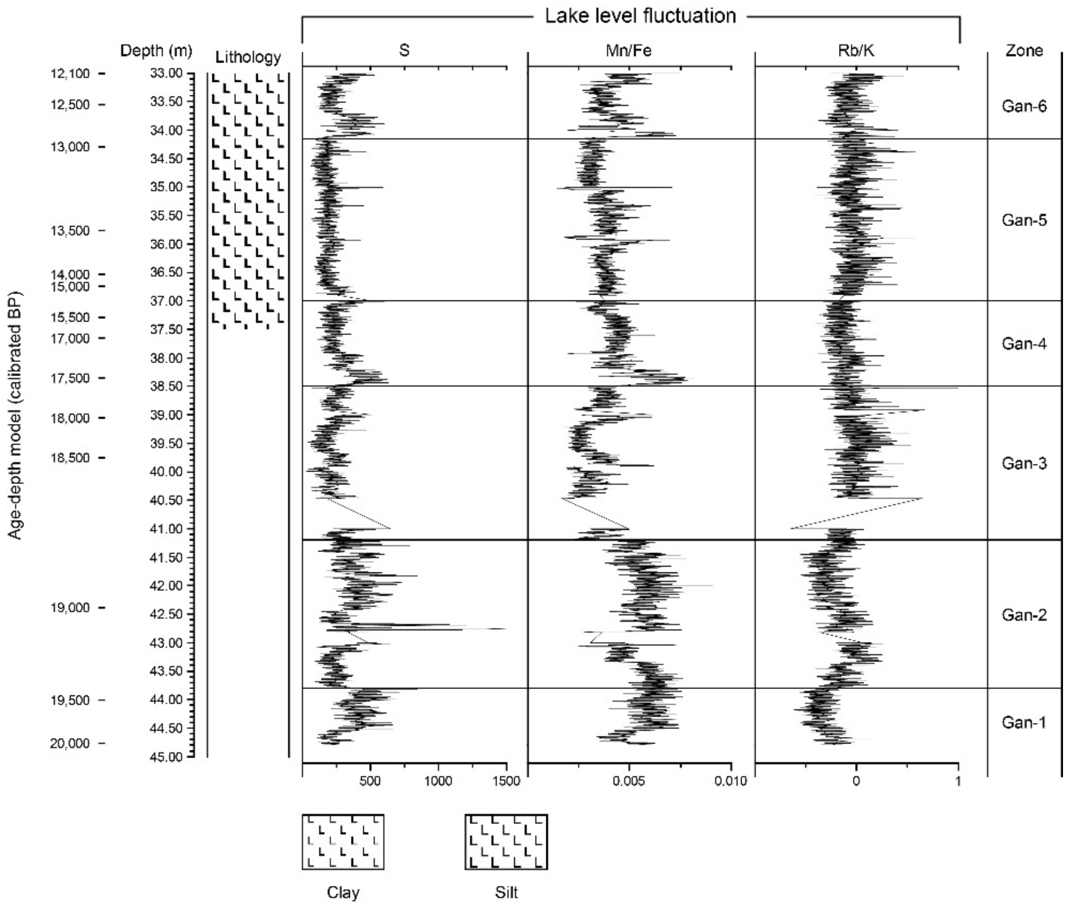

Figure 8-6: ITRAX data showing lake level fluctuations and terrigenous input signals from Lake Ganau

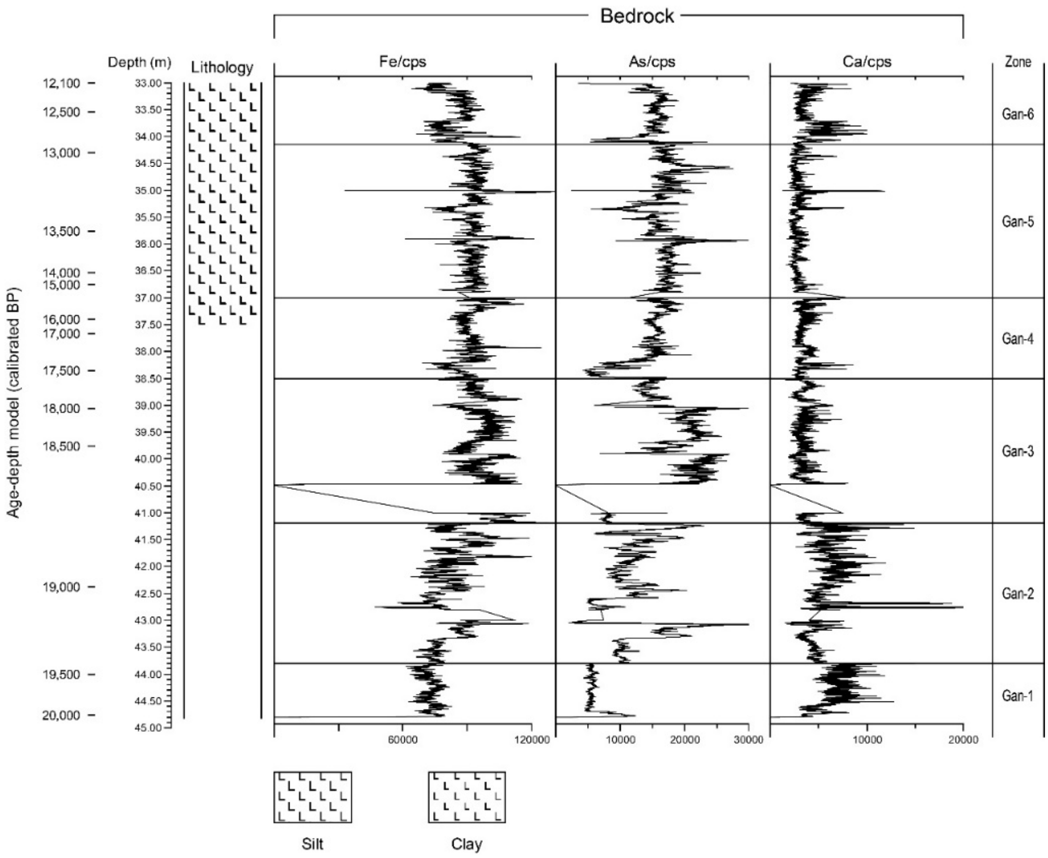

Figure 8-7: ITRAX data showing bedrock input signals from Lake Ganau

Table 8-7: Description of elemental ratios and cps data derived from ITRAX core scanner for Lake Ganau

Depth (m)	Zone	Time period (yrs BP)
34.15-33.00	**Gan-6**	**~12,900-12,100**
Zone Gan-6 is marked at the beginning with increasing and highly fluctuating values of Mn/Fe ratio and S/cps between 34.15-33.70m (~12,900-12,600 yrs BP). Rb/K ratio also experiences a small peak between 34.10-33.95m (~12,870-12,770 yrs BP), followed by a decline and increase again towards the end of the zone. Mn/Fe and S/cps also are low in values after 33.70m (~12,600 yrs BP) followed by an increase again towards the end of the zone.		
37.00-34.15	**Gan-5**	**~15,200-12,900**
Zone Gan-5 is characterised by slightly higher fluctuating values of Rb/K ratio, and low fairly constant values of S/cps which experiences two small peaks at 35.95m (~13,510 yrs BP) and 35.02m (~13,320 yrs BP) that coincide with peaks in Mn/Fe ratio. Mn/Fe ratio values decline from 35m onwards with two elevated intervals between 36.05-35.92m (~13,540-13,510 yrs BP) and 35.42-35.30m (~13,470-13,410 yrs BP).		
38.50-37.00	**Gan-4**	**~17,600-15,200**

<table>
<tr><td colspan="3">Rb/K ratio remains low in zone Gan-4, while both Mn/Fe ratio S/cps experience elevated values at the beginning of the zone between 38.50-38.20m (~17,620-17,430 yrs BP) and 38.13-37.95m (~17,400-17,290 yrs BP). S/cps remains low in the remaining part of the zone while Mn/Fe ratio experiences another increase between 37.90-37.30m (~17,250-15,540 yrs BP) after which it declines.</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>41.20-38.50</td><td>Gan-3</td><td>~18,800-17,600</td></tr>
<tr><td colspan="3">In zone Gan-3, Rb/K remains high and only starts to decline slightly from 39.50m (~18,440 yrs BP) onwards, with a peak at 38.55m (~17,660 yrs BP). Mn/Fe ratio sharply declines at the beginning of the zone, gradually increasing slightly and elevated values occur between 40.50-40m (~18,630-18,550 yrs BP), 39.90-39.68m (~18,530-18,490 yrs BP), and 39.20-39.05m (~18,200-18,000 yrs BP). From 38.55m (~17,660 yrs BP), Mn/Fe ratio starts increasing sharply. S/cps values remain fairly constant and low, increasing from 38.55m (~17,660 yrs BP) onwards.</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>43.80-41.20</td><td>Gan-2</td><td>~19,350-18,800</td></tr>
<tr><td colspan="3">Zone Gan-2 is characterised by continued high values of Mn/Fe ratio until 43.37m (~19,210 yrs BP) after which it declines abruptly and generally remains low. During this depth interval, 43.80-43.37m (~19,360-19,210 yrs BP), S/cps values declines abruptly from 43.80m (~19,360 yrs BP) and remains low, while in contrast Rb/K ratio increases. From 42.80m (~19,080 yrs BP) onwards Mn/Fe values increase again, gradually declining towards the end of the zone (from 41.90m (~18,900 yrs BP) onwards). S/cps also increases and gradually slightly declines from 41.90m (~18,900 yrs BP) onwards. Two sharp peaks in S/cps values occur at 42.75m (~19,070 yrs BP) and 42.70m (~19,060 yrs BP), with the latter one smaller in value. Rb/K ratio, in contrast, declines in value and remains low, only starting to increase from 41.45m (~18,810 yrs BP) onwards.</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>44.80-43.80</td><td>Gan-1</td><td>~20,000-19,350</td></tr>
<tr><td colspan="3">The start of the zone Gan-1 is characterised by low values and gradual decline in Rb/K ratio, while both Mn/Fe ratio and S/cps increase from low values to very high values between 44.68-43.80m (~19,950-19,360 yrs BP).</td></tr>
</table>

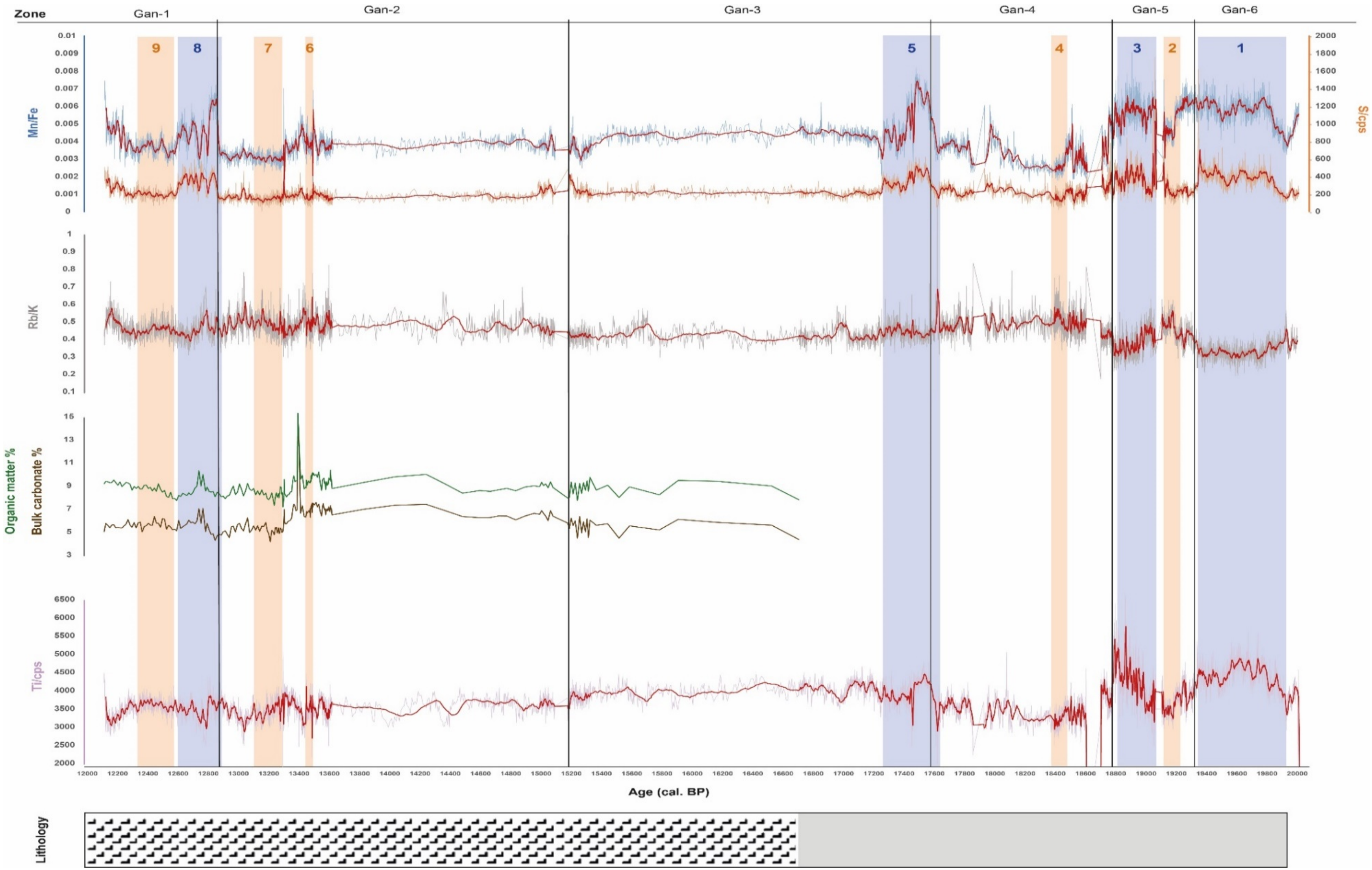

Figure 8-8: Ratios of Mn/Fe, Rb/K and S/cps, Ti/cps plotted against organic matter %, bulk carbonate %, lithology and chronology. Blue boxes indicate periods of high lake levels and orange boxes indicate periods of lower lake levels, marked by number for cross-correlations

8.2 Biostratigraphy

8.2.1 Pollen, non-pollen palynomorph and microcharcoal

The results of the pollen, non-pollen palynomorphs and microcharcoal are described in Table 8-8. The pollen, non-pollen palynomorph and microcharcoal results are expressed as a percentage of total land pollen (trees, shrubs and herbs). Pollen concentration and influx are expressed as grains/cm^2 and grains/cm^2/year, respectively.

The pollen percentage, influx and ratio diagram (Figure 8-9; Figure 8-10; Figure 8-11) have been divided into three local pollen assemblage zones with two subzones using visual and statistical (constrained cluster analysis) methods. The full pollen, non-pollen palynomorph and microcharcoal counts can be found in the Appendix.

Table 8-8: Description of pollen zones for Lake Ganau

<table>
<tr><th>Depth (m)</th><th>Zone</th><th>Main taxa</th><th>Time period</th></tr>
<tr><td>37.48-36.50</td><td>LG1</td><td>Poaceae- Amaranthaceae - Artemisia</td><td>~16,500-13,600</td></tr>
<tr><td colspan="4">Zone LG1 is dominated by high values of herbs, followed by trees and shrubs. Low values of aquatics, very low values of npps, and high values of algae are present in this zone. Microcharcoal values are fluctuating, increasing slightly towards the end of the zone (max. 52%).

Tree taxa is dominated by Quercus (~4%) which slightly increases to ~6%. Low values of Tamarix (~2%), Corylus (~1%), Pinus (less than 1%), Prosopis farcta (less than 1%), Fraxinus (less than 1%), Salix (less than 1%) and Pistacia (less than 1%) are present. The herbaceous taxa is dominated by Amaranthaceae (~28%) Poaceae (~30%) and Artemisia (~8%). Artemisia values start declining from 36.86m (~15,090 yrs BP) onwards to ~4%. Other herbaceous taxa include Brassicaceae (~2%), Caryophyllaceae (~2%), Cichoriaceae (~4%) with a peak at 37.16m (~24%) (~15,300 yrs BP), Eremurus-type (less than 1%), Filipendula (~1%), Galium (~2%), Plantaginaceae (~2%), Senecio-/Filago-type (~2%), Thalictrum (~2%), Apiaceae undiff. (~7%), Asteroideae (~2%), Centaurea-solstitialis-type (~2%), and Matricaria-type (~2%). Poaceae >40micron remains low between 37.48-37m (~2%) (~16,550-15,190 yrs BP) and then increases to ~4%. The aquatics are characterised by low values of Cyperaceae (~2%) and Sparganium-type (~3%). Botryococcus is dominating the algae assemblage (~20%) with Pediastrum increasing from 3% to 5% from 37m (~15,190 yrs BP) onwards. Npps are characterised by Coniochaeta (less than 1%), Sordaria-type (~2%), Type 1081 (~2%), and Type 1150 (less than 1%).

Pollen concentration for total land pollen fluctuates slightly declining towards the end of the zone (min.7975 grains/cm^2 and max.15543 grains/cm^2. The pollen influx of Amaranthaceae (values between 0-7 grains/cm^2/year), Poaceae (values between 0-9 grains/cm^2/year), and microcharcoal (values between 1-19 particles/cm^2/year) is low and behaves in a similar manner increasing between 37.24 – 36.74m which is reflected in the pollen influx of the total land pollen influx. Quercus influx (values between 0-1 grain/cm^2/year) is very low throughout the zone, while Artemisia slightly increases between 37.20-37.78m (values between 0-2 grains/cm^2/year). There is no pollen influx for Poaceae >40micron in this zone.</td></tr>
</table>

Poaceae/Amaranthaceae and (*Artemisia*+Amaranthaceae)/Poaceae ratio are vey low throughout the zone. Poaceae/ *Artemisia* and Amaranthaceae/*Artemisia* ratio are also low with minor fluctuations.

36.50-35.50	**LG2-a**	**Poaceae- Amaranthaceae - *Artemisia***	**~13,600-13,500**

Zone LG2-a is characterised by high values of herbs, low values of trees and very low values of shrubs. Aquatics and npps are present in low values. Algae values are fluctuating but generally high. Microcharcoal values increases slightly from ~32% to ~60% at 35.60m.

Tree taxa is still dominated by *Quercus* (~6%) which slightly decreases over time to ~4%. The zone is characterised by the appearance of several trees including *Acer*, *Pistacia*, *Prosopis farcta*, *Thymelaea*, *Juniperus*, *Hippophaë rhamnoides* (all less than 1%). *Tamarix* remains very low (less than 1%) and starts to increase from 35.70m (~2%) (~13,500 yrs BP). Herbaceous taxa is dominated by Amaranthaceae (~30%) which decreases overtime to ~25%. Poaceae starts the zone with low values of ~25% which overtime increases to ~40%. *Artemisia* starts with lower values (~5%) that increases slightly to ~6%. Low values of Poaceae >40micron (~4%), Brassicaceae (~2%), Caryophyllaceae (~2%), Cichoriaceae (~4%), Fabaceae (less than 1%), *Filipendula* (~1%), *Galium* (~2%), Plantaginaceae (less than 1%), Plumbaginaceae (~2%), *Senecio-/Filago-type* (~2%), *Thalictrum* (~2%), Apiaceae (~6%), Asteroideae (~3%), *Centaurea undiff*. (~1%), *Centaurea solstitialis-type* (~2%), *Cousinia* (less than 1%) and *Matricaria-type* (~2%) are present. The aquatics are dominated by low values of Cyperaceae (~2%) and *Sparganium-type* (~4%). *Pediastrum* (~5%) declines from 35.85m (~13,500 yrs BP) to ~3%. *Botryococcus* remains high with ~15%, increasing between 35.65-35.55m (~13,490-13,470 yrs BP) to ~40%. Npps are characterised by very low values of *Coniochaeta* (less than 1%), *Sordaria-type* (~1%) and *Type 1081* (~1%).

Pollen concentration for total land pollen slightly increases at the start of the zone to 16042 grains/cm^2 at 36.14m after which it declines slightly. Total land pollen influx increases initially, followed by a decline, after which it increases again and then declines towards the end of the zone (values between 2-234 grains/cm^2/year) with two peaks at 36.30m (107 grains/cm^2/year) and 35.85m (232 grains/cm^2/year). *Quercus* (values between 1-10 grains/cm^2/year), Amaranthaceae (values between 0-71 grains/cm^2/year), *Artemisia* (values between 1-14 grains/cm^2/year), Poaceae (values between 1-87 grains/cm^2/year) and microcharcoal influx values increase (highest in the record) and follow the same trend as the total land pollen influx with lowest influx values at 36.06m. Poaceae >40micron appears in this zone in low influx values (values between 0-7 grains/cm^2/year)

Poaceae/Amaranthaceae and (*Artemisia*+Amaranthaceae)/Poaceae ratio remain very low throughout the zone. Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* ratio also remain low with minor fluctuations.

35.50-34.00	**LG2-b**	**Poaceae- Amaranthaceae – *Artemisia* - *Tamarix***	**~13,500-12,800**

Zone LG2-b is characterised by high values of herbs, and low values of trees and shrubs. Aquatics and npp remain low, while algae fluctuates and increases. Microcharcoal fluctuates and remains high (min.35% and max.68%).

Tree taxa is still dominated by fluctuating values of *Quercus* (~5%), followed by *Tamarix* (~1%). Other tree taxa include *Acer*, *Alnus*, Ephedraceae, *Juniperus*, *Pinus*, *Pistacia*, *Platanus*, *Prosopis farcta*, *Fraxinus*, and *Salix* (all less than 1%). Amaranthaceae and *Artemisia* values remain constant ~30% and ~6%, respectively. Poaceae slightly increases over time from ~32% to ~38%. Other herbaceous taxa include Poaceae >40micron (~4%), Brassicaceae (~1%), Caryophyllaceae (~2%), Cichoriaceae (~3%), *Eremurus-type* (less than 1%), Fabaceae (less than 1%), *Filipendula* (~1%), *Galium* (~2%), *Haplophylum* (less than 1%), *Onobrychis* (less than 1%), Plantaginaceae (less than 1%), Plumbaginaceae (less than 1%), *Polygonum aviculare-type* (less than 1%), Ranunculaceae (less than 1%), *Rumex acetosa-type* (less than 1%), *Senecio-/Filago-type* (~2%), *Thalictrum* (~2%), Apiaceae undiff. (~6%), *Bupleurum-type* (~1%), Asteroideae (~3%), *Centaurea solstitialis-type* (~2%), *Centaurea undiff*. (~1%), *Carthamus-type* (~1%), *Cousinia* (less than 1%) and *Matricaria-type* (~2%). Aquatics are characterised by low values Cyperaceae (~2%) and *Sparganium-type* (~4%). *Pediastrum* remains low (~4%), while *Botryococcus* values increase between 35.05-34.15m (~13,320-12,900 yrs BP) from 17% to ~27% (peak ~40% at 34.60m;13,200 yrs BP). Towards the end of the zone *Botryococcus* values decline to ~13%. Npp is dominated by low values of *Coniochaeta* (~1%) and *Sordaria-type* (~2%).

Pollen concentration for total land pollen continues to fluctuate and increases from 4032 grains/cm^2 to 17155 grains/cm^2 towards the end of the zone. Total land pollen influx peaks at the start of the zone (max.258 grains/cm^2/year) after which it gradually starts to decline except between 35.05-34.80m where it peaks again (max.123 grains/cm^2/year). *Quercus* (values between 0-15 grains/cm^2/year), Amaranthaceae (values between 2-75 grains/cm^2/year), *Artemisia* (values between 0-13 grains/cm^2/year), Poaceae (values between 2-91 grains/cm^2/year), Poaceae >40micron (values between 0-7 grains/cm^2/year) and microcharcoal (values between 0-193 particles/cm^2/year) follow the same trend as the total land pollen influx. Poaceae >40micron disappears from the influx diagram from 34.50m onwards.

Poaceae/Amaranthaceae and (*Artemisia*+Amaranthaceae)/Poaceae ratio continue to remain very low throughout the zone. Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* ratio also continue to remain low with minor fluctuations.

34.00-33.50	**LG3-a**	**Amaranthaceae – *Artemisia* - Poaceae**	**~12,800-12,500**

Zone LG3-a is characterised by a slight decline in trees, high values of herbs and very low values of shrubs. Aquatics and npps are present in very low values, while algae experience an increase followed by a decline. Microcharcoal remains high (~60%) except between 33.80-33.50m (~12,670-12,470 yrs BP) where it drops to ~50%.

Tree diversity significantly reduces with *Quercus* still being the dominant tree taxa. *Quercus* values slightly decline to ~4%. *Tamarix* disappeared during the beginning of the zone, and *Corylus* appear toward the end of the zone (~1% each). Amaranthaceae and *Artemisia* increase to ~33% and ~8%, respectively. Poaceae, in contrast, declines to ~28%. Poaceae >40 micron reaches its lowest values of ~1%. *Cousinia* is present throughout the zone (less than 1%). Low values of *Senecio-/Filago-type*, *Thalictrum*, Apiaceae undiff. (6%), Asteroideae (~1%) and *Centaurea solstitialis-type* (~1%) are present in this zone. The herbaceous taxa start to increase towards the end of the zone such as Poaceae >40micron, Cistaceae, *Filipendula*, *Galium*, *Mentha-type* and *Matricaria-type*. *Sparganium-type* values remain constant (~4%), while Cyperaceae declines to ~1%. The decline of Cyperaceae coincides with the significant increase of *Botryococcus* to ~42% at 33.80m (~12,670 yrs BP), after which it declines to ~25%. *Pediastrum* declines to ~1%. Npps are characterised by the presence of Type 1081 (~1%) at the start of the zone, and the decline of *Coniochaeta* and *Sordaria-type* (both less than 1%).

Pollen concentration for total land pollen declines reaching the lowest values in the record of 7093 grain/cm^2 and remains low. Total land pollen influx declines to its lowest values, slightly increasing towards the end of the zone (values between 11-12 grains/cm^2/year) which is reflected in the Amaranthaceae (values between 3-4 grains/cm^2/year), Poaceae (values between 3-4 grains/cm^2/year) and microcharcoal (values between 13-17 particles/cm^2/year) influx values. *Artemisia* (values between 1 grain/cm^2/year) influx values decline in remain very low throughout. Poaceae >40micron and *Quercus* are no longer present in the influx diagram.

Poaceae/Amaranthaceae and (*Artemisia*+Amaranthaceae)/Poaceae ratio continue to remain very low. Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* ratio decline slightly.			
33.50-33.00	**LG3-b**	**Amaranthaceae – Poaceae >40micron-*Artemisia***	**~12,500-12,100**

Zone LG3-b is characterised by high values of herbs and a slight increase of trees. Both algae and aquatics decline over time, while npps are very low in values. Microcharcoal increases from ~54% to ~65%.

Quercus increases slightly to ~5% and trees start to appear again in very low values in this zone, including Juglandaceae, *Abies*, *Pinus*, *Fraxinus* and *Tamarix* (~1% or less). The herbaceous taxa is dominated by Amaranthaceae which increases to ~38% at 33.20m (~12,260 yrs BP) after which it starts to decline. *Artemisia* starts to increase after 33.20m (~12,260 yrs BP) from ~6% to ~9%. Poaceae slightly declines to ~26% but starts to increase from 33.20m (~12,260 yrs BP) to ~35%. Poaceae >40micron, in contrast, increases to ~3% and then declines from 33.20m (~12,260 yrs BP) to ~2%. Apiaceae undiff. declines over time from ~8% to ~3%. Two small peaks occur in the herbaceous taxa. The first one occurs between 33.40m (~12,400 yrs BP) and includes taxa such Cistaceae, *Galium*, *Mentha-type*, *Bupleurum-type* (~1% or less). The second small peak occurs between 33.20m (~12,260 yrs BP) and includes taxa such as Plantaginaceae, *Scilla-type*, *Turgenia*, and *Cousinia* (~1% or less). Aquatics are dominated by *Sparganium-type* (~4%) which declines towards the top of the zone. *Lythrum* appears in the zone between 33.60-33.20m (less than 1%) (~12,530-12,260 yrs BP). *Pediastrum* remains low (~1%) and *Botryococcus* further declines to ~18%. Npps are characterised by very low values of *Coniochaeta* and *Sordaria-type* (less than 1%).

Pollen concentration for total land pollen increases to 11770 grains/cm^2 at 33.40m after which it declines to 7502 grains/cm^2. Total land pollen influx slightly increases followed by a decline towards the end of the zone (values between 11-18 grains/cm^2/year). Amaranthaceae (values between 4-6 grains/cm^2/year) and Poaceae (values between 3-5 grains/cm^2/year) influx values also slightly increase followed by a decline. *Quercus* and *Artemisia* influx values are very low (values between 20-21 particles/cm^2/year). Microcharcoal influx slightly increases (values between 0-9 grains/cm^2/year)

Poaceae/Amaranthaceae and (*Artemisia*+Amaranthaceae)/Poaceae ratio are still very low. Poaceae/*Artemisia* and Amaranthaceae/*Artemisia* ratio increase slightly.

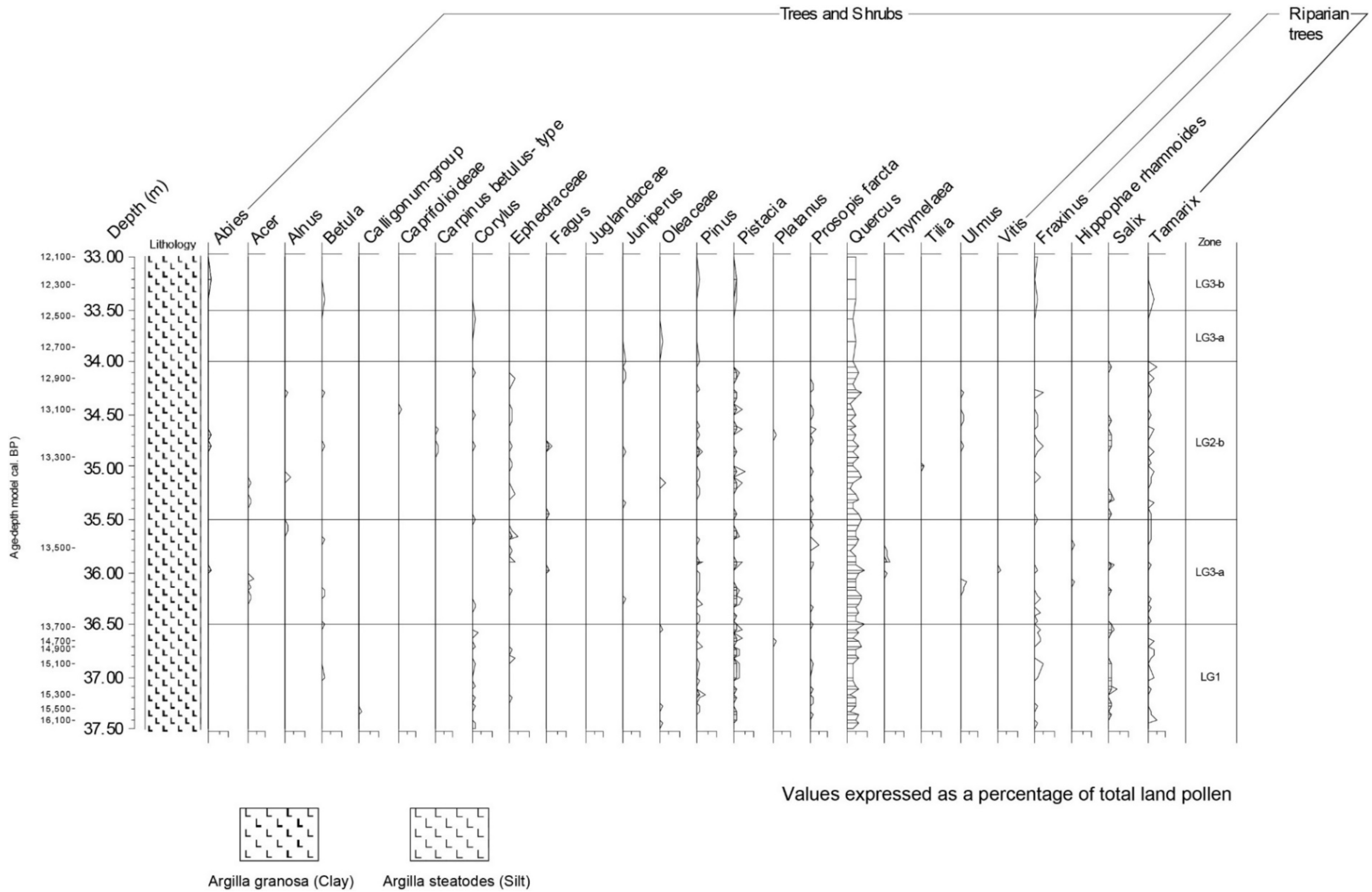

Figure 8-9: Pollen percentage diagram of Lake Ganau with selected taxa exaggerated by factor 3 (Part 1)

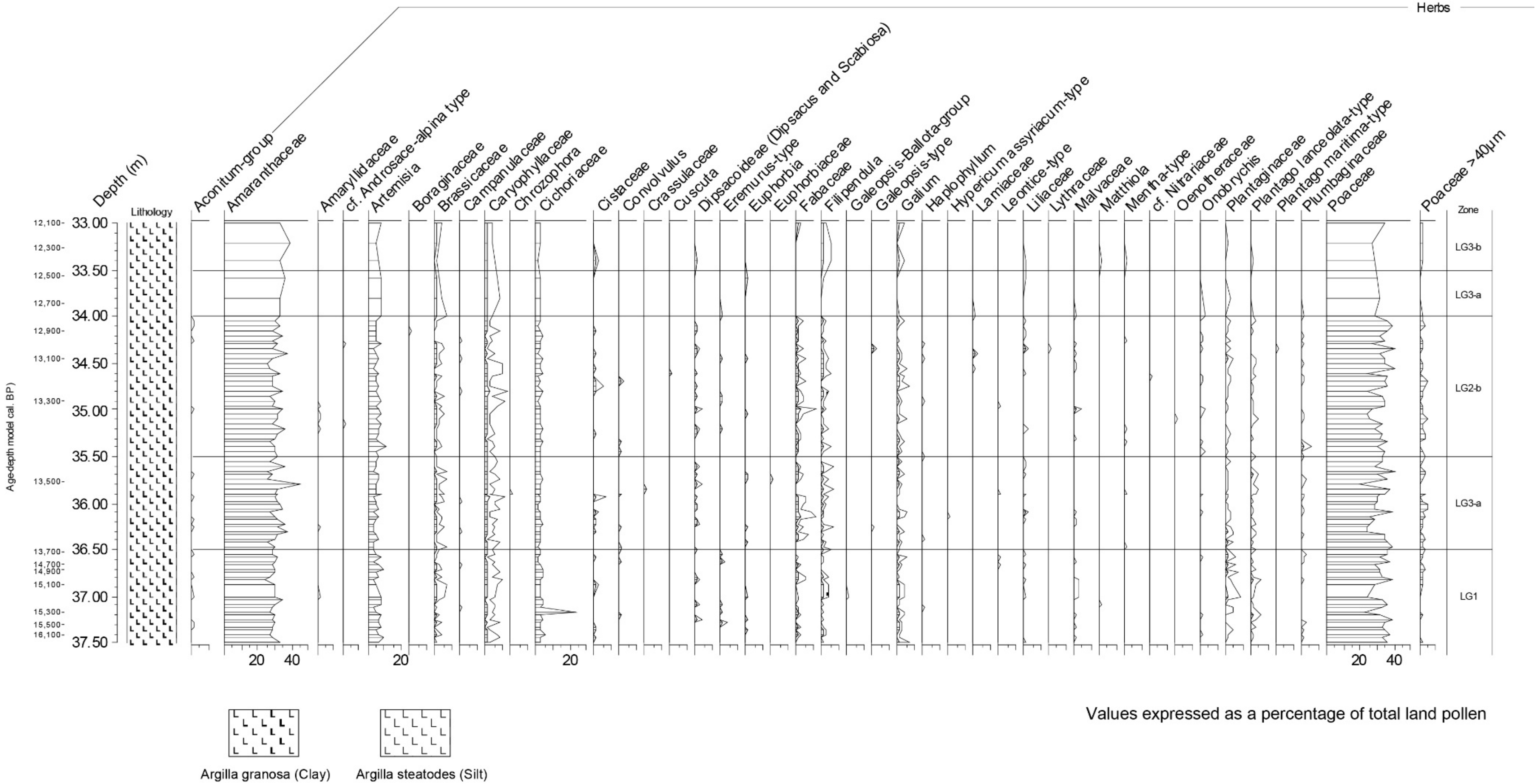

Figure 8-9: Pollen percentage diagram of Lake Ganau (Part 2)

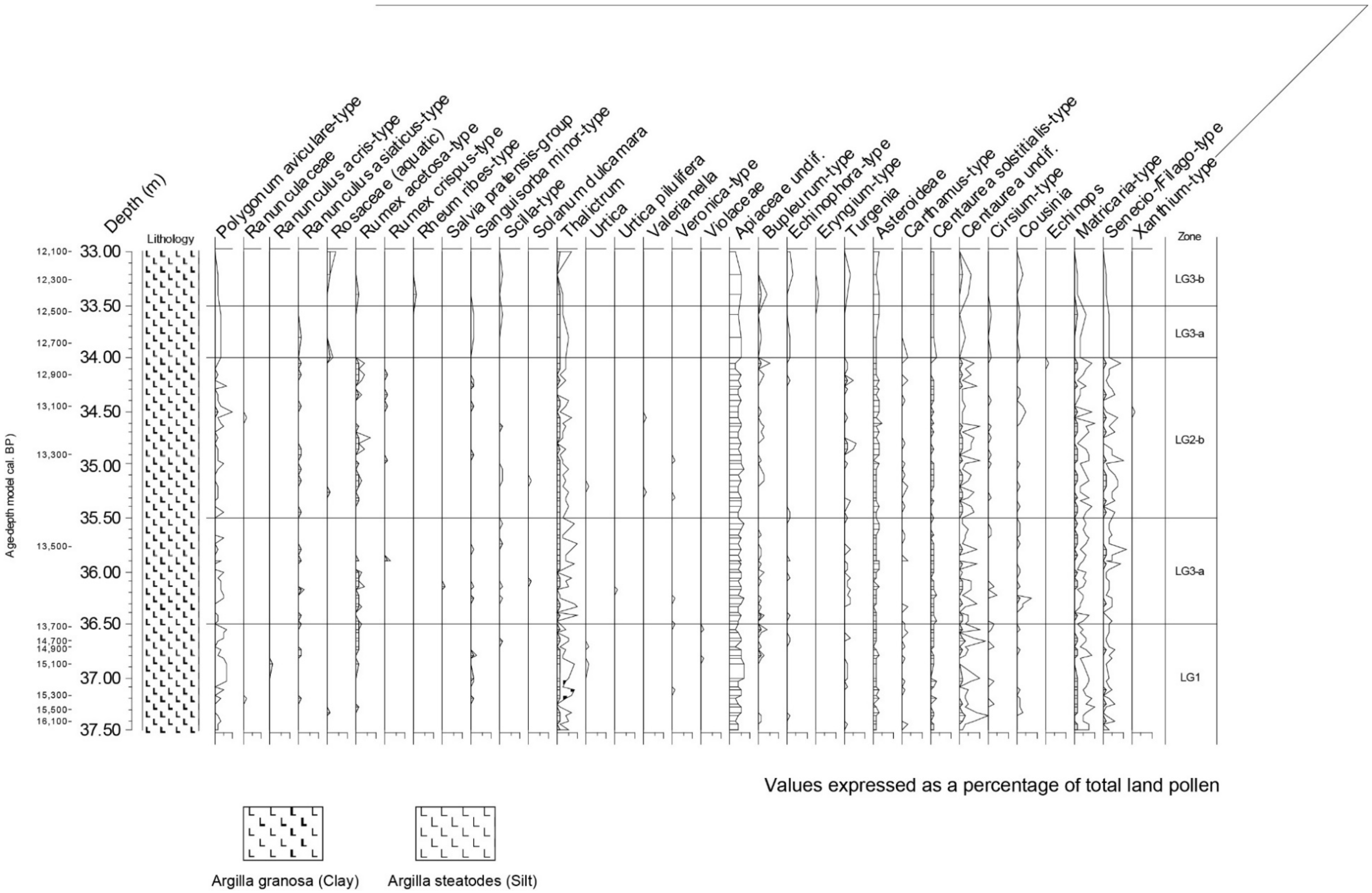

Figure 8-9: Pollen percentage diagram of Lake Ganau (Part 3)

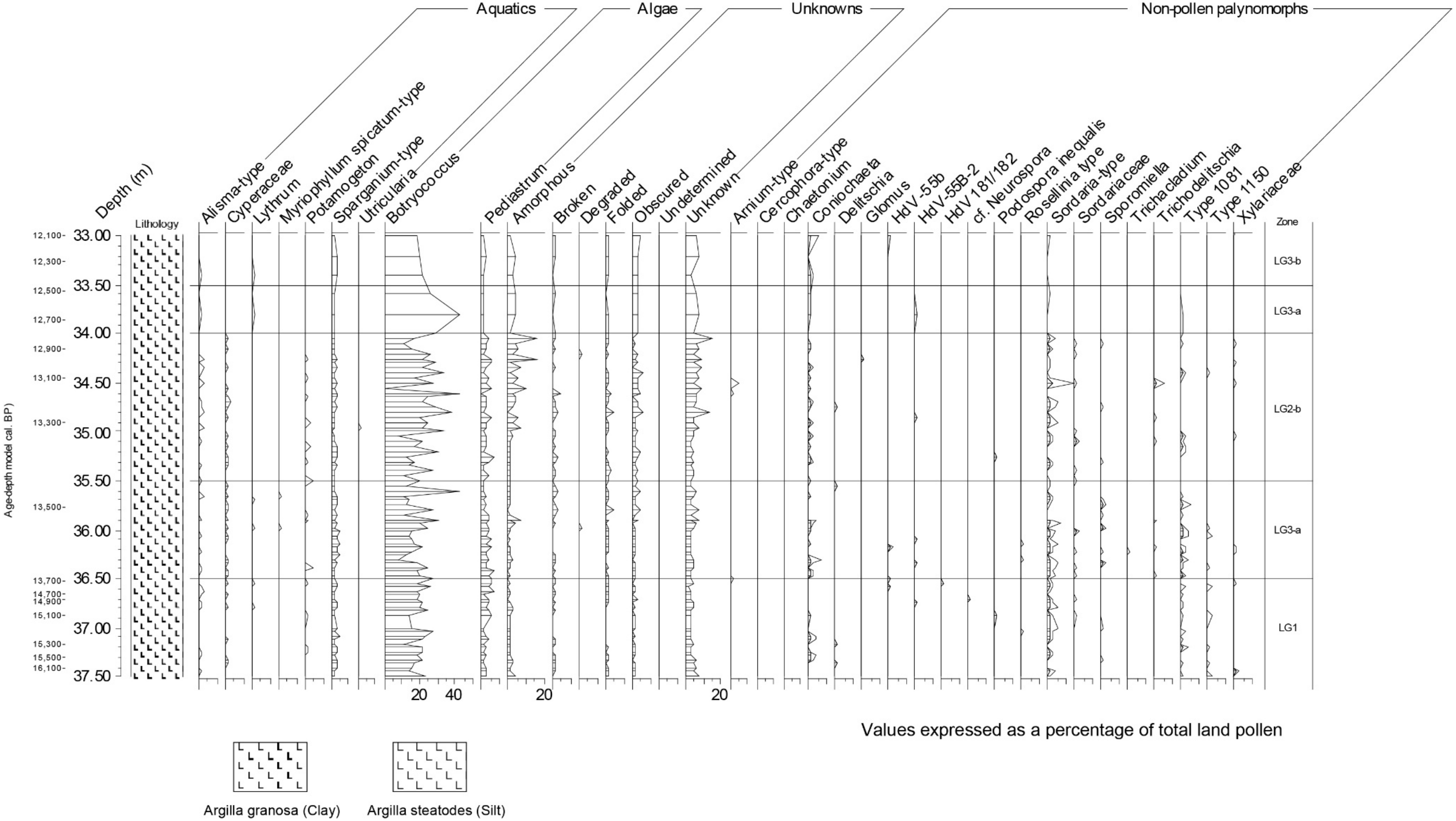

Figure 8-9: Pollen percentage diagram of Lake Ganau (Part 4)

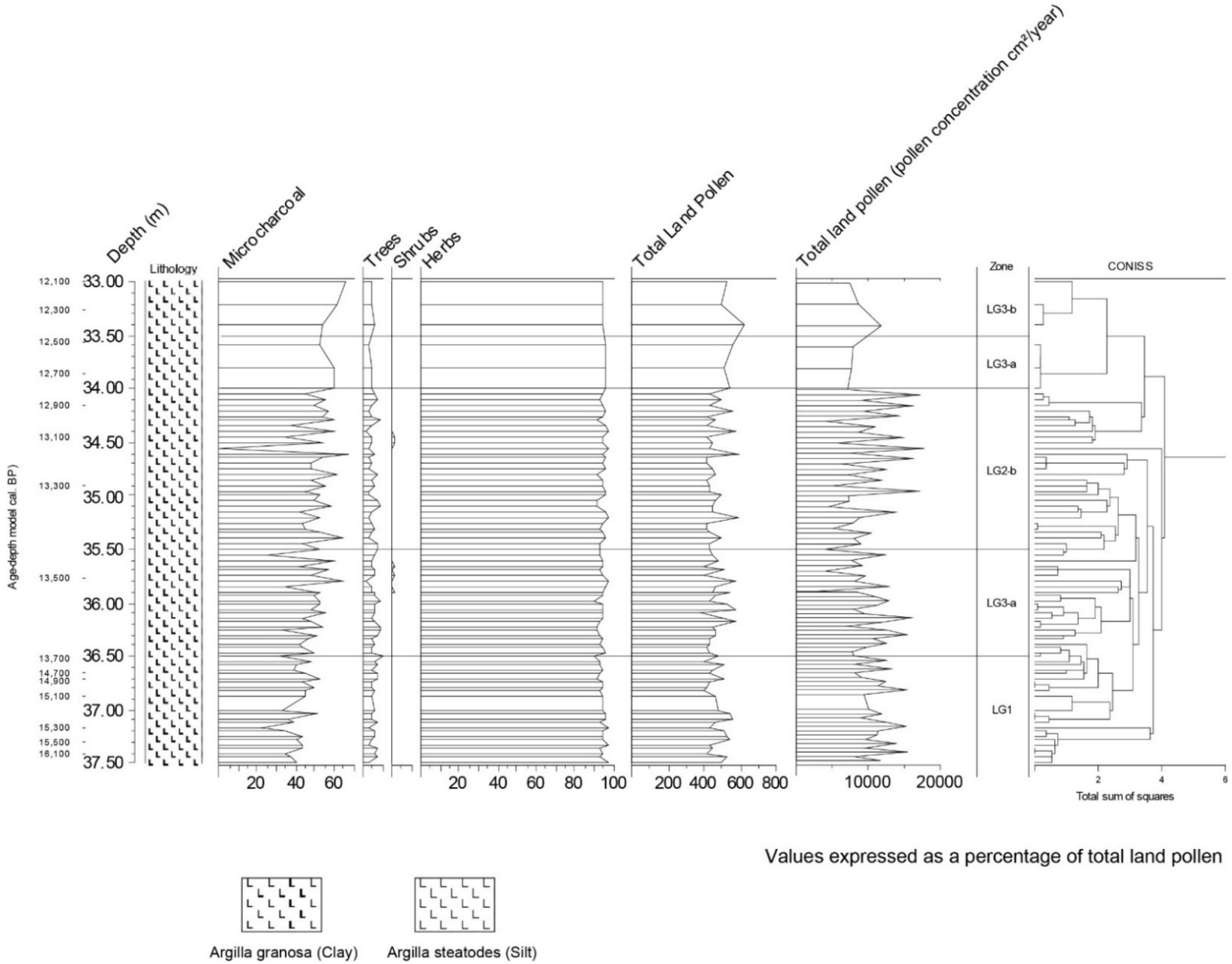

Figure 8-9: Pollen percentage diagram of Lake Ganau (Part 5)

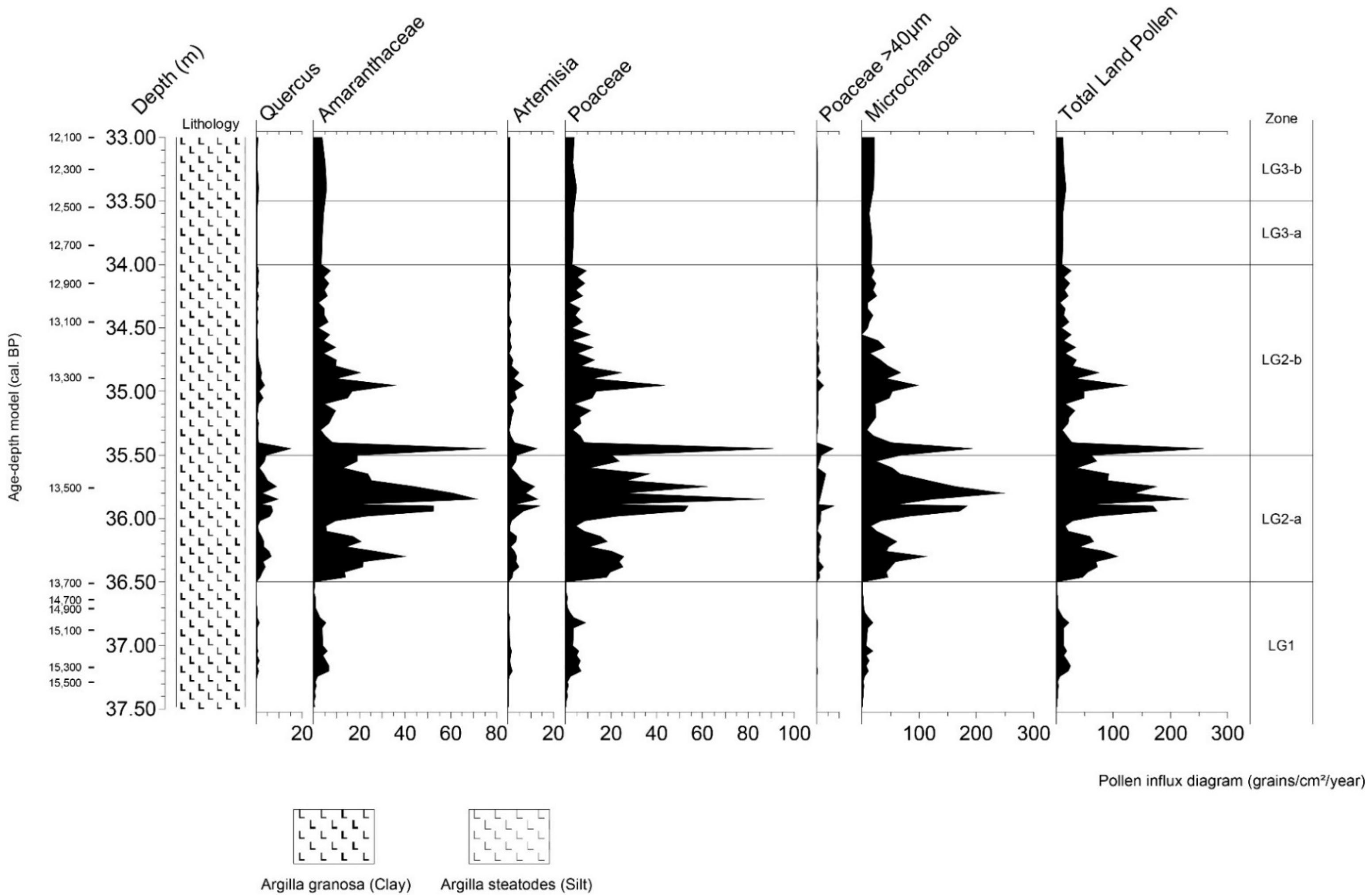

Figure 8-10: Pollen influx diagram of Lake Ganau

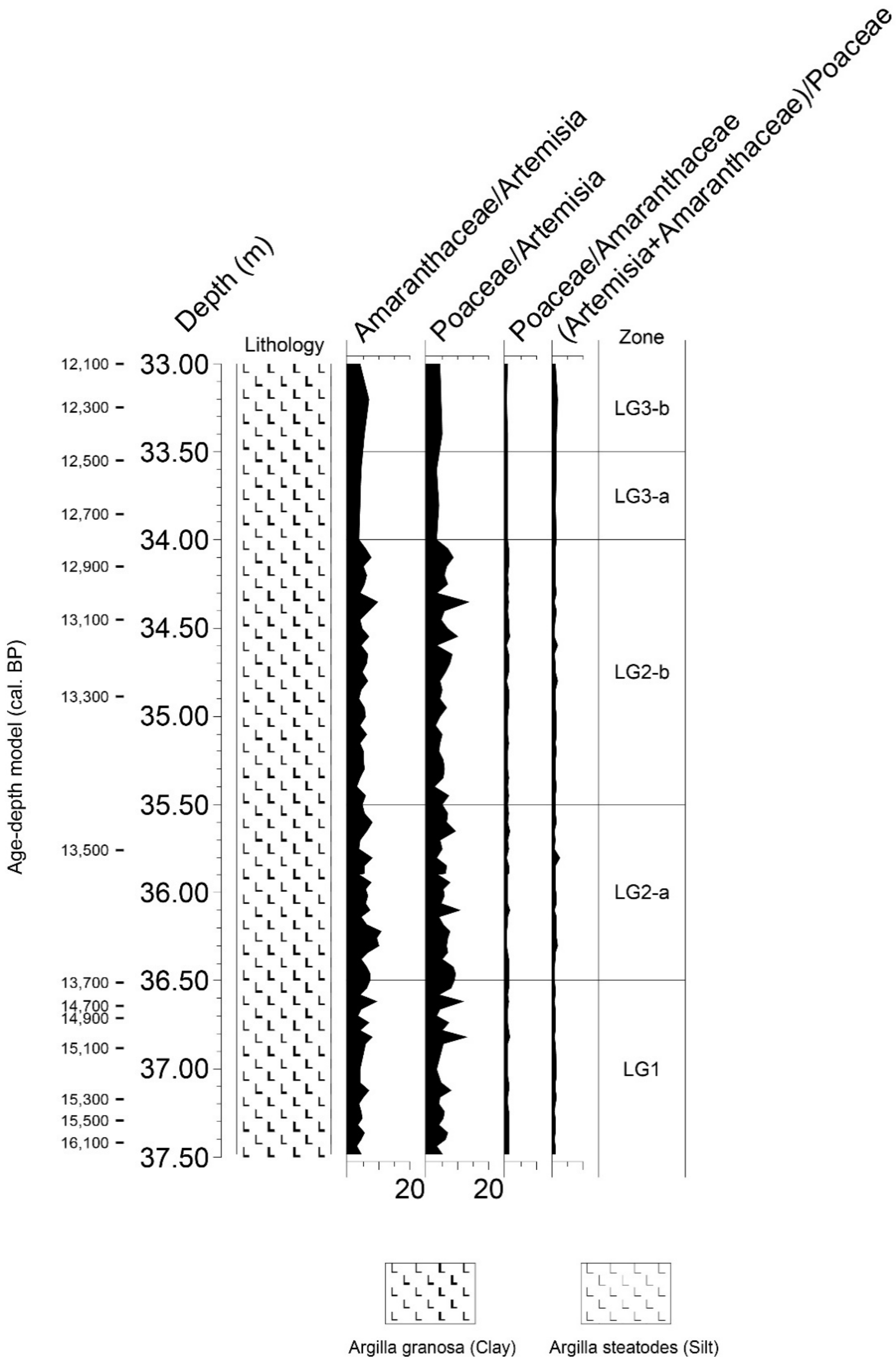

Figure 8-11: Pollen ratio of Lake Ganau

8.3 Sedimentary history

The presence of silty clay throughout the core sequence (33.00-37.50m) suggests the presence of a standing body of water with slow moving water.

Gan-1 44.80-43.80m ~20,000-19,350 yrs BP

Zone Gan-1 (20,000-19,350 yrs BP; ~650 yrs) corresponds to the Late Pleniglacial period (GS-2; ~22,900-14,700 yrs BP). High Mn/Fe and S/cps, and low Rb/K ratio suggest high lake levels between ~19,950-19,350 yrs BP (see Figure 8-8 no.1).

Gan-2 43.80-41.20m ~19,350-18,800 yrs BP

From ~19,350-18,800 yrs BP (zone Gan-2; ~550 yrs), one period of low lake water level (see Figure 8-8 no.2) followed by a high lake water level period (see Figure 8-8 no.3) occurred between ~19,200-19,150 yrs BP (low Mn/Fe, low S/cps, high Rb/K, low Ti/cps) and ~19,080-18,800 yrs BP (high Mn/Fe, high S/cps, low Rb/K, high Ti/cps), respectively. Fluctuations in lake water level could be related to changes precipitation levels and/ or temperature.

Gan-3 41.20-38.50m ~18,800-17,600 yrs BP

The time period between ~18,800-17,600 yrs BP (zone Gan-3; ~1200 yrs) is characterised by stable lake water level except between ~18,500-18,400 yrs BP where lake water level decline (high Rb/K, low Mn/Fe, low S/cps, low Ti/cps) (see Figure 8-8 no.4).

Gan-4 38.50-37.00m ~17,600-15,200 yrs BP

Zone Gan-4 corresponds to the time interval 17,600-15,200 yrs BP (Zone Gan-4; ~2400 yrs). During this interval lake water level remains stable, except between ~17,650-17,300 yrs where high lake water levels prevail (high Mn/Fe, high S/cps, low Rb/K, high Ti/cps) (see Figure 8-8 no.5). No change in the lithology (continuous silty clay deposition), stable organic matter and bulk carbonate content as well as stable lake level water, suggest that the environment between ~16,700-15,200 yrs BP was stable unlike the previous zones where lake water fluctuation suggest a dynamic environment. This time interval corresponds to GS-2.1a (~17,500-14,700 yrs BP).

Gan-5 37.00-34.15m ~15,200-12,900 yrs BP

Between ~15,200-12,900 yrs BP (zone Gan-5; ~2300 yrs), lake water levels continue to remain fairly stable with two short low lake water levels between ~13,530-13,470 yrs BP and 13,300-13,160 yrs BP (see Figure 8-8 no.6 and 7), suggesting a change in climatic conditions. These two short intervals at Lake Ganau occur during the GI-1 (~14,700-12,900 yrs BP; Bølling–Allerød) in which two short cold intervals have been identified between ~14,075-13,950 yrs BP (GI-1d) and 13,300-13,100 yrs BP (GI-1b). A slight increase in organic matter and bulk carbonate content during ~15,200-12,900 yrs BP, possibly suggest an increase in material being washed into the lake or an increase in organic productivity within the lake.

Gan-6 34.15-33.00m ~12,900-12,100 yrs BP

The short time interval between ~12,900-12,100 yrs BP (zone Gan-6; ~800 yrs), corresponds to the Greenland Stadial 1 (~12,900-11,700 yrs BP; Younger Dryas). The lake experienced an increase in lake water level at the onset of the stadial 1 period, between ~12,900-12,650 yrs BP (see Figure 8-8 no.8), which suggests that the start of the stadial period was characterised by short- wet interval that coincides with southward shift in the Mid-latitude Westerly Jets which means more moisture availability in the region (Sharifi *et al.* 2018). A peak in organic matter and bulk carbonate content at ~12,800 yrs BP could be indicative of riverine input further suggesting wetter climatic conditions. This wet interval within the stadial period is followed by a decline in lake water level, between ~12,650-12,370 yrs BP (see Figure 8-8 no.9).

8.4 Vegetation history

LG1 37.48-36.50m ~16,500-13,600 yrs BP

The late Pleniglacial period is characterised by an open Irano-Turanian mountain steppe landscape, dominated by Amaranthaceae and *Artemisia*, with Apiaceae and Poaceae also playing a prominent role in the vegetation composition. Some of the species of Amaranthaceae, unlike *Artemisia*, were likely growing near the lake shore in saline habitats as some species are halophytic. A number of species of Apiaceae were growing on open and dry slopes including *Bupleurum-type*, *Echinophora-type*, *Eryngium-type* and *Turgenia*, increasing in percentage values from ~15,200 yrs BP onwards (Djamali *et al.* 2009b: 129), forming part of the steppe vegetation. A variety of Asteraceae species were also present in the landscape including *Carthamus-type*, *Centaurea*, *Cirsium-type*, *Cousinia*, *Echinops*, *Matricaria-type* and *Senecio-/Filago-type*. *Centaurea solstitialis-type* are mostly found in disturbed habitats and would have also been part of the steppic vegetation (Van Zeist and Bottema 1977: 63). *Cousinia*, a cold-adapted and an under-represented Irano-Turanian flora in the modern pollen rain, was likely also an important part of the glacial landscape growing on the mountain slopes and well-drained plains (Djamali *et al.* 2011: 3399; Djamali *et al.* 2012).

The low and sporadic pollen values of Oleaceae and *Pinus* indicate long distance transport of the pollen grains by wind. The presence of trees such as *Betula*, *Alnus* as well as *Corylus* indicate that they were growing in northern Iran in the Hyrcanian forest, and that their grains were also transported long distances. The continuous pollen curve of *Quercus*, which is present nowadays at the foothills of the Kewa Resh mountains, suggests the presence of a small relict populations in the valley floor. Likewise, low pollen values of *Pistacia*, an under-represented plant, suggests the presence of relict populations in remote and protected valley floors and rocky habitats. Unlike in the eastern Zagros region, the presence of *Pistacia* and *Quercus* suggests that the climatic conditions in the western Zagros region were suitable for tree growth i.e. it was not too cold and dry for tree growth. A change occurs at ~15,100 yrs BP (36.86m), with *Quercus* pollen percentage slightly increasing, along with Poaceae, Poaceae >40 micron, and *Pediastrum*, possibly suggesting a slight improvement in climatic conditions. An increase in pollen influx and concentration between ca,15,300-15,100 yrs BP could be related to stable climatic conditions as reflected by stable lake levels during this time interval. *Prosopis farcta*, another under-represented pollen grain, is a desertic plant and often is part of the xeric *Artemisia* steppe. The presence *Prosopis farcta* pollen suggests the dominance of a warmer desert in the lowlands to the south in Zagros foothills. Thermophilous taxa such as *Tamarix* and *Salix along with Fraxinus*, which were growing along water courses in the area or even along the lake (Freitag 1977:

88), suggest that aridity rather than temperature was likely the primary factor preventing major tree growth and expansion (Freitag 1977: 94). The aquatic environment is dominated by shallow water reed *Sparganium-type (*which also includes *Typha-type)* and *Botryococcus*. Low and continuous presence of Cyperaceae pollen suggests the presence of some form of marsh vegetation belt around the lake. Besides being part of the steppe vegetation, some Poaceae pollen must have also originated from the local marsh vegetation lake. Other herbs that would have been part of the upland steppe vegetation include among many Ephedraceae (*Ephedra distachya-type* and *Ephedra fragilis-type*), Caryophyllaceae and Brassicaceae, with Brassicaceae possibly also growing as part of the local marsh vegetation (Wasylikowa *et al.* 2008: 69).

The environment largely remains the same as the Lateglacial Interstadial starts at ~14,700 yr BP.

LG2-a and LG2-b 36.50-34.00m ~13,600-12,800 yrs BP

Zone LG2-a and b correspond to the Lateglacial Interstadial period. No major change in vegetation composition can be identified. An increase in tree diversity is visible in the interstadial period with trees such as *Alnus*, *Betula*, *Ulmus*, and *Fagus* likely being a pollen signal of the Hyrcanian forest in northern Iran (Van Zeist and Bottema 1977: 64). Pollen grains of *Juniperus*, a cold and drought resistant tree, and *Platanus* also originate from distant areas such as the Elburz Mountains (Iran). Besides *Quercus* and *Pistacia* being the dominant trees growing in sheltered areas that had moister conditions such as ravines, rock crevices and narrow valleys (Van Zeist and Bottema 1977: 72), *Acer* also appears in the landscape, which like *Pistacia* is underrepresented in the pollen rain (Van Zeist and Bottema 1977: 74). *Artemisia* slightly declines in Zone LG2-a, while Apiaceae's share in the upland vegetation remains the same. Poaceae slightly increases probably at the expense of Artemisia declining. Thus, although the interstadial period was still characterised by an open *Artemisia*-Amaranthaceae steppe, grasses started to play a slightly larger part in the vegetation composition in the upland area. The continued presence of Poaceae >40micron suggest an increase in the number of wild cereal grasses in the landscape mostly found in the steppe vegetation. The slight increase of Poaceae over time suggests slightly moister conditions during the interstadial. The aquatic assemblage also diversifies in the interstadial with low percentage values of Cyperaceae, *Lythrum*, *Myriophyllum spicatum-type*, *Potamogeton* and *Sparganium-type*, as well as algae *Pediastrum* and *Botrycoccus*. *Botryococcus* values experience major fluctuations in Zone LG2-b (~13,500-12,800 yrs BP), increasing between 13,320-12,900 yrs BP. Cyperaceae continued to grow near the edge of the lake while the presence of submerged *Potamogeton* suggests eutrophic lake conditions (Wasylikowa 2008: 149). Myriophyllum spicatum-type that was loosely floating under the water at Lake Ganau suggests stagnant and flowing water (Wasylikowa 2008: 141). The continued but sporadic presence of *Tamarix*, *Salix* growing near water sources and *Prosopis farcta* suggest that temperatures were warm enough to enable their growth. *Salix* trees could have been growing on the lake edge if salinity was low. The very low pollen values of Fraxinus and *Hippophae rhamnoides* also suggest that these two tree populations were growing in riverine habitats.

The presence of a variety of dung spores, including *Coniochaeta*, *Delitschia*, *Sordaria-type*, *Cercophora-type*, *Chaetonium*, *Trichodelitschia*, and *Arnium-type* suggest that the lake and the surrounding area was visited by herbivores regularly during the interstadial.

Microcharcoal increases over time suggesting increased burning events. Between 13,640-13,470 and 13,320-13,280yrs BP pollen influx increases, possibly related to the low lake levels identified between ~13,530-13,470 yrs BP and ~13,300-13,160 yrs BP, as well as a slight increase in organic matter percentage between 15,200-12,900 yrs BP.

LG3-a and LG3-b 34.00-33.00m ~12,800-12,100 yrs BP

Zone LG3-a and b corresponds to the Lateglacial Stadial period which experiences a decline in tree, shrub and herb cover and diversity, possibly related to the climate changing to drier and colder climatic conditions. *Pistacia* and *Quercus* tree population decline while *Acer* completely disappears from the landscape. Poaceae also decline in percentage value, while Amaranthaceae and *Artemisia* rise suggesting enhanced aridity. Riparian trees *Tamarix*, *Salix, Fraxinus and Hippophae rhamnoides* as well as *Prosopis farcta*, which prefers warmer temperature, all decline and/or disappear from the landscape possibly due to the colder climatic conditions associated with the stadial period. Although the hydrology Lake Ganau seems to have remained the same for most of the period, a hydrological change occurred at ~12,870 yrs BP which is characterised by an increase of *Botryococcus* and decrease of *Pediastrum*. Cyperaceae decreases and submerged aquatic genus *Potamogeton* disappears, while *Sparganium-type* is still present.

The landscape between 12,800-12,100 yrs BP changed from an open *Artemisia*-Amaranthaceae steppe rich in herbs and high in Poaceae to an open *Artemisia*-Amaranthaceae dominated steppe with a lower diversity in herbs. Tree stands of *Pistacia* and *Quercus* declined as well during the stadial period. Microcharcoal percentage remains high but the influx values for microcharcoal are low. Pollen concentration and influx also decline between 12,800-12,100 yrs BP, possibly related to climate deterioration associated with the stadial period, except at 12,400 yrs BP when pollen concentration peaks.

9 Discussion

This chapter will discuss the results of Hashilan wetland and Lake Ganau for the time interval 17,700-2200 yrs BP to shed light onto human-environmental interactions in the Zagros region. The chapter is divided into three sections that are based upon: the vegetation history, the climate history, and human and environmental interactions.

The rationale behind the study of the vegetation and climate history first is to provide an outline and explanation for the changes visible in the records and, by extension, how they relate to the palaeoenvironmental evidence from other sites. This approach would allow us to identify any differences and similarities between palaeoenvironmental records, which, in turn, would promote the formation of a comprehensive discussion in an effort to try to determine human impact on the environment and assess the resilience of human communities to climatic and environmental changes.

The section on the vegetation and climate history have been further sub-divided according to the climatic period (Late Pleniglacial, Lateglacial, Early Holocene, Middle Holocene, and Late Holocene), while the section on human environmental interaction is divided into sub-themes including the broad spectrum revolution, the onset of cultivation in the Kermanshah region, the impact of climate change on human activity, as well as the impact of human activity on the environment during the Chalcolithic to Iron Age periods.

9.1 Vegetation history

9.1.1 Late Pleniglacial (17,700-14,700 yrs BP)

The vegetation cover in the Late Pleniglacial at Hashilan wetland (eastern Zagros) and Lake Ganau (western Zagros) was characterised by a relatively open dry steppe environment dominated by Amaranthaceae and *Artemisia*, with Poaceae and Apiaceae also playing a significant part in the vegetation composition (Figure 9-1). Similarly, an open dry Amaranthaceae and *Artemisia* steppe has also been identified at Lake Zeribar, Lalabad spring and Lake Nilofar (Kermanshah valley) during the Pleistocene, with Apiaceae also being an important constituent of the vegetation cover (Van Zeist and Bottema 1977; Wick *et al.* 2003; Van Zeist 2008: 92-96). Trees such as *Pistacia* and *Quercus* were absent in the vicinity of Lake Zeribar during the Late Pleniglacial likely due to the cold and dry climatic conditions (Van Zeist and Bottema 1977; Wasylikowa *et al.* 2008). Likewise, trees were scarcely present in the landscape of Hashilan wetland and Lake Ganau, limited to sheltered places, which had higher moisture availability. At Hashilan wetland, for instance, only riparian trees *Fraxinus*, *Salix* and *Tamarix* were growing at the edge the wetland. The low values of *Quercus* and *Pistacia* in the pollen record of Hashilan wetland during the Pleniglacial are likely a regional signal rather than local, which will be discussed in the Lateglacial section in more detail.

A major difference between the Hashilan wetland and Lake Ganau landscape was that trees were present in slightly higher quantities in the Lake Ganau area during both the Late Pleniglacial and Lateglacial. Furthermore, tree population at Lake Ganau was not restricted to riparian trees growing on the margins of the lake but also included a small relict population of *Quercus* and *Pistacia* which were growing in remote and protected valley floors and rocky habitats. The only other evidence for the presence of trees in the western Zagros region during the Pleniglacial comes from the archaeological site of Palegawra (Asouti *et al.* 2020). This difference between the eastern and western Zagros region allows us to fill the gaps in knowledge and start building a more complete picture of what the environment looked like in the Zagros region.

Figure 9-1: Location of archaeological sites (yellow circle) and palaeoenvironmental records (red circle) mentioned in this section (author's own - base map: Google maps)

9.1.2 Lateglacial Interstadial and stadial (14,700-11,700 yrs BP)

The transition into the Lateglacial Interstadial at Hashilan wetland, the timing of which will be discussed in section 9.2, continues to be characterised by an open Irano-Turanian mountain steppe dominated by Amaranthaceae and *Artemisia* with Poaceae slowly starting to become an increasingly important constituent of the steppe landscape at the expense of *Artemisia* and Apiaceae, which agrees with the Lake Zeribar pollen data (Van Zeist and Bottema 1977). Despite the climatic amelioration associated with the Lateglacial Interstadial, unlike at Lake Zeribar, *Pistacia* was still unable to establish itself at Hashilan wetland. Tree growth, therefore, was not favourable during the Lateglacial Interstadial at Hashilan wetland despite the climatic amelioration which was identified at Lake Zeribar between 15,400-12,600 yrs BP. The oxygen isotope record of Lake Zeribar suggests an increase in effective moisture between 15,200-14,200 yrs BP, and an increase in temperatures for the Lateglacial Interstadial is deduced from the presence of warmer temperature preferring diatoms and charophytes (Wasylikowa *et al.* 2008: 314).

Van Zeist (2008: 79) argues that the reason why trees such as *Quercus* did not re-establish themselves in the interstadial period might be due to precipitation not increasing (or not increasing enough) to compensate for the higher temperatures leading to greater climatic aridity. At Lake Zeribar, a decline in *Salix* occurred at ~14,000 yrs BP, argued to be a result of rising water level (Wasylikowa *et al.* 2008: 314), which suggests that although precipitation increased it was not enough to allow *Quercus* to re-establish itself in the Zeribar area. This might also be the reason why arboreal vegetation at Hashilan wetland remained constricted to the valley floor with scattered trees of *Salix* and *Tamarix*, which completely disappeared at ~13,400 yrs BP (302cm), possibly connected to the dry climatic interval identified in the geochemical record of Hashilan wetland between ~13,200-12,700 yrs BP (see section 9.2).

It is important to highlight here that the Lateglacial Interstadial at Hashilan wetland is constrained by only one radiocarbon date located at 291cm (291cm = 13,067-12,858 yrs BP) after which the geochronology is based on interpolation and the assumption that sedimentation remained constant through time (291-550cm). If the pollen record of Hashilan wetland is interpreted without considering the geochronology after 291cm, it can be argued that the Lateglacial Interstadial corresponds to the high values in *Salix* population between 398-338cm, which suggests the reactivation of the fluvial system (Figure 9-2). This assumption is further confirmed by the presence of *Quercus* and *Pistacia* pollen grains during this depth interval in the pollen record. This would agree with the Lake Zeribar record in terms of trees re-establishing themselves in the regional landscape during the Lateglacial Interstadial. Furthermore, Poaceae is high and Amaranthaceae and *Artemisia* are lower in value during this interval (Figure 9-2). At Lake Van, slightly higher pollen values of *Quercus*, *Pistacia* and *Salix* are also visible in the pollen record (Wick *et al.* 2003). If indeed the depth interval 398-288cm corresponds to the Lateglacial Interstadial then the chronology below ~13,000 yrs BP (13,067-12,858 yrs BP) has a higher degree of uncertainty. Furthermore, it suggests that the interstadial was a period characterised by fluctuating values of Poaceae, *Artemisia* and Amaranthaceae. The Greenland ice record identified three warm and two cold sub-events within the Greenland Interstadial 1 (Table 9-1) (Rasmussen *et al.* 2014). Therefore, it is possible that the fluctuating values of Poaceae, *Artemisia* and Amaranthaceae might be related to intervals of warmer and colder intervals within the Lateglacial Interstadial. Furthermore, the presence of trees during the Lateglacial Interstadial suggests that climatic conditions were changing to warmer and possibly wetter conditions, allowing trees to expand, although the presence of *Quercus* was still likely a regional signal with the grains possibly being transported from the western Zagros region.

Table 9-1: Sub-division of the Greenland Interstadial 1 (Rasmussen et al. 2014)

Greenland Interstadial 1 sub-events	**Age yrs BP**	**Climatic condition**
GI-1a	13,099-12,896	Warm
GI-1b	13,311- 13,099	Cold
GI-1c	13,954- 13,311	Warm
GI-1d	14,075- 13,954	Cold
GI-1e	14,692- 14,075	Warm

The lithological changes associated with this depth interval (398-288cm) indicate that the coring location kept changing from one sub-environment to another (i.e. peatland changing into an aerially exposed island), which would suggest the presence of a very dynamic wetland environment during the Lateglacial Interstadial. It can thus be argued that although the Lateglacial Interstadial experienced climate amelioration in the eastern Zagros region (i.e. warmer climate), it was a period of climatic instability.

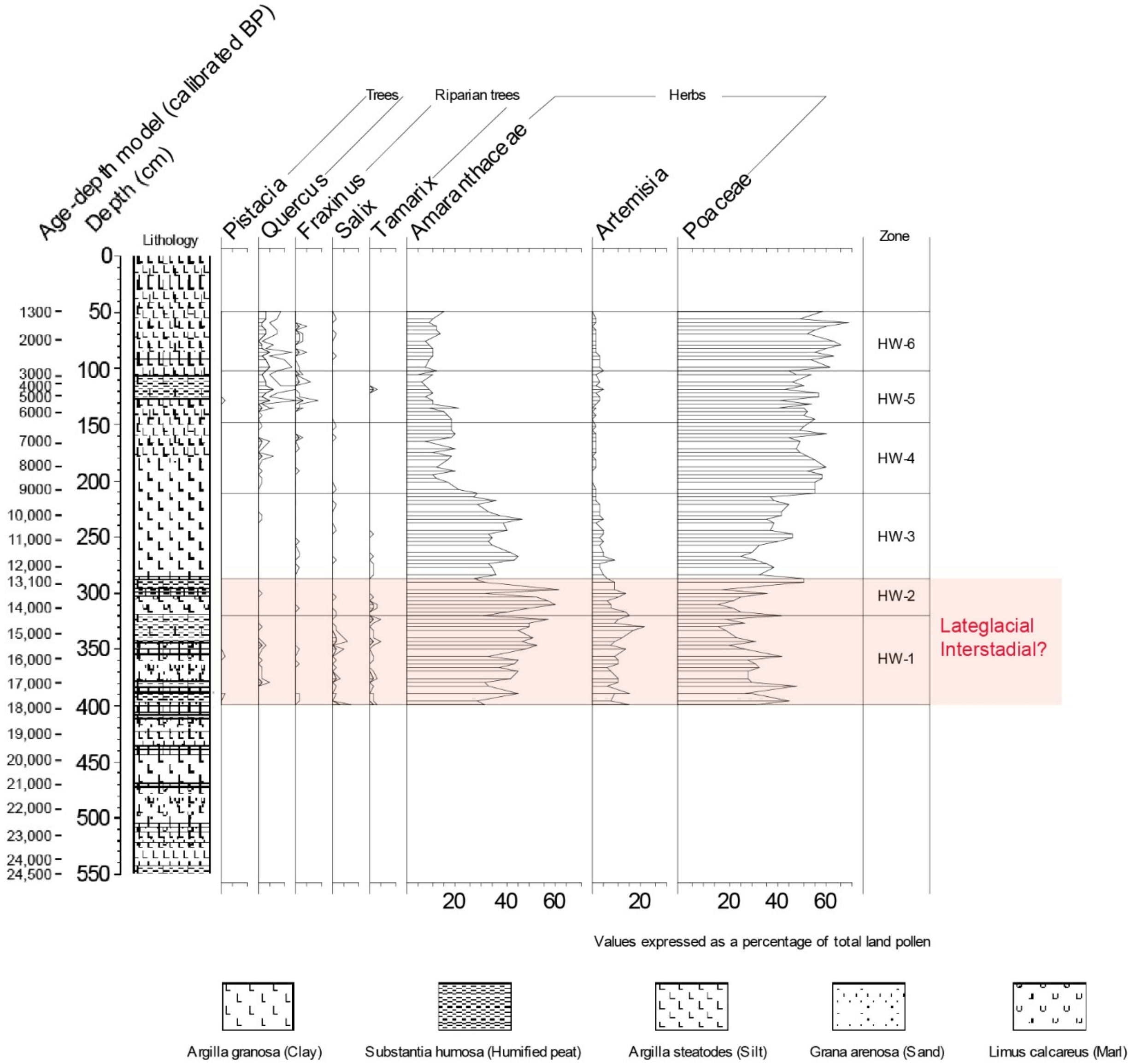

Figure 9-2: Pollen diagram of selected taxa. Red box highlights the possible Lateglacial Interstadial sequence based on pollen data only

The vegetation changes at Lake Ganau, in contrast, remained fairly constant throughout the Lateglacial Interstadial and stadial (16,100-12,100 yrs BP), characterised by an open Irano-Turanian mountain steppe landscape. Minor fluctuations in vegetation composition occur at the onset of the Lateglacial Interstadial with grasses increasing slightly, probably at the expense of *Artemisia*, and a slight diversification of the herbaceous taxa. *Cousinia* continues to be part of the vegetation composition during the Lateglacial Interstadial along with Apiaceae and Asteraceae. During the Lateglacial Interstadial, trees continued to be present in higher quantity at Lake Ganau compared to the eastern Zagros region and northwestern Iran, which is in agreement with the Shanidar cave pollen record (Wahida 1981: 35) and the Palegawra macrobotanical data (Asouti *et al.* 2020). The tree composition near Palegawra cave, however, was different from Lake Ganau, with an open *Amygdalus-Quercus* woodland present along with *Pistacia*, while at Lake Ganau a small relict population of *Quercus* and *Pistacia* was present. Besides a small relict population of *Quercus* and *Pistacia* present in the landscape, *Acer* also became part of the tree population during the Lateglacial Interstadial at Lake Ganau along with *Hippophaë rhamnoides* which was growing near the lake with the other riparian trees. As both *Pistacia* and *Acer* are insect pollinated, their presence in the pollen record is underrepresented. This feature means that both trees may have been present in the landscape in higher quantities than can be inferred from the pollen percentages. In general, it indicates that there is a clear difference between the western and eastern Zagros region in terms of vegetation composition, specifically regarding the presence of trees. In the Zeribar area, only *Pistacia* was able to grow (excluding riparian trees), while in the western Zagros region there is evidence for the presence of *Pistacia*, *Quercus*, *Acer* and *Amygdalus* during the Lateglacial Interstadial.

Similar to Hashilan wetland, a diversification of aquatic plants occurred at Lake Ganau during the Lateglacial Interstadial which included Cyperaceae, *Lythrum*, *Urticularia*, *Myriophyllum spicatum-type*, *Potamogeton* and *Sparganium-type*, as well as algae *Pediastrum* and *Botrycoccus*. This suggests that besides higher effective moisture, compared to the eastern Zagros, the climate was probably also warm which allowed higher plant diversity. Unlike at Hashilan wetland where fluctuating values of Poaceae, Amaranthaceae and *Artemisia* are visible, there are no significant changes happening in the vegetation composition at Lake Ganau, suggesting that climatic conditions were more stable in the western Zagros during the Lateglacial Interstadial. To confirm whether climatic conditions in the western Zagros were more stable requires palaeoclimatic data for this time interval, which at present is not available for the western Zagros region.

The Lateglacial Stadial, also referred to as the Younger Dryas, at Hashilan wetland continued to be defined by an open dry steppe environment dominated by Amaranthaceae and *Artemisia*, with Asteraceae and Cichoriaceae becoming an increasingly significant part of the steppe from ~12,600 yrs BP onwards, while the presence of grasses declined. At Lake Ganau, a slight decline in overall plant diversity is noticeable in the landscape with Amaranthaceae slightly increasing, while grasses slightly declined. Furthermore, the start of the Lateglacial Stadial at Lake Ganau is marked by a decline in trees with *Salix*, and *Acer* no longer being part of the vegetation cover. In comparison to the eastern Zagros region, however, trees did not entirely disappear from the Lake Ganau area with *Pistacia* and *Quercus* still present in the landscape although in lower quantity. This decline in numbers and diversity was not limited to trees and herbs but also included aquatic plants.

The Lateglacial Stadial at Lake Zeribar, which has been dated to 12,600-12,000 yrs BP, also indicates the increased presence of Amaranthaceae and *Artemisia* in the landscape (Van Zeist and Bottema 1977; Wasylikowa *et al.* 2008). This open dry steppe environment was, however, not limited to the Zagros region but was also found in the Lake Urmia area and at Lake Neor in north-western Iran (Djamali *et al.* 2008; Aubert *et al.* 2017) and at sites in Turkey (e.g. Wick *et al.* 2003; Roberts *et al.* 2016). This type of vegetation composition has been argued to be a result of the changing climatic conditions. The Lake Zeribar oxygen isotope data, for instance, indicates low effective moisture levels between 12,900-12,300 yrs BP along with low and/or fluctuating water levels which reflects climatic aridity (Wasylikowa *et al.* 2008: 315). The change in the vegetation composition at Lake Ganau, outlined above, which occurred at ~12,800 yrs BP could thus be related to the climate deterioration associated with the Lateglacial Stadial period.

9.1.3 Holocene vegetation history

The Holocene vegetation history focusses on the pollen data of Hashilan wetland due to the Lake Ganau pollen record encompassing only the Late Pleniglacial and Lateglacial.

Early Holocene (11,700-8200 yrs BP)

The onset of the Early Holocene at Hashilan wetland led to an increase in grasses while dry steppe taxa Amaranthaceae and *Artemisia* started declining, signalling a change in climatic conditions - a trend that has been identified at other sites in the region including Lake Zeribar (Van Zeist and Bottema 1977), Lake Urmia (Djamali *et al.* 2008) and Lake Van (Wick *et al.* 2003), with the increase in grasses being a result of an increase in spring/summer precipitation (i.e. precipitation was no longer confined to winter seasons) (Wasylikowa *et al.* 2008: 316). Despite the transition from dry steppe to grassland at the onset of the Holocene, Amaranthaceae remained a dominating taxon until ~10,200 yrs BP. At Lake Zeribar, Amaranthaceae and *Artemisia* decline rapidly while at Lake Mirabad the Early Holocene was marked by a high presence of Amaranthaceae which has been interpreted to suggest that dry climatic conditions persisted during the Early Holocene (Van Zeist and Bottema 1977; Stevens *et al.* 2006). Whether dry climatic conditions also prevailed at Hashilan wetland during the Early Holocene and whether the slow decline in Amaranthaceae pollen values reflect dry conditions will be discussed in detail in section 9.2. Based on the increase in Poaceae and the decline in both Amaranthaceae and *Artemisia*, Hashilan wetland witnessed the start of the Holocene at ~11,500 yrs BP, which would be in agreement chronologically with the evidence retrieved from the Lake Neor, Jazmurian playa and Lake Van records (Çağatay et al. 2014; Sharifi et al. 2015; Vaezi et al. 2019).

Despite the ameliorating climatic conditions associated with the Early Holocene, the expansion of trees such as *Quercus* and *Pistacia* at Hashilan wetland did not occur until ~8600 yrs BP. Instead, trees continued to be restricted to the edge of the wetland (*Fraxinus*, *Salix* and *Tamarix*).

At Lake Zeribar, in contrast, an open woodland with widely scattered trees, mainly *Pistacia*, and a grass-dominated steppe-like ground vegetation started forming at ~12,000 yrs BP. *Quercus*, on the other hand, was not yet able to re-establish itself in the Zeribar area which suggests that climatic conditions were favourable for *Pistacia* but not *Quercus*. From ~10,000 yrs BP, *Quercus* started to expand slowly in the wider region. Van Zeist and Bottema (1977) argue that despite very low pollen percentages of *Pistacia* at Lake Zeribar, it was the dominant arboreal component of open upland *Pistacia* - *Quercus* forest steppe that slowly developed in the Early Holocene. At 6900 yrs BP, *Quercus* started to expand in the Zeribar area, which has been attributed to an increase in spring precipitation (Wasylikowa *et al.* 2008: 317), and within 700-1000 years the Zagros *Quercus* woodland managed to establish itself. At Lake Neor, in contrast, *Quercus* starts to increase from 8700 yrs BP onwards (Aubert *et al.* 2017), while in north-eastern Iran (Gomishan area), *Quercus* already started to increase from ~9400 yrs BP onwards along with *Carpinus betulus*, reaching it densest form at ~8200 yrs BP (Leroy *et al.* 2013). At Lake Van, *Quercus* also starts to expand from 8200 yrs BP onwards, with maximum extension of the forest steppe achieved between 6200-4000 yrs BP (Wick *et al.* 2003). At Hashilan wetland, in contrast, a continuous low presence of the *Quercus* curve starts from ~8600 yrs BP onwards, which agrees with the Lake Neor date. It can, however, be argued that *Quercus* was already present from ~10,200 yrs BP onwards, based on a small peak in *Quercus* pollen value, which would agree with the Lake Zeribar date of ~10,000 yrs BP. Nonetheless, the low *Quercus* pollen values at Hashilan wetland from ~10,200 yrs BP or 8600 yrs BP onwards suggest that *Quercus* did not reach the Hashilan area yet and, thus, is a regional signal. While at Lake Zeribar *Quercus* expands locally at ~6900 yrs BP, at Hashilan wetland an increase has been noted at ~5900 yrs BP. As can be seen, the timing of *Quercus* expansion and woodland formation varied across Iran which could be related to unsuitable climatic conditions, but the role of anthropogenic activity cannot be ruled out. In section 9.2, this issue will be examined closely to determine the contributing factors to the delay in woodland expansion during the Early Holocene.

Besides the delay in Quercus woodland in the region, an increase in the frequency of Poaceae >40micron in the landscape occurs from ~9800 yrs BP onwards, which could be a signal of anthropogenic activity in the vicinity of Hashilan wetland. However, although Poaceae >40micron can be an indicator of cereal cultivation, they can also be produced by progenitor wild grass species and by naturally-occurring wild grass species (Djamali *et al.* 2009b). At Lakes Zeribar and Urmia, as well as

Hashilan wetland, pollen grains of Poaceae >40micron have been identified during the Pleistocene period (Van Zeist and Bottema 1977) (Djamali *et al.* 2008) (Djamali *et al.* 2009b). Therefore, unless other anthropogenic disturbance indicators are present, the presence of Poaceae >40micron to infer agricultural activity needs to be used with caution. A detailed discussion on the impact of human activity on the landscape and when human activity becomes visible in the pollen record of Hashilan wetland will featured in section 9.3.

Middle Holocene (8200-4200 yrs BP)

A relatively open grass-steppe continues to prevail in the Middle Holocene at Hashilan wetland from 8200 yrs BP onwards, while at Lake Zeribar an open *Pistacia-Quercus* forest steppe was present (Van Zeist and Bottema 1977). *Quercus* already started to increase from ~6900 yrs BP onwards and within approximately 700 years *Quercus* woodland was formed at Lake Zeribar (~6200/5900 yrs BP) (Van Zeist 1967; Van Zeist and Bottema 1977). Only from ~5900 yrs BP onwards *Quercus* starts to expand at Hashilan wetland (reaching up to ~6% at ~4100 yrs BP). The low values of *Quercus* in the pollen record of Hashilan wetland, however, could suggest that it reflects the regional presence of *Quercus* rather than local. This factor is also the case for Lake Neor, where low *Quercus* values (max.10%) have been questioned as to whether it was present locally. The low presence of *Quercus* in the pollen record can be explained by two competing theories: 1) *Quercus* was not present in the vicinity of the wetland and its pollen grains were brought in via long-distance transportation; 2) summer droughts were longer which inhibited fast expansion of *Quercus* (Aubert *et al.* 2017: 163). To identify which of these theories is applicable to the low *Quercus* pollen values at Hashilan wetland, see section 9.2. Similarly, the presence of *Pistacia* at ~5300 yrs BP in the Hashilan wetland record could be indicative of *Pistacia* growing in the wider landscape. There is a possibility, however, that scattered trees of *Pistacia* were present locally based on the macrobotanical study carried out at the Neolithic site of Sheikh-e Abad, where nuts of *Pistacia* have been recovered (Whitlam *et al.* 2013). Furthermore, the botanical survey carried out at Hashilan wetland and the surrounding mountain areas identified *Pistacia* growing between 1300-2000m at the present day (Safaierad in press). This could suggest that *Pistacia* was present locally during the Middle Holocene in the Hashilan area and is very underrepresented in the pollen record which could also be related to the pollen preservation issues identified for this time interval. *Pistacia* has also been identified in the southeast of the Zagros at Lake Maharlou, where an increase in both *Pistacia* and *Quercus* occurred at ~5500 yrs BP, approximately 400 years later than at Hashilan wetland. This delayed woodland expansion at Lake Maharlou, in comparison to the Lake Zeribar record, has been attributed to its southerly position (Djamali *et al.* 2009b) and could also explain the lag between the Lake Zeribar record and the Hashilan wetland record.

An increase in *Fraxinus*, *Artemisia*, Apiaceae and Poaceae >40micron also occurred at ~5900 yrs BP along with the rise in *Quercus*, indicating a change in the vegetation composition around Hashilan wetland. Other changes in the herbaceous pollen taxa visible from ~6100 yrs BP onwards included the appearance of *Plantago lanceolata* and *Rumex*, and increase in Plantaginaceae, *Polygonum aviculare, Carthamus*, *Galium* and Poaceae >40micron, which collectively are potential indicators of disturbance caused by human activity in the area (see section 9.3). At Hashilan wetland despite changes in the vegetation composition, tree diversity remained considerable low during the Middle Holocene when compared to Lake Zeribar and Lake Mirabad. At Lake Mirabad, for instance, besides *Quercus* which was the predominant tree after 6900 yrs BP, *Pistacia*, *Acer*, *Pyrus syriaca*, *Daphne*, *Amygdalus*, *Crataegus* and *Prunus* were also part of the woodland (Van Zeist and Bottema 1977). While at Lake Zeribar the woodland cover also included *Pistacia*, *Pyrus*, *Acer*, *Lonicera*, *Daphne*, and *Crataegus* (Van Zeist and Bottema 1977). Despite the differences between the Lake Zeribar and Hashilan wetland records, in terms of timing of change and the vegetation composition, similarities are also present such as the temporary increase in *Fraxinus* at Lake Zeribar which occurred at approximately the same time as *Quercus* expands in both areas (Van Zeist 2008 87-88).

A decline in *Quercus* woodland at Lake Zeribar and Mirabad started at ~5400 yrs BP, with an increase in herbaceous taxa, mainly Poaceae, indicating the presence of an open woodland between ~5400-3100 yrs BP (Van Zeist and Bottema 1977), while at Hashilan wetland a gradual decline in *Quercus* occurs from ~4100 yrs BP onwards which is in agreement with the Lake Van record (~4000 yrs BP)(Wick *et al.* 2003). The increase and subsequent decline in *Quercus* could be related to climate change but anthropogenic activity could have also played a part in this, which will be discussed in further detail in section 9.2 and 9.3.

Late Holocene (4200 yrs BP to the present day)

The Late Holocene environment around Hashilan wetland continued to be dominated by a grass-steppe with another decline in Quercus at ~2500 yrs BP. Changes in the herbaceous taxa included the highest values of Poaceae >40micron, presence of Apiaceae, *Artemisia*, slight increase in Amaranthaceae, and decline in Asteraceae. Furthermore, pollen taxa indicative of human activity continue to be present during the Late Holocene, including *Galium*, *Plantago-lanceolata*, Poaceae >40micron, *Polygonum aviculare*, and *Centaurea undif*. The Lake Zeribar area, although still characterised by an open woodland, also experienced another decline in *Quercus* at ~2700 yrs BP. This decline has also been noted at Lake Maharlou at ~2800 yrs BP (Saeidi Ghavi Andam *et al.* 2021) and at Lake Parishan at ~ 2500 yrs BP (Jones *et al.* 2015; Djamali *et al.* 2016). As can be seen, a decline in *Quercus* has been noted in all sites located in the Zagros region, although the timing differed which could be related to dating uncertainties or lags in change. In northwestern Iran, in contrast, an almost treeless Irano- Turanian steppe vegetation prevailed at both Lake Urmia and Lake Neor (Talebi *et al.* 2016; Alinezhad *et al.* 2021), while the landscape at Lake Almalou was dominated by mainly by *Quercus*, *Artemisia* and Amaranthaceae (Djamali *et al.* 2009a).

In summary, clear differences between the western and eastern Zagros region have been identified with the help of Lake Ganau and Hashilan wetland, such as the diversity and quantity of trees present during the Late Pleniglacial and Lateglacial. It also highlighted the importance of increasing the spatial coverage of pollen records for the Zagros region but also the temporal coverage. The discussion above also made it apparent that caution needs to be taken when comparing palaeoenvironmental records but also the archaeological record with the palaeoenvironmental records as differences in timing of change are visible and the contributing factors might vary which will become apparent in the forthcoming discussion. It is also important to bear in mind that the chronology of some records such as the Zeribar record are subject to dating uncertainties which impacts the palaeoenvironmental interpretations in terms of timing and thus such records should be used with caution.

9.2 Climate history

9.2.1 Late Pleniglacial (17,700-14,700 yrs BP)

The results of this study have shown a higher level of climatic variability and complexity in the Pleistocene compared to the succeeding Holocene. Based on the recorded high values of Amaranthaceae and *Artemisia* as well as the presence of *Cousinia* (a cold-adapted plant), both Hashilan wetland and Lake Ganau experienced dry and cold climatic conditions during the Late Pleniglacial period.

Figure 9-3: Location of archaeological sites (yellow circle) and palaeoenvironmental records (red circle) mentioned in this section (author's own)

Using a multi-proxy approach at Hashilan wetland has enabled the identification of periods that were marked by enhanced dust input between 24,500-24,100 yrs BP, 23,400-22,800 yrs BP, 22,300-22,700 yrs BP, 21,100-19,200 yrs BP, and 18,400-16,800 yrs BP. As no other proxy data is available for Hashilan wetland for the time interval 24,500-17,700, except the geochemical data, no other inferences can be made except that it was dusty during the above mentioned intervals. These dusty events could be related to the dry climatic conditions identified in the oxygen isotope record of Lake Zeribar and the geochemical record of Lake Van which will be discussed below (Stevens *et al.* 2008; Çağatay *et al.* 2014). High values of Rb/K ratio in the Jazmurian playa multi-proxy record (southeast Iran) also indicate two episodes of increased aeolian activity (arid conditions) at ~19,000 and 16,800 yrs BP (Vaezi *et al.* 2019: 765), which overlap with the periods of enhanced dust input identified at Hashilan wetland between 21,100-19,200 yrs BP and 18,400-16,700 BP, respectively.

The driest interval identified in the Zeribar record occurred between 16,300-15,300 yrs BP which has been linked to Heinrich event 1 (Stevens *et al.* 2008; Wasylikowa *et al.* 2008: 313). At Hashilan wetland, however, no elevated dust values can be noted between 16,300-15,300 yrs BP. Instead, an interval of increased dust input has been identified between 15,300-14,200 yrs BP which correspond to high Amaranthaceae and *Artemisia* values, and low Poaceae values, indicating drier climatic conditions.

The micro- and macrocharcoal data of Hashilan wetland also do not indicate a period of increased fire activity between 16,300-15,300 yrs BP which suggests reduced aridity. At Lake Ganau as well, no evidence for enhanced dry climatic conditions could be identified in the lake level record. Periods of low lake levels instead have been identified between 19,200-19,150 yrs BP, and 18,500-18,400 yrs BP, and periods of high water levels between 19,950-19,350 yrs BP, 19,080-18,800 yrs BP, and 17,650-17,300 yrs BP. It is important to bear in mind, however, that low water levels may not necessarily indicate a decline in precipitation levels but could also reflect episodes of increased evaporation related to increased temperature, or a combination of both (Precipitation: Evaporation balance).

From a wider regional perspective, a cold peak has been identified at ~16,500 yrs BP in the oxygen isotope record of Soreq cave (Bar-Matthews *et al.* 1999) and low lake levels have been identified in the Dead Sea between 17,400-16,000 yrs BP (Stein *et al.* 2010). The geochemical record of Lake Van also indicates a period of cold and dry climate along with low lake levels between 33,500-14,500 yrs BP (Çağatay *et al.* 2014). The Soreq cave and Dead Sea data, specifically, overlap with the Heinrich event 1 (~16,800 yrs BP) (Bond *et al.* 1992; Bond *et al.* 1993). The dust interval between 18,400-16,700 yrs BP identfied at Hashilan wetland could, thus, also be related to the Heinrich event 1. An increase in local fire has also been noted during this interval peaking at ~17,600 and 17,250 yrs BP, possibly linked to climate aridity rather than human activity. The reason why the Lake Zeribar record indicates a slightly later date for the Heinrich event 1, in comparison to the above mentioned records and Hashiland wetalnd, could be related to dating uncertainties. It has been pointed out by Stevens *et al.* (2008), for instance, that there is a likelihood that there is a 2000- year offset that has been identified at 26,000 yrs BP. Based on the oxygen isotope data of Lake Zeribar, enhanced aridity did not occur during the Last-Glacial Maximum (~24,000 yrs BP) but instead occurred at ~26,000 yrs BP. This 2000-year offset may be a result of the chronological uncertainties (Stevens *et al.* 2008: 295-296), including hard-water effect. Since the hard-water effect does not remain constant over time, it can be argued that the dry interval that has been correlated to Heinrich event 1 is also slightly offset in the Zeribar record. This would explain why this dry interval has not identified in the geochemical and fire record of Hashilan wetland. There is, however, also a possibility that the absence of dry climatic conditions between 16,300-15,300 yrs BP could also be related to the uncertainties of the age-depth model of Hashilan wetland (see section 9.1).

9.2.2 Lateglacial Interstadial and stadial (14,700-11,700 yrs BP)

The Lateglacial Interstadial and stadial have been identified at Lake Zeribar between 15,000-12,600 yrs BP and 12,600-12,000 yrs BP, respectively, which varies both in timing and duration from the Greenland ice core records (Wasylikowa *et al.* 2008). At Lake Zeribar, the Lateglacial Interstadial is expressed as increase in effective moisture (based on oxygen isotope data) and likely increase in temperature as indicated by the diatom and charophyte data. The Lateglacial Stadial, in contrast, is expressed as arid conditions (low effective moisture, low water levels and increased water salinity)(Wasylikowa *et al.* 2008: 314-315). According to the Greenland data, the Lateglacial Interstadial (GI-1) and stadial (GS-1) occurred between 14,700-12,900 yrs BP and 12,900-11,700 yrs BP, respectively (Rasmussen *et al.* 2014). This discrepancy in both the timing and duration could be related to radiocarbon dating uncertainties at Lake Zeribar. There is, however, also the need to consider the possibility that although a teleconnection between North Atlantic climate and Southwest Asia exists, the timing might vary across regions that is connected partly to the sensitivity of the climate proxy used to detect change.

At Hashilan wetland, a period of enhanced dust input has been identified between 15,300-14,200 yrs BP, which coincides with the start date of the Lateglacial Interstadial at Lake Zeribar and overlaps with a decline in oxygen isotope values identified between 15,200-14,200 yrs BP (Wasylikowa *et al.* 2008: 314). Peaks in macrocharcoal at ~15,200 yrs BP and ~14,500 yrs BP, as well as increase microcharcoal percentage suggest that the period of enhanced dust input between 15,300-14,200 yrs BP was dusty as well as dry. Furthermore, neither the pollen record of Hashilan wetland nor the Poaceae/*Artemisia* ratio, which is indicative of moisture availability, suggest an increase in temperatures or increase in moisture availability starting at either 15,200 or 15,000 yrs BP. Based on the pollen data from Hashilan wetland, however, a change in the vegetation composition, started to occur from ~14,700 yrs BP onwards with Poaceae starting to increase while *Artemisia* and Apiaceae start to decline. Similar changes in the vegetation cover have been noted at Lake Zeribar (Van Zeist 2008: 79) during the Lateglacial Interstadial including *Pistacia* re-establishing itself in the area which, however, has not been noted at Hashilan wetland. This suggests that the climatic preconditions for *Pistacia* were not met in the Hashilan area and climatic conditions remained relatively arid inhibiting tree growth (see section 9.1 for alternative hypothesis to explain absence of trees in the Lateglacial Interstadial at Hashilan wetland associated with the chronology). Based on the vegetation changes outlined, it can be argued that the Lateglacial Interstadial started at ~14,700 yrs BP at Hashilan wetland which coincides with the start of the Greenland Interstadial 1 (~14,700 yrs BP) (Rasmussen *et al.* 2014). The absence of trees (such as *Pistacia* and *Quercus*) during the Lateglacial Interstadial suggests that climatic conditions remained dry during the interstadial which has also been argued for the Lake Neor region between 15,500-12,500 yrs BP based on the pollen and chironomid data (Aubert *et al.* 2017). Due to the high degree of uncertainty with the chronology before ~13,000 yrs BP, the interpretation of the climatic conditions during the Lateglacial Interstadial, however, remains open for discussion until further radiocarbon dates are obtained for the Lateglacial and Late Pleniglacial.

Another interval of enhanced dust input has been identified at Hashilan wetland between 13,200-12,700 yrs BP, which corresponds to the oxygen isotope peak between 13,500-12,700 yrs BP in the Lake Zeribar record (Stevens *et al.* 2008: 292) suggesting dry climatic conditions. Furthermore, microcharcoal percentage is high between ~13,500-12,400 yrs BP which coincides with an increase macrocharcoal counts between 13,500-12,650 yrs BP. Both the local and regional fire signal, thus, overlaps with the dust event between 13,200-12,700 yrs BP, providing evidence that this interval was likely a result of climatic aridity as no human signal is visible in the pollen record. This dry interval within the Lateglacial Interstadial has also been identified in the Lake Neor dust record between13,500-12,500 yrs BP as an increase in dust influx (Sharifi et al. 2015). The question arises whether this dry and dusty interval corresponds to the Lateglacial Stadial or is part of the Lateglacial Interstadial. In the geochemical record of Jazmurian playa in south-eastern Iran the start of the Lateglacial Stadial has been identified at ~13,200 yrs BP (Vaezi *et al.* 2019). Furthermore, in the $\delta^{18}O$ record of Soreq Cave, the Lateglacial Stadial has been identified dating between 13,200-11,400 yrs BP (Bar-Matthews *et al.* 1999: 90). The onset of dry and dusty climatic conditions at Hashilan wetland, thus, are in agreement with the Soreq cave oxygen isotope data and the Jazmurian geochemical record, although the precise duration of the dry conditions varies. It can, therefore, be argued that the Lateglacial Stadial started at ~13,200 yrs BP based on the geochemical data of Hashilan wetland. However, the geochemical and pollen data of Hashilan wetland are in contradiction in terms of the timing of the Lateglacial Stadial, which will be discussed below.

According to the Lake Zeribar data, besides an increase in oxygen isotope values, dry steppe Amaranthaceae and *Artemisia* increased and, low and fluctuating water level were prevailing along with increased water salinity, which suggests climatic aridity between 12,600-12,000 yrs BP. At Hashilan wetland, the pollen record also indicates an increase in Amaranthaceae and *Artemisia* along with a decline in Poaceae, which appears to be in agreement with the pollen data of Lake Zeribar and thus the onset of the stadial can be argued took place at ~12,600 yrs BP based on the pollen data of Hashilan wetland. Asteraceae and Cichoriaceae also increase rapidly from 12,600 yrs BP onwards, which could reflect conditions that can be associated with the desiccation of the wetland, possibly related to the impact of dry climatic conditions. The discrepancy between the geochemical and pollen data can be explained by arguing that it took approximately 600 years for the vegetation to respond to the drier climatic conditions that started at 13,200 yrs BP. Alternatively, it can be argued that this dry interval between 13,200-12,700 yrs BP is not the Lateglacial Stadial signal but rather is a dry sub-interval within the Lateglacial Interstadial, which is likely to be the case.

By contrast, the transition from Late Pleniglacial to Lateglacial Interstadial, and Lateglacial Interstadial to Lateglacial Stadial at Lake Ganau is less clear. Both the pollen and the geochemical data suggest that climatic and environmental conditions remained fairly constant and stable during these periods. A slight increase in Poaceae and Poaceae >40micron along with an increase in plant diversity is recorded from 15,200 yrs BP onwards, which may reflect slightly ameliorating climatic conditions connected to the onset of the Lateglacial Interstadial. A general decline in plant diversity, which includes a decline in *Pistacia* and *Quercus* tree population, the disappearance of *Acer* from the landscape, a reduction in grasses, and the increase in Amaranthaceae and *Artemisia* seem to point towards conditions that were characterised by increased aridity at Lake Ganau starting ~12,800 yrs BP. *Prosopis farcta*, which favours warmer temperature also disappears from the landscape during this time possibly due to colder climatic conditions that are associated with the stadial period.

Based on high Mn/Fe, high S/cps and low Rb/K values, high lake levels were present between 12,900-12,650 yrs BP, which, decreased between ~12,650-12,400 yrs BP possibly linked to a shift towards drier climatic conditions. Both the Hashilan wetland as well as Lake Zeribar pollen records indicate the onset of dry climatic conditions at 12,600 yrs BP. It can, therefore, be argued that the onset of the Lateglacial Stadial at Lake Ganau was also at ~12,650 yrs BP. The potentially wet interval documented at Lake Ganau between 12,900-12,650 yrs BP may correspond to the southward shift in Mid-latitude Westerly Jets, which brought in more atmospheric moisture to the region (Sharifi *et al.* 2018), leading to higher water levels at Lake Ganau (Figure 9-4). An increase in water levels has also been identified in the Dead Sea between 13,200-11,100 yrs BP, although it was longer in duration (Stein *et al.* 2010). At Hashilan wetland, a slight increase in Poaceae/*Artemisia* has also been identified between 12,900-12,000 yrs BP which could also be related to the Mid-latitude Westerly Jets. The Lake Van data shows a contrasting view, indicating a drop in lake level and dry and cold climate during the Lateglacial Stadial (Wick *et al.* 2003; Çağatay *et al.* 2014). No increase in dust input is visible for the Lateglacial Stadial at Hashilan wetland, which however, could be related to a potential change in dust source (Sharifi *et al.* 2018), which needs to be investigated further.

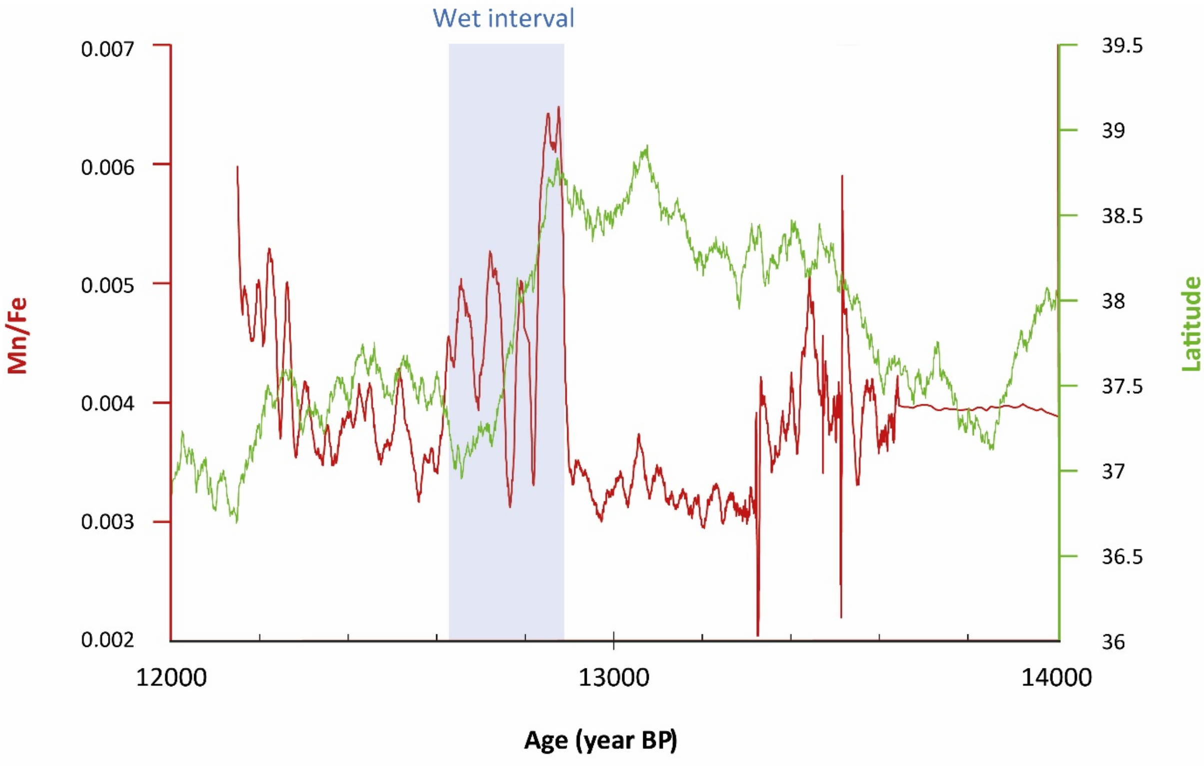

Figure 9-4 Lake Ganau lake level (red) mapped against the position of the Mid-latitude Westerly Jets (green) (Sharifi et al. 2018)

Based on the pollen assemblage of Lake Ganau, dry climatic conditions prevailed throughout the Late Pleniglacial and Lateglacial, with a slight climatic amelioration during the interstadial (i.e. warmer and moister conditions), which agrees with the results of the macrobotanical study carried out at the archaeological site of Palegawra as well as the pollen analysis of the layer B2 sample from Shanidar cave, which indicate the presence of trees during the Late Pleniglacial (for example: 6% *Quercus* pollen percentage and 1% *Pistacia* pollen percentage) (Wahida 1981; Asouti *et al.* 2020). Although the pollen study of Shanidar cave is unreliable and suffers from multiple issues including pollen preservation, chronological uncertainties, and low sampling resolution, it does verify the spread of tree populations in the landscape of the Late Pleniglacial (B2 layer) in the western Zagros region. The pollen and macrobotanical analyses of the records from Lake Ganau, Shanidar cave, and Palegawra, thus, provide important data that climatic conditions slightly differed from the eastern Zagros region (i.e. higher moisture availability in the western Zagros), where evidence for trees such as *Pistacia* is visible from Lateglacial Interstadial onwards.

9.2.3 **Holocene climate history**

Early Holocene (11,700-8200 yrs BP)

From 12,100 yrs BP onwards, only the pollen and geochemical results of Hashilan wetland are available to determine and discuss the dynamics of climate variability during the Holocene period.

At Lake Zeribar, the following vegetation changes suggest an increase in temperature and moister climatic conditions at the onset of the Early Holocene: Amaranthaceae and *Artemisia* declined, Poaceae increased rapidly, and trees started to expand in the area (Wasylikowa *et al.* 2008: 315). During the Early Holocene, moisture availability was likely dependent on the position of the subtropical westerly jet and the westerly disturbances (Sharifi et al. 2015; Sharifi et al. 2018). The start of the Holocene at Hashilan wetland at ~11,500 yrs BP is also characterised by a decline in dry steppic plants Amaranthaceae and *Artemisia*, and increase in grasses, although Amaranthaceae remained high until ~10,200 yrs BP despite a decline. The increase in grasses at the start of the Holocene could represent a key marker for change in seasonality from a system based on winter-dominated precipitation to possibly winter and spring/summer precipitation. The regional burning signal becomes more stable and higher during the Holocene period, from ~11,350 yrs BP onwards, when the landscape changes into a grass dominated steppe which might have acted as a fuel source to fire (Turner *et al.* 2010). Slightly increasing values of Poaceae/*Artemisia* ratio and low dust input provide further evidence in favour of slightly increasing moisture availability. The increase in moisture, however, appears to not have been high enough to allow the expansion of trees at Hashilan wetland. *Quercus brantii Lindl*., which is the most xerophilous oak species found in the region, requires spring precipitation for regeneration purposes and is sensitive to the effects of a long dry summer season (El-Moslimany 1986). A short-lived dry season, hence, favours the expansion of *Quercus brantii*. which would be possible through an increase in the growing-season precipitation and short-lived dry season (increase in either spring or summer precipitation) (Djamali *et al.* 2010a: 816-817).

Since at Hashilan wetland, *Quercus* does not appear in the landscape at the start of the Early Holocene it suggests that conditions were probably still not moist enough to stimulate tree expansion despite climate having changed to potentially wetter and more moist conditions after the preceding dry Lateglacial Stadial. Djamali *et al.* (2010) proposed a model according to which the northward migration of the ITCZ and the strengthening in the intensity of the Indian Summer Monsoon in the Early Holocene led to the formation of a stable, high-pressure system over north-western regions of Iran. This development led to an impact on the existing system of precipitation seasonality, changing it from spring-dominated to winter-dominated climate and thereby causing an increase in the duration of dry summer months. This impact resulted in the formation of a typical continental Mediterranean-type climate over western Iran, and the seasonality pattern could explain why *Quercus* expansion did not occur in the Early Holocene.

A major rapid intensification in the Indian Summer Monsoon has been identified between 10,500-9,500 yrs BP in the oxygen isotope record from southern Oman, which provides evidence for the northward migration of the ITCZ, with reduced monsoon precipitation levels chronologically coinciding with the Greenland cooling events at 9.3 and 8.2 ka BP (Fleitmann *et al.* 2003; Fleitmann *et al.* 2007). The geochemical data for Hashilan wetland indicate a drop in water levels between 10,700-9400 yrs BP along with an increase in dust input and magnetic susceptibility, which peak at ~10,200 yrs BP. The geochemical data, thus, indicates a potential correlation between the strengthening in the intensity of the Indian Summer Monsoon, and the water level and dust input at Hashilan wetland during the Early Holocene (10,700-9400 yrs BP).

The pollen data of Hashilan wetland supports the interpretation of the geochemical data: Poaceae increases from 11,500 yrs BP onwards and continues to do so until 10,900 yrs BP, which is a time when slightly dry and dustier climatic conditions start. Amaranthaceae also remains relatively high until ~10,200 yrs BP. Climatic conditions, however, improved from ~9200 yrs BP onwards with Poaceae increasing again, possibly reflecting an increase in moisture availability, which is confirmed by the recorded increase in the Poaceae/*Artemisia* ratio from ~9200 yrs BP onwards specifically between 9000-8280 yrs BP and ~7150-6500 yrs BP. The *Quercus* pollen curve also changes and becomes somewhat continuous (although still low in values) from ~8600 yrs BP onwards. These developments suggest that we are possibly witnessing a slow transformation in terms of a change in the climate (i.e. increase in effective moisture) as *Quercus* requires high effective moisture levels. The role of human activity in the expansion of *Quercus*, however, cannot be ruled out (Roberts 2002; Asouti and Kabukcu 2014). Wetter and less dusty climatic conditions have also been identified in the geochemical record of Lake Neor between 9000-6000 yrs (Sharifi et al. 2015) and at Katalekhor cave between 9500-7000 yrs BP based on the isotope data (Andrews *et al.* 2020). The weakening in the intensity of the Indian Summer Monsoon and the shift of the ITCZ southwards could explain the onset of wetter climatic conditions (Djamali *et al.* 2010a). Along with the southward movement of the ITCZ, especially after 6300 yrs BP, the position of the Northern Hemisphere Summer Westerly Jets also moved southward over time, which would have led to an increase in the amount of precipitation in spring seasons coming from the Mediterranean and the Black Sea (Fleitmann *et al.* 2003; Fleitmann *et al.* 2007; Djamali *et al.* 2010a).

The recorded increase in dust input between 10,700-10,200 yrs BP at Hashilan wetland, was smaller in magnitude in contrast to the documented Pleniglacial and Lateglacial dust inputs. According to Sharifi et al (2018), the dust input recorded at Lake Neor was characterised by changes in the dust source during the Early Holocene as a result of the southward movement of the Northern Hemisphere Summer Westerly Jets (NHSWJ). This shift caused a reduction in the transport of African dust to Western Asia and, as such, the provenance of the dust coming mainly from Mesopotamia and Central Asian sources during the Early Holocene (in low amounts). This shift in dust source might also be the reason why the dust input in the Early Holocene at Hashilan wetland is lower in magnitude in comparison to the preceding periods. The peak at ~10,200 yrs BP could also be related to the 10.2 ka RCC event, which has been identified in GISP2 nss [K^+] record at ~10,277 yrs BP (Weninger *et al.* 2009: 14-15), indicating a correspondence between the record of Hashilan wetland and Greenland ice record.

In summary, the Hashilan wetland pollen and geochemical data provide an important insight into the 'Early Holocene precipitation paradox' (see Chapter 2:): The Hashilan data indicates that climatic conditions were wetter and less dusty at the start of the Early Holocene compared to the Lateglacial, lasting approximately for 600 years. From ~10,700 yrs BP to 9400 yrs BP, climatic conditions appear to have changed to a slightly drier climate, potentially linked to the strengthening in the intensity of the Indian Summer Monsoon, as evidenced by the increase in dust input, the decline in water levels, and the trend in Poaceae values outlined earlier. From 9200 yrs BP onwards, an increase in moisture can be detected in the pollen and geochemical record. As such it becomes clear that the Early Holocene period was characterised by a series of complex processes. There is evidence of wet climatic conditions, which were punctuated by an interval of less favourable climatic conditions between 10,700-9400 yrs BP (peaking at ~10,200 yrs BP), probably leading to effective moisture deficiency, which, in turn, hindered tree expansion in the region. The Dead Sea lake level record also indicates a drop in lake level between ~11,000-10,000 yrs BP (Stein *et al.* 2010), followed by a period of increased moisture availability between 10,000-8600 yrs BP (Migowski *et al.* 2006). Other records which indicate a wet Early Holocene are the oxygen isotope records of Eski Acıgöl and Lake Van (Jones and Neil Roberts 2008; Çağatay *et al.* 2014).

<u>Climatic events: 11.4 ka, 9.3 ka, and 8.2 ka events</u>

The signal for the 11.4 ka climatic event appears not to have been picked up by the pollen or geochemical record of Hashilan wetland. Similarly, this cold and dry climatic event, that has been identified in the Greenland ice record, has also not been identified in any other environmental records of this region. One exception is the peat bog record of the site of Konar Sandal in south-eastern Iran, where an increase in lithogenic elements has been interpreted to represent an increase in dryness. Likewise, as far as the 9.3 ka and 8.2 ka climatic events are concerned, no increase in dust input has been noted at Hashilan wetland. The Poaceae/*Artemisia* ratio, in contrast, indicates a sharp drop in moisture availability between ~9430-9200 yrs BP and 8280-7700 yrs BP, which overlaps with the timing of the Greenland ice core data of 9350-9240 yrs BP and 8300-8236 yrs BP, respectively. While the 9.3 ka event has not been identified in any other records from Iran, the 8.2 ka event has been identified positively in the Jazmurian playa and at Konar Sandal bog records based upon enhanced aeolian dust particles, while the Dead Sea lake level record identified two abrupt arid events at 8600 and 8200 yrs BP (Migowski *et al.* 2006). Both climatic events were also identified at Nar Lake (Turkey) between ~9460-9150 yrs BP and 8500-8200 yrs BP (Dean *et al.* 2015).

Since the duration of these two climatic events appears to be longer at Hashilan wetland when compared to the Greenland ice core record, it is possible that additional controls and processes were affecting the hydroclimatic regime. Furthermore, since the 9.3 ka and 8.2 ka events are not visible in the dust record, it can be inferred that both climatic events perhaps were not as severe or that vegetation is more sensitive in picking up climatic changes. The decline in moisture availability, between ~8280-7700 yrs BP, has also been captured by the $\delta^{13}C$ record of Katalekhor cave (between 8300-7700 yrs BP), which has been attributed to an increase in the Siberian high-pressure system (Andrews *et al.* 2020). Due to the long duration of this event (~8300-7700 yrs BP) in the $\delta^{13}C$ record of Katalekhor cave, Andrews *et al.* (2020) suggested that the 8.2 ka event was potentially superimposed on a broader pre-existing dry RCC climate event. Since the interval of low moisture availability at Hashilan wetland also has a long duration, it was potentially part of the 9000-8000 yrs BP RCC climatic event (Mayewski *et al.* 2004; Rohling and Pälike 2005; Rohling *et al.* 2019). In contrast, the Soreq Cave oxygen isotope record indicates an increase in precipitation between 8500-7000 yrs BP with a short-lived cooling event between 8200-8000 yrs BP (8.2 ka event) superimposed on the wet interval (Bar-Matthews *et al.* 1999: 91).

In summary, the dust record of Hashilan wetland did not identify the presence of the dry and cool 11.4 ka, 9.3 ka and 8.2 ka climatic events identified in the Greenland ice record at 11,520-11,400 yrs BP, 9350-9240 yrs BP, and 8300-8236 yrs BP. The Poaceae/*Artemisia* ratio, in contrast, identified periods of reduced moisture availability, i.e. dry climate, between ~9430-9200 yrs BP and 8280-7700 yrs BP, with the latter one likely connected to the 9000-8000 yrs BP RCC event. As can be seen, the timing of the 8.2 ka event varies across sites, with some of the records indicating that it was superimposed on either a wet or dry interval that started at ~8500 yrs BP. This highlights the complexity associated with the 8.2 ka climatic event and the fact that the interval 8600-7000 yrs BP can vary in the way it Is expressed.

Middle Holocene (8200-4200 yrs BP)

In general, climatic conditions were relatively wet at Hashilan wetland from 9200 yrs BP onwards as indicated by the low dust input, and high Poaceae/*Artemisia* ratio. At Lakes Zeribar and Mirabad, the onset of wetter climatic conditions start from ~6500 yrs BP onwards, which are believed to be a result of a shift in the precipitation seasonality from winter-dominated to winter/spring dominated, which allowed *Quercus* woodland to form in the Zeribar area (Stevens *et al.* 2001). The increase in *Quercus* in the Hashilan wetland pollen record at ~5900 yrs BP, thus, could also be related to seasonality changes i.e. increase in spring precipitation and reduction in the dry season. A slight increase in Poaceae/*Artemisia* values is noted to have occurred between ~6100 - 5900 yrs BP, suggesting an increase in moisture availability prior to the *Quercus* expansion in the Hashilan wetland record.

A gradual increase in dust input at Hashilan wetland can be observed from ~6000 yrs BP onwards suggesting that climatic conditions were yet again going through a transformation. An increase in local biomass burning occurs between 5900-2900 yrs BP which could be related to dry climatic conditions and/or human activity. This gradual rise in dust input could be related to the shift in dust source identified by Sharifi *et al.* (2018) at ~6000 yrs BP, where dust was being transported from both western Asia and north-eastern Afri~ Besides possibly showing a change in dust source, it may also reflect a change towards a drier Middle Holocene. The Poaceae/*Artemisia* ratio, although higher compared to the Early Holocene values, also starts to decline from ~6500 yrs BP onwards, which is indicative of a decline in moisture availability. Both the Lake Zeribar and Mirabad oxygen isotope records provide evidence for the onset of a severe dry interval between 5600-5000 yrs BP, which has been interpreted as a regional climatic event since it has been identified at both sites occurring at the same time (see Chapter 2) (Stevens *et al.* 2006). The Hashilan wetland data supports this interpretation, with an interval of low moisture availability identified between ~5900-5300 yrs BP based on the Poaceae/*Artemisia* ratio. This short decline in moisture availability, however, is part of an already drying climate that started from ~6000 yrs BP onwards, lasting until ~3000 yrs BP. The change towards a drier Middle and Late Holocene period is also confirmed by the data of the Lake Neor dust record, which indicates drier climatic conditions from ~6000 yrs BP onwards (Sharifi et al. 2015; Alinezhad et al. 2021). It is also recorded and visible in the oxygen isotope record of Katalekhor cave (between ~6600-4500 yrs BP) as well as the geochemical record of Jazmurian playa (between ~6000-5000 yrs BP) (Vaezi *et al.* 2019: 764). Based on the record of Lake Neor, dust input remains largely low during the Early Holocene, while the succeeding Middle and Late Holocene period is characterised by longer and more frequent dust events, in agreement with the Hashilan wetland data (Sharifi et al. 2015; Sharifi et al. 2018).

Within the dusty period identified at Hashilan wetland between ~6000-3000 yrs BP, two intervals of enhanced dust input have been noted between ~5300-4100 yrs BP and 4050-3900 yrs BP with the latter one stronger in magnitude. The dust input between 5300-4100 yrs BP overlaps with a drop in lake level at Lake Maharlou between 5100-4000 yrs BP along with a decline in *Pistacia–Amygdalus* shrub, suggesting drier climatic conditions as well as in the Gorgan Plain (northeast Iran) between 5300-4000 yrs BP (Shumilovskikh *et al.* 2016a: 1687) and the Dead Sea lake level record between 5300-5100 yrs BP (Migowski *et al.* 2006).

In contrast, records from the Eastern Mediterranean indicate an opposite trend with climate conditions being wet, based on pollen and Dead Sea lake level data with the pollen evidence indicating a wet period between 6300-3300 yrs BP while the lake level record indicates a wet phase between 5600-3500 yrs BP (Migowski *et al.* 2006; Litt *et al.* 2012). The Lake Van record pollen record as well indicates a period of optimum climatic conditions (low water salinity and high lake level) between 6200 and 4000 yrs BP (Wick *et al.* 2003).

Late Holocene (4200 yrs BP to the present day)

The start of the Late Holocene period is characterised by an abrupt climatic event, known as the 4.2 ka event, that has been identified in several records (see summarised in Table 9-2). including at Red Sea (~4000 yrs BP)(Arz *et al.* 2006), Gulf of Oman (~4025 yrs BP) (Cullen *et al.* 2000), Lake Iznik (4400-4200 yrs BP) (Ülgen *et al.* 2012), Tecer Lake (4200-3750 yrs BP) (Kuzucuoğlu *et al.* 2011), Dead Sea (~4300-4000 yrs BP) (Migowski *et al.* 2006), and Soreq cave (4100-4000 yrs BP)(Bar-Matthews *et al.*1999). The evidence for the presence of this climatic event is not limited to the wider geographical region but also found in Southwest Asia with the timing also varying across sites. Enhanced aeolian input indicative of the 4.2 ka event has been identified at Jazmurian playa, Lake Urmia and Lake Neor at ~4200 yrs BP (Vaezi et al. 2019; Haghipour et al. 2020; Sharifi et al. 2015). At Gol-e Zard Cave, in contrast, the oxygen isotope record and Mg/Ca ratio indicate two intervals of increased dust influx and aridity between 4510-4400 yrs BP and 4260-3970 yrs BP (Carolin *et al.* 2019). Similarly, two intervals of enhanced dust input have been identified at Hashilan wetland between ~5300-4100 yrs BP and 4050-3900 yrs BP, while the Poaceae/*Artemisia* ratio indicates a decline in moisture between 4500-4100 yrs BP and 4035-3220 yrs BP. Although dry climatic conditions were prevailing during the 4.2 ka event based on both the dust input and the Poaceae/*Artemisia* ratio, peaking at ~3900 yrs BP, it was part of a longer climatic event. This has also been identified at sites such as Soreq cave and Jeita cave where the 4.2 ka event was part of a longer drying event that started at ~4500 and 5300 yrs BP, respectively (Bar-Matthews *et al.* 1999; Cheng *et al.* 2015). Regardless, the dry interval identified at Hashilan wetland does overlap with the collapse of the Akkadian empire across Mesopotamia at ~4190 yrs BP (Weiss *et al.* 2012: 184). In summary, intervals of dry climatic conditions have been identified across various sites in the region, although the timing, duration and expression varied. Various reasons can be put forward to explain these differences including dating accuracy, the impact of hard-water effect on the dating of sediment samples, the nature of the proxy used, and the sensitivity of the affected areas in response to a decrease in precipitation patterns (Roberts *et al.* 2011).

Table 9-2: Summary of palaeoenvironmental records showing the 4.2 ka events or dry climatic conditions

Record	**Age (yrs BP)**	**Proxy**	**Reference**
Gulf of Oman	4025± 150	Increase in aeolian dolomite and calcite deposition	Cullen *et al.* 2000
Red Sea	~4000	Increased sea surface salinity and the termination of laminate deposition	Arz *et al.* 2006
Lake Neor	~4200	Enhanced aeolian input	Sharifi *et al.* 2015
Jazmurian playa	~4200	Enhanced aeolian input	Vaezi *et al.* 2019
Lake Neor	4300-3200	Increase in chenopods and a decrease in (A+P)/C ratio; δD values increase to less negative values; increase in Ti abundance and low values of palaeoredox proxies	Alinezhad *et al.* 2021
Lake Urmia	~4200	Enhanced aeolian input	Haghipour *et al.* 2020
Gol-e Zard Cave	4510- 4400 and 4260-3970	Mg/Ca - dust flux identified	Carolin *et al.* 2019
Soreq Cave	~4100 (started from ~4500 yrs BP)	Oxygen isotope	Bar-Matthews *et al.* 1999; Bar-Matthews *et al.* 2003
Jeita Cave	~4200 – located within a longer dry climatic event lasting between 5300-4200 yrs BP	Oxygen isotope	Cheng *et al.* 2015
Katalekhor cave	4300-2000	General increase in $\delta^{13}C$ values along with a reduction in growth diameter	Andrews *et al.* 2020

Lake Zeribar	4000-3500	Increase in *Salix* pollen and detrital minerals, suggesting lowered lake levels	Stevens *et al.* 2001
Lake Iznik	4400-4200	Drop in lake level	Ülgen *et al.* 2012
Tecer Lake	4300-3850	Increase in gypsum-rich sand and drop in lake level	Kuzucuoğlu *et al.* 2011
Dead Sea	4200-3900	Drop is water level and deposition of gypsum laminae	Migowski *et al.* 2006

Based on Hashilan's declining Poaceae/*Artemisia* values and intervals of enhanced dust input, the Late Holocene climate was dry which agrees with a number of palaeoenvironmental records of the region including Nar Lake (4200-1500 yrs BP)(Dean *et al.* 2015), Lake Zeribar (4000-3500 yrs BP)(Stevens *et al.* 2001), Katalekhor cave (4300-2000 yrs BP)(Andrews *et al.* 2020) and Lake Van (from 4000 yrs BP onwards)(Wick *et al.* 2003). From 3000 yrs BP onwards, the dust input at Hashilan wetland starts to decline and an increase in moisture availability is noted indicating a short interval of climatic amelioration between ~3200-2300 yrs BP. During the Late Holocene, evidence of a wet interval is also available from other sites including Lake Neor (~3150-2215 yrs BP), Ganli-Gol (~2850-2650 yrs BP), Lake Almalou (~2900 yrs BP), Lake Maharlou (~3800-2000 yrs BP), Kongor Lake (~2700 yrs BP onwards), and Kuna Ba cave (Djamali *et al.* 2009b; Shumilovskikh *et al.* 2016a; Zavvar *et al.* 2017; Brisset *et al.* 2019; Sinha *et al.* 2019b; Alinezhad *et al.* 2021). In the Kuna Ba oxygen isotope record a short wet interval has been identified between 2925-2725 yrs BP, which peaked between 2800-2690 yrs BP and was followed by the onset of a short dry interval between 2650-2500 yrs BP (termed the Assyrian Megapluvial and Megadrought, respectively) (Sinha *et al.* 2019b). The Poaceae/*Artemisia* ratio indicates a period of higher moisture availability between 3200-2780 yrs BP which overlaps with the Megapluvial. In regard to the Megadrought, the dust record of Hashilan wetland appears to not have picked the short dry event. By contrast, a decline in moisture availability can be seen between 2780 - 2690 yrs BP, which appears to have occurred slightly earlier in time than the Megadrought identified in the Kuna Ba record (2650-2500 yrs BP). This difference in timing between these two records, however, could be related to the precision of the Hashilan wetland age-depth model.

<u>Summary</u>

As can be seen in the above discussion, a great deal of variability and complex dynamics have been noted both in the Pleistocene and Holocene climate. The region is climatically sensitive with a number of complex factors and systems affecting the prevailing climatic conditions including the Siberian anticyclone, the Indian Ocean Summer Monsoon and the Northern Hemisphere Summer Westerly Jet, along with the impact of external forces such as solar irradiance and insolation (Sharifi *et al.*2018;

Sharifi *et al.*2015). Just as there is evidence for shifts happening in dust source areas, changes in moisture availability and in the hydrological systems is documented to have occurred in the region (Sharifi et al. 2015; Sharifi et al. 2018). This highlights the importance of obtaining further palaeoenvironmental records to reconstruct climatic conditions of southwestern Asia, which ultimately will help improve our understanding of the complex processes involved and assess the impact of these changes on human civilisations in the past.

9.3 Human-environmental interactions

In this section we highlight and critically evaluate the impact of changes in the environment and climate on human activity and vice versa, drawing on evidence in the pollen records of Hashilan wetland and Lake Ganau.

Figure 9-5: Location of archaeological sites (yellow circle) and palaeoenvironmental records (red circle) mentioned in this section (author's own - base map: Google maps)

9.3.1 Broad Spectrum Revolution

The Epipalaeolithic period, ~ 20,000-12,000 yrs BP, is marked by a diversification of the human diet, also known as the 'Broad Spectrum Revolution' (BSR). The two main hypotheses, outlined in the Chapter 4, which attempt to explain the context in which the change in Epipalaeolithic diet occurred are: 1) Broadening of the human diet occurred in resource-depleted environments caused by either demographic pressure or environmental deterioration (Stiner 2001; Flannery 1969); 2) Broadening of the human diet occurred in resource-rich environments (Zeder 2012). How does the new evidence from Hashilan and Ganau impact upon the interpretive value of these opposing interpretive frameworks?

Based on the pollen data of Lake Ganau, the environment was characterised by plant diversity and slight climate amelioration during the Lateglacial Interstadial in comparison to the preceding cold and dry Late Pleniglacial period. Epipalaeolithic hunter-gatherer groups, therefore, would have had access to a range of edible plant resources ranging from fruits and nuts (pistachio, juniper), to different species of Brassicaceae (mustard family), Fabaceae (legume/pea family), Poaceae >40 micron (Cerealia type), and Apiaceae (parsley family). For instance, evidence for the consumption of plant resources by Epipalaeolithic communities comes from the site of Palegawra, located 70km south of Lake Ganau, where *Amygdalus* (wild almond) and potentially *Pistacia* nutshells as well as Brassicaceae seeds and Fabaceae have been retrieved, suggesting that these plant resources might have been collected on a regular basis by the inhabitants and thus formed part of their subsistence. Alternatively, it is also possible that the plant material recovered from Palegawra were not consumed by humans but brought into the cave by wild animals. This is, however, less likely to be the case as Asouti *et al.* (2020: 82) point out that similar plant resources have been recovered from Palaeolithic sites in the Eastern Mediterranean region The increasing pollen values of wild grasses in the landscape around Lake Ganau suggest that wild seed may have played an important part in the diet of the Epipalaeolithic communities. Both small and large seeded grasses (Poaceae) were also retrieved from the site of Palegawra indicating the exploitation of grasses by Epipalaeolithic communities (Asouti *et al.* 2020: 67).

Besides the available dryland resources, Epipalaeolithic communities would also have had access to Cyperaceae (sedges) and *Sparganium* (reeds) found in the locality of Lake Ganau. Trees such as *Quercus* (oak), *Salix* (willow), *Fraxinus* (ash) and *Pistacia* (pistachio) attested in the vicinity of Lake Ganau could have also been used as a source of firewood by Epipalaeolithic communities. At Hashilan wetland, by contrast, the choice for source of fuelwood was considerably lower during the Lateglacial Interstadial since trees were scarcely present in the landscape. *Salix* (willow) along with other riparian trees (*Fraxinus*, *Tamarix*) would have been the only source of wood fuel. Based on ethnographic studies, however, Asouti *et al.* (2020: 84), point out that shrubby Amaranthaceae and *Artemisia* are known to be used as a fuelwood source in the Iranian plateau and the lowland plains of Iraq. Despite the slight decline noted in Amaranthaceae and *Artemisia* values during the interstadial, they represent the dominant plant taxa in the upland area of Hashilan wetland, and as such, could have been used as fuelwood source instead. Similar to Lake Ganau, Hashilan wetland and the surrounding vegetation would have provided a great range of plants that could have been gathered to form part of Epipalaeolithic communities' subsistence including Apiaceae (parsley family), Fabaceae (legume/pea family), Brassicaceae (mustard family), and potentially Rhamnaceae (buckthorn family) and *Pistacia* (pistachio) nuts. Wetland plant resources available to hunter-gatherer communities included Cyperaceae (sedges) and potentially *Phragmites* (Poaceae >40micron). Furthermore, the wetland was likely an important habitat for a variety of animal species in the past, as it is in the present day, that could have been exploited by Epipalaeolithic hunter-gatherers and also later by Neolithic communities. At Lake Ganau, the evidence for the continuous presence of indicators of herbivore dung (e.g. *Sordaria-type* and *Coniochaeta*) suggests that the lake was regularly visited by herbivores, which, in turn, would have been become an ideal hunting ground for Epipalaeolithic communities.

The low and sporadic pollen values of Poaceae >40micron detected in the Hashilan wetland pollen record, suggest that wild cereal grasses, in comparison to the western Zagros, probably did not form an important part of Epipalaeolithic subsistence. The sporadic presence of Poaceae >40micron in the Pleniglacial and Lateglacial corresponds to peat units, and thus may reflect evidence of *Phragmites* growth in the wetland rather than being a signal for the presence of wild cereal in the landscape. Since no macrobotanical data from archaeological sites is available for the high/eastern Zagros from the Lateglacial interval, it is difficult to verify and determine the role of wild cereal grain in Epipalaeolithic subsistence. Despite this, the environment would have provided Epipalaeolithic communities, both in the western/low and eastern/high Zagros, access to exploit a range of grasses, legumes, nuts and fruits during the Lateglacial Interstadial, which probably formed part of their plant subsistence. This environment would have allowed these communities to thrive and flourish during the interstadial period. Besides the Palegawra macrobotanical study, the only other site which carried out an archaeobotanical analysis is the cave site of Zarzi. Here, only seeds of *Rhamnus catharticus* were identified (Wahida 1981: 29). This aspect clearly demonstrates the lack of archaeobotanical analysis performed at archaeological sites, which obscures and limits our understanding of human interaction with the environment and the subsistence strategies employed by Epipalaeolithic communities.

In summary, the results of the pollen analysis of Hashilan wetland and Lake Ganau appear to be in agreement with Zeder's (2012) argument that the broadening of the human diet occurred in resource-rich environments. In terms of the climatic conditions during the Lateglacial Interstadial, both the Lake Ganau and Hashilan wetland data indicate a slight climate amelioration period characterising this interval, which not only led to the diversification of plant species in the landscape but also to more stable and warmer climatic conditions at Lake Ganau (based on stable water level and presence of certain plant taxa). At Hashilan wetland, by contrast, although slightly warmer climate conditions were present during the Lateglacial Interstadial, based on the increase in arboreal values, it was also interrupted by a period of dry and cold climatic conditions between ~13,200-12,700 yrs BP. The impact of this dry interval and the Lateglacial Stadial on Epipalaeolithic communities will be discussed below.

9.3.2 The impact of Lateglacial Stadial/ Younger Dryas on Epipalaeolithic communities

The Lateglacial Stadial at Hashilan wetland, based on the pollen assemblage of the site, was a climatically cold and dry interval with less dusty conditions that started at ~12,600 yrs BP. At Lake Ganau, by contrast, it was characterised by a lowering of the water level between 12,650-12,400 yrs BP and a reduction in plant diversity between 12,800-12,400 yrs BP, which suggests the onset of colder and drier climatic conditions. The extent and nature of the impact that these climatic conditions had on settlements in the western and eastern Zagros region is the question that remains open to debate. Based on the archaeological data, the occupation of some sites appears to discontinue during the Lateglacial Stadial while at other sites there is slight evidence for uninterrupted continuation in occupation, such as the site of Haji Bahrami Cave (TB75) located in the Fars region of the southern Zagros (Tsuneki et al. 2007; Tsuneki 2013) (Table 9-3 and Figure 9-6).

Table 9-3: Epipalaeolithic site chronology

Site name	Occupation history – Age (yrs BP)
Shanidar Cave B1 sequence	12,400 (uncertain dating)
Zawi Chemi Shanidar	13,000-12,400 (uncertain dating)
Haji Bahrami Cave	17,000-9500 (secure)
Sheikh-e Abad	11,800-9600 (secure)
Chogha Golan	11,750-9650 (secure)
TB130 (Tang-e Bolaghi region)	12,000-9400 (secure)

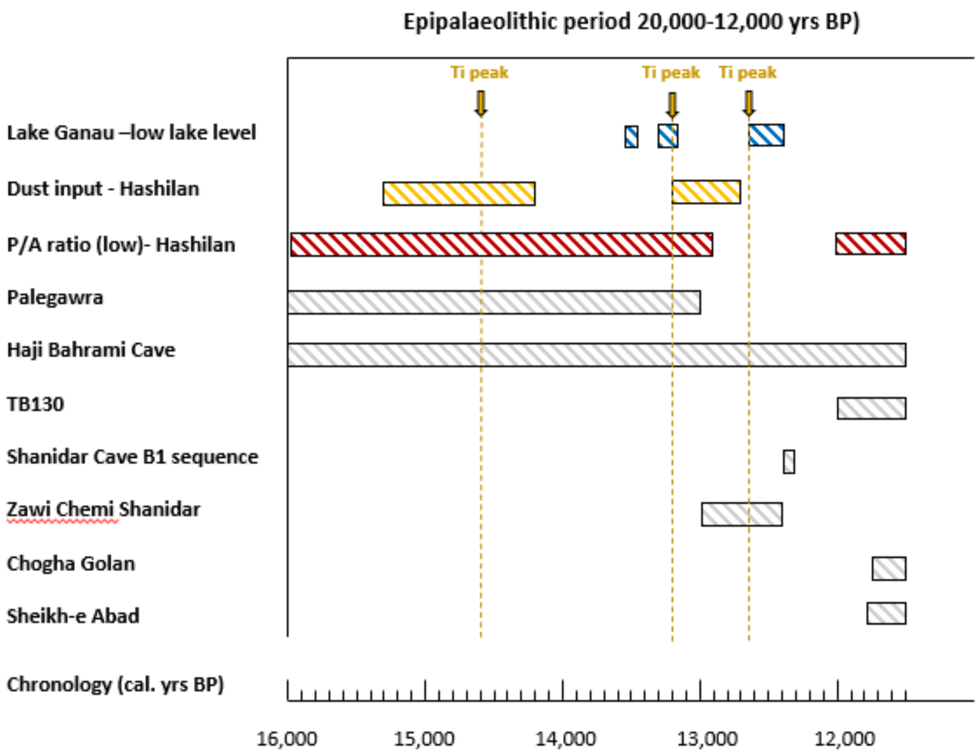

Figure 9-6: Site occupation of Epipalaeolithic and Neolithic sites mapped against Lake Ganau lake level, and Poaceae/Artemisia ratio and dust input of Hashilan wetland (author's own)

The sites of Shanidar cave and Zawi Chemi Shanidar, for instance, are argued to have been abandoned at ~12,400 yrs BP (Solecki 1963; Solecki and Solecki 1983), possibly as a result of the cold climatic conditions. Asouti *et al.* (2020: 6-7), however, point out that the radiocarbon dates of the sites of Shanidar Cave and Zawi Chemi Shanidar suffer from very large standard errors and limited information related to the stratigraphic position of the dated samples is available, which makes the radiocarbon dates unreliable. Gaps and uncertainties in the archaeological record thus make it difficult to investigate the role of climate change on the lives of Epipalaeolithic communities.

The site of Palegawra, by contrast, was abandoned at ~13,000 yrs BP, so before the onset of Lateglacial Stadial (Asouti *et al.* 2020). The abandonment of Palegawra, however, overlaps with the dry period identified between 13,200-12,700 yrs BP in the Hashilan record. There is also evidence that cave sites such as TB130 and TB75 in Fars were occupied during the latter half of the Lateglacial Stadial (Tsuneki 2013; Tsuneki et al. 2007). This fact raises the question whether the cold and dry climatic conditions associated with the Lateglacial Stadial were harsh enough to impact Epipalaeolithic communities. Although the cold and dry climatic conditions identified at Lake Ganau, between ~12,650-12,400 yrs BP, impacted plant diversity, plant resources were only one part of human subsistence at that time (see Garrod 1930; Braidwood and Howe 1960; Solecki 1963; Wahida 1981; Olszewski 2012). The fact that the occupation history of sites such as TB75 continued throughout the Lateglacial, suggests that some Epipalaeolithic communities were resilient to the climatic adversity, at least in the lowland southern Zagros, but much further investigation is required on this issue. It is important to bear in mind that the chronology of numerous archaeological sites is characterised by uncertainties, which makes it difficult to propose and make precise correlations between the palaeoenvironmental and archaeological data.

9.3.3 The Neolithic period – start of cereal cultivation

Based on the analysis of seeds, cereal cultivation in the Zagros region was believed to have started at ~9800 yrs BP (Riehl *et al.* 2013; Riehl 2016). The recent macrobotanical analysis of samples from the archaeological site of Sheikh-e Abad, however, pushes this date a little further back in time to between ~10,230-9730 yrs BP (Whitlam *et al.* 2013: 184). A continuous but low pollen curve for Poaceae >40micron starts in the Hashilan wetland pollen record from ~9800 yrs BP onwards. Due to poor preservation issues, Poaceae >40micron could not be identified to species level. As previously mentioned in section 9.1, however, Poaceae >40micron needs to be interpreted with caution to infer potential links with agricultural activity as these pollen grains also tend to be produced by progenitor wild grass species as well as by naturally occurring grass species (Djamali *et al.* 2009a; Djamali *et al.* 2009b). To determine whether these pollen grains are domesticated grasses, other secondary anthropogenic disturbance indicators need to be present. *Centaurea-solstitialis-type*, a weed of cereal cultivation (Bottema and Woldring 1990), becomes more frequent and increases slightly in the pollen record of Hashilan wetland between 9400-7000 yrs BP, corresponding to part of the Neolithic period. Based on the pollen evidence of Hashilan wetland, therefore, cereal cultivation in the Kermanshah region appears to have started between 9800-9400 yrs BP, which is in agreement with the proposed date for cultivation at both Sheikh-e Abad and Chogha Golan (Riehl *et al.* 2013; Whitlam *et al.* 2013; Riehl 2016). Further evidence for humans manipulating their environment comes from a gradual increase in local biomass burning from ~9600 yrs BP onwards, peaking at ~8300 yrs BP. This trend coincides roughly with the start of cereal cultivation in the Kermanshah region identified at ~9800-9400 yrs BP, which raises the possibility that fire was used by Neolithic communities to create open grassland areas for cultivation. However, the role of climate change cannot be entirely ruled out since the interval between 9600-8300 yrs BP overlaps with both the 9.3 ka and 8.2 ka climatic events, when naturally caused fire events may have been more frequent,

As to the question why did cereal cultivation not start earlier? The dust record of Hashilan wetland indicates that drier climatic conditions prevailed from ~10,700 yrs BP onwards persisting until at least

10,200 yrs BP, which suggests that precipitation was neither sufficiently reliable nor high enough for cereal cultivation in the eastern Zagros region until at least ~9800 yrs BP. Another variable that could explain the start of cereal cultivation between ~9800-9400 yrs BP may potentially be linked to the decline in other plant resources such as Brassicaceae, Apiaceae and Fabaceae from ~10,400 yrs BP onwards as noted in the pollen record of Hashilan wetland. The study of more archaeobotanical samples has the potential to shed light on this aspect in the future.

Nevertheless, the results of this study dismiss the theory put forward by Bar-Yosef (2011) that the Levant region was the 'core area' where the cultivation of wild cereals started and was then introduced to 'secondary centres' including the Eastern Fertile Crescent. Rather, according to the pollen data of Hashilan wetland, cereal cultivation occurred locally in the Zagros region and the reason why cereal cultivation did not start as early as in the western Levant region was potentially related to climatic conditions not being suitable to sustain cultivation. To strengthen this hypothesis, further archaeobotanical data is needed for the Zagros region. Bar-Yosef (2000), further argues that during the Lateglacial Stadial wild cereals were only available in the Levantine region, based on plant material recovered from archaeological sites. The Lake Ganau pollen record clearly indicates the presence of wild cereals in the landscape from the Lateglacial Interstadial onwards, if not earlier, which indicates that Epipalaeolithic communities were exposed to environments that could be manipulated to their advantage if and when needed to cope with environmental degradation and/or increase in population size. Furthermore, the Lake Ganau data indicates that despite a decline in wild cereals in the Lateglacial Stadial, they were still present in the landscape and potentially increased again towards the end of the stadial as evidenced by an increase in the percentage values of Poaceae >40micron. Furthermore, the presence of *Galium* and *Centaurea solstitialis-type,* although low (<1% and 3%, respectively), could suggest that cultivation in the western Zagros region started already in the Epipalaeolithic period – a theory that needs much further investigation. This idea would suggest that there were more than one 'core area' where cereal cultivation started. However, this theory requires more archaeological and palaeoenvironmental work in the western Zagros region.

9.3.4 Impact of climate change on human activity

As discussed earlier, the dust record of Hashilan wetland does not indicate drier and dustier climatic conditions during the 9.3 and 8.2 ka events. Notably, the Poaceae/*Artemisia* ratio indicates a sharp decline in moisture availability between 9430-9200 yrs BP and 8280-7700 yrs BP, which overlaps with the timing of the climatic events. As can be seen in Figure 9-7, the abandonment of Neolithic sites had already started prior to the decline in moisture availability. Neolithic sites also continued to be occupied during the dry climatic conditions between ~10,700-10,200 yrs BP. The pollen data of Hashilan wetland also suggests that cereal cultivation in the region continued without any break until at least ~8100 yrs BP, if not later, based on the presence of *Centaurea solstitialis* and *Galium*. There seems to be no major change in vegetation composition during the 9.3 ka event, while the impact of the 8.2 ka event on the vegetation composition includes a decline in Poaceae >40micron, which increases again after ~7150 yrs BP. Regardless, human communities still continued to have access to resources from both the dryland and wetland areas, and since the abandonment of Neolithic sites does not coincide chronologically with the timing of the climatic events, it is difficult to assess the impact of the 9.3 ka ad 8.2 ka events in relation to the phases of abandonment.

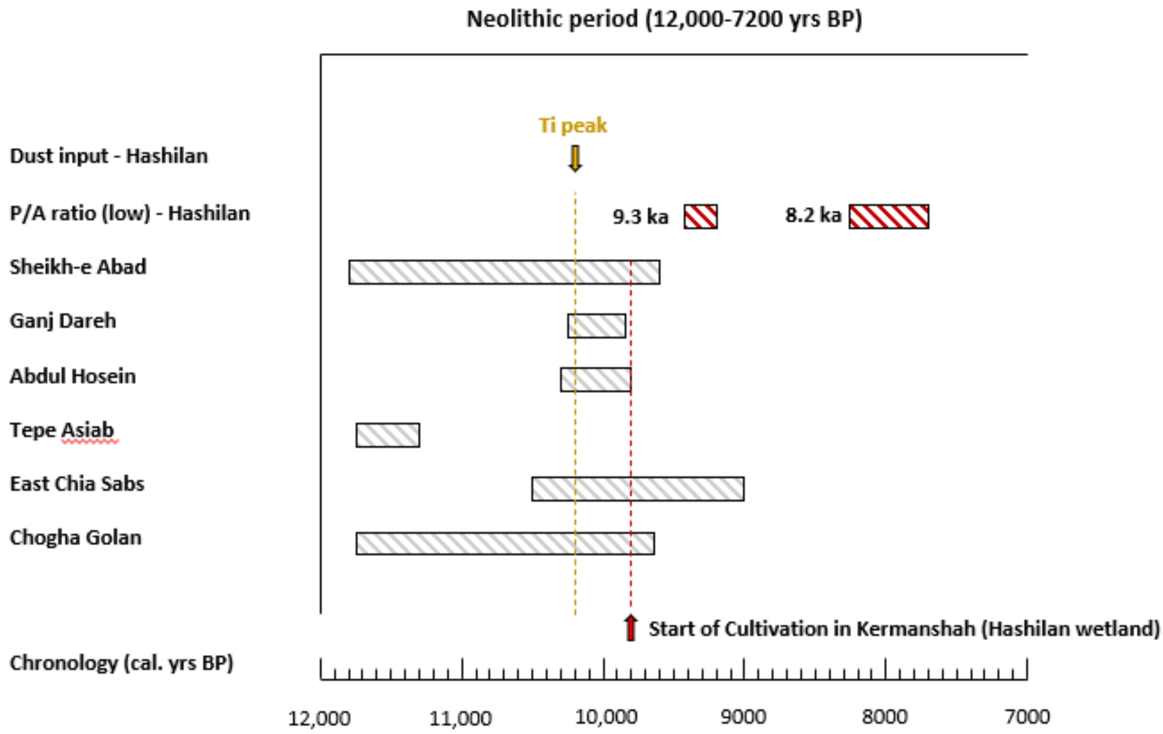

Figure 9-7: Site occupation of Neolithic sites mapped against the dust input and Poaceae/Artemisia ratio of Hashilan wetland (author's own)

Since numerous Neolithic sites had access to the resources of a range of ecological zones and used diverse subsistence practices and strategies, they were probably resilient and adjusted to the effects of the dry 10.2 ka, 9.3 ka and 8.2 ka climatic events (Matthews 2013a: 18; Flohr *et al.* 2016; Matthews *et al.* 2020b: 633). More archaeological evidence is no doubt needed to better understand the impact of the rapid climatic events on Neolithic societies of the region.

While these climatic events, which took place during the Early Holocene, do not overlap with the abandonment of Neolithic sites, the decline in moisture availability between ~5900-5300 yrs BP, during the Chalcolithic period, coincides with changes in settlement patterns (Hopper and Wilkinson 2013). Furthermore, the dry climatic intervals at Hashilan wetland identified between 4500-4100 yrs BP and 4035-3220 yrs (Figure 9-8) overlap with significant changes in the archaeological record of the regions and include the collapse of the Early Trans-Caucasian settlements in Iran (Summers 2014), collapse of the Akkadian empire across Mesopotamia (Weiss 2015), and settlement changes across Iran and Iraq (see Chapter 4)(Sumner 1972; Sumner 2003). However, despite the correlation between drier climatic conditions and changes in the archaeological record, this aspect does not necessarily imply causation. There is, for instance, a possibility that the Gutian invasion might have played a role in the collapse of the Akkadian empire (Miller 2014: 122).

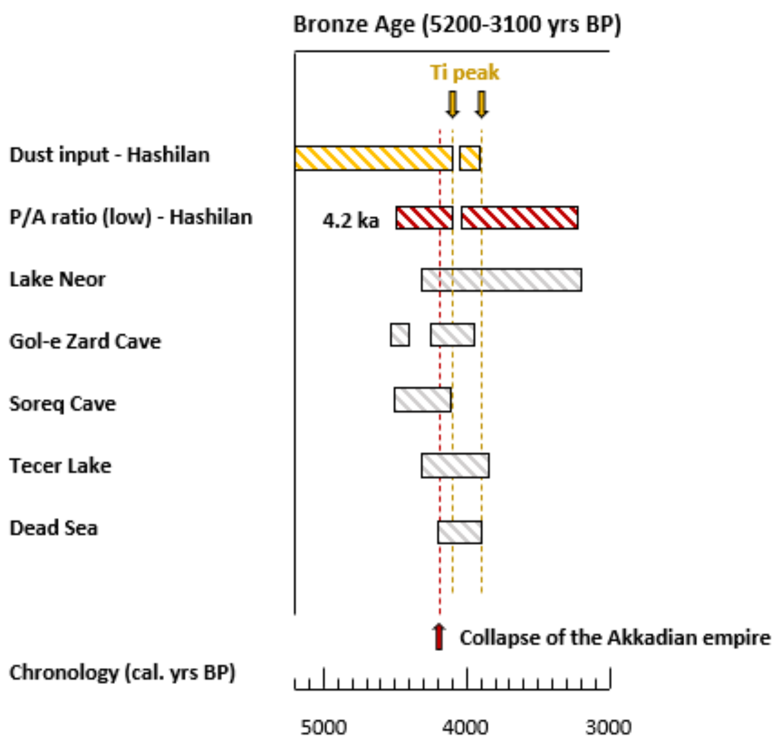

Figure 9-8: Dust input and Poaceae/Artemisia ratio of Hashilan wetland mapped against other palaeoenvironmental records (author's own)

9.3.5 Human impact on the environment - Chalcolithic to Iron Age (7200-2200 yrs BP)

Low-intensity grazing in the environment becomes visible in the pollen record of Hashilan wetland from ~6100 yrs BP onwards by the low and sporadic presence of *Plantago lanceolata-type*. The low presence of *Polygonum aviculare-type* and Plantaginaceae may also suggest anthropogenic disturbances in the landscape such as livestock trampling and overgrazing (Djamali *et al.* 2009b; Leroy *et al.* 2013). Whether the increased presence of these taxa, which are indicative of grazing activities, is a response to the drying climate trend that started at ~6000 yrs BP is difficult to assess since the grazing signal is low. Coprophilous spores (*Sordaria-type* and *Sporormiella-type*) indicative of herbivore presence are very low in the pollen record of Hashilan wetland, starting to appear sporadically from ~7300 yrs BP onwards, which coincides with the start of the Chalcolithic. There is evidence in the archaeological record that Chalcolithic communities might have had a stronger emphasis on animal herding and that potentially this cultural period was characterised by the development of some type of pastoralism, although this interpretation is hotly debated (Potts 2014).

Poaceae >40micron increases from ~5400 yrs BP onwards, peaking at ~4100 yrs BP, which could be indicative of cereal cultivation as *Galium-type*, an arable weed, starts to increase from 4100 yrs BP onwards. *Centaurea solstitialis-type*, however, is only sporadically present in the pollen record from ~5300 yrs BP onwards, which could be related to the poor preservation of the pollen grains during the Holocene sequence. Due to the poor pollen preservation, *Centaurea* was only identified to species level if it could be confidently identified. It is, thus, possible that the Poaceae >40micron curve in the pollen record of Hashilan wetland picked up both a human signal but also is indicative of naturally occurring grass species which produce large sized grains such as *Phragmites*.

An increase in human activity, although still low, is visible from the Bronze Age onwards and includes *Polygonum aviculare-type*, Poaceae >40micron, *Plantago lanceolate-type*, *Galium*, *Euphorbia* and *Carthamus,* which are indicative of both grazing and agricultural activities. Evidence for increased human activity, which includes tree cultivation and increased grazing and agricultural activities, is also visible in other records during the Late Holocene including Lake Maharlou (~4200 yrs BP), Konar Sandal (~3800 yrs BP), Lake Almalou (~3300 yrs BP), Lake Zeribar and Mirabad (~3200 yrs BP), Gorgan Plain (~2700 yrs BP), Lake Parishan (~2500 yrs), , Lake Urmia (~2500 yrs BP), and Ganli- Gol wetland (Van Zeist and Bottema 1977; Djamali *et al.* 2009a; Djamali *et al.* 2009b; Jones *et al.* 2015; Shumilovskikh *et al.* 2016a; Talebi *et al.* 2016; Zavvar *et al.* 2017; Gurjazkaite *et al.* 2018). Unlike other pollen records of the region, which indicate the start of significant arboriculture from ~3300 yrs BP onwards (Djamali *et al.* 2009a; Talebi *et al.* 2016; Zavvar *et al.* 2017), there is no evidence for the start of arboriculture in the area around Hashilan wetland.

An increase in local burning between ~2700-2200 yrs BP has been noted that occurred during a period of ameliorating climate commencing at ~3200 yrs BP, based on a reduction in dust input and increase in moisture availability. Since there is evidence in the pollen data for anthropogenic activity during this time interval, it can therefore be argued that this is a signal of anthropogenic activity, with climatic aridity playing a minor role as the only decline in moisture availability occurs between ~2780-2690 yrs BP. This interval, archaeologically corresponds to the rise of the Persian Achaemenid Empire (~2550-2330 yrs BP), which we know was a time of significant agricultural extensification and intensification (Djamali *et al.* 2009a; Djamali *et al.* 2010b; Shumilovskikh *et al.* 2016a; Gurjazkaite *et al.* 2018).

Quercus expansion

As mentioned in this chapter, *Quercus* pollen values remain low throughout the sequence of the record, so it is likely that *Quercus* was not present in the close vicinity of Hashilan wetland. Based on the present-day position of the nearest *Quercus* woodland area, which is approximately 30km west of Hashilan wetland (Safaierad in press), and the low *Quercus* pollen values (~6%), it is possible that the *Quercus* values in the pollen record are of regional origin. At Lake Zeribar and Lake Van, for instance, *Quercus* pollen values reach, up to ~40% during the Middle Holocene (Van Zeist and Bottema 1977; Wick *et al.* 2003).

There are three competing theories that have been put forward to explain the delay in *Quercus* woodland formation (see Chapter 3 and 4 for detailed discussion). It has been proposed that: 1) climatic aridity during the Early Holocene (i.e. low effective moisture) prevented *Quercus* expansion (Van Zeist and Bottema 1977; Stevens *et al.* 2001; Djamali *et al.* 2010a); 2) Neolithic communities used fire to manipulate the natural vegetation and maintained landscapes for cultivation of crops, along with woodcutting for fuel and timber as well as to increase grazing grounds for animals. These activities, therefore, prevented *Quercus* expansion (Roberts 2002)(; 3) Neolithic landscape practices provided *Quercus* with the competitive advantage over grasses and other woody plants, stimulating its gradual expansion (Asouti and Kabukcu 2014).

Based on the palaeoenvironmental record of Hashilan wetland, a few comments can be made with regards to the delay in the formation of *Quercus* woodland. According to the Poaceae/*Artemisia* ratio, a slow increase in moisture availability can be noted from the start of the Holocene, although it may not have been enough to stimulate *Quercus* expansion. A short interval of dry climatic conditions can be detected in the dust record, the magnetic susceptibility and the pollen data, which coincides chronologically with the 10.2 ka event and may also possibly be related to the position of the Indian Summer Monsoon and ITCZ at the time (Djamali *et al.* 2010a). Such climatic conditions would have not favoured the expansion of *Quercus*, which requires high effective moisture to expand. According to the pollen values, *Quercus* appears for the first time in the Early Holocene sequence at ~10,200 yrs BP, but it seems to be only marginally represented (~1%). A somewhat continuous but still low pollen curve for *Quercus* starts from ~8600 yrs BP onwards. This increase in *Quercus* corresponds to the highest Poaceae/*Artemisia* values in the record, indicating that moisture availability was very high and likely played an important part in stimulating *Quercus* to expand in the wider regional landscape.

The reason why *Quercus* pollen values increased in the Lateglacial despite the low moisture availability (low Poaceae/*Artemisia*), can be explained by attributing the origin of these pollen values to the wider region such as the western Zagros region where moisture availability was higher (see section 9.2). Despite a potential correlation between the high moisture availability and the appearance of *Quercus* in the pollen record at ~8600 yrs BP, rapid expansion of *Quercus* is visible at ~5900 yrs BP (~6%). This expansion coincides chronologically with an increase in moisture availability between 6100-5900 yrs BP followed by a decline in moisture. *Quercus* pollen values remain high, despite the gradual decline in moisture availability, which suggests that additional factors might also be at play that enabled *Quercus* to maintain itself in the landscape despite evidence for a decline in moisture availability and drier climatic conditions. Both the local and regional fire frequency increases from 5900 yrs BP onwards and evidence for human interference (both agricultural and animal grazing) increases in the landscape from ~6100 yrs BP onwards, which culturally corresponds to the latter half of the Chalcolithic period that is characterised by an increase in human activity (see Chapter 4). Based on the available evidence, it is likely that a number of factors contributed to the expansion of *Quercus* at ~5900 yrs BP. This discussion highlights the difficulty in differentiating between the role of climate change and human activity on changes in the environment during the Holocene period. Carrying out more archaeobotanical analyses of samples from nearby archaeological sites in the future may help us in determining whether *Quercus* was present in the local area and exploited by human communities.

9.4 Summary

In summary, the changes in the vegetation cover in the Hashilan and Lake Ganau area appear to agree with the series of changes documented at other sites in the wider region, although some variations in the timing for these changes have been noted. The discussion that has been produced in relation to the vegetation history of the region highlights the importance of establishing and using reliable site chronologies. A robust and precise chronology is, in fact, of crucial significance as it allows us to cross correlate our data with other palaeoenvironmental records and, in the process, to produce more rigorous interpretations. It is also apparent that the vegetation composition and climate of the Zagros region are diverse and complex, as notable differences can be observed between the western and eastern Zagros region.

Based on the pollen, charcoal, and geochemical data of both Hashilan wetland and Lake Ganau, climate variability was high, especially at Hashilan wetland, during the Late Pleniglacial and Lateglacial. The succeeding Holocene period is, likewise, characterised by a series of climatic events that punctuated the warm and wet climatic conditions, with both changes registered in the source of moisture and potentially dust. The timing of these dry climatic events appears to have varied across the region, which may be related to a number of factors including chronological uncertainties, the sensitivity of the proxy used to detect changes in the climate, and also potential time-lags. Even when a potential link between the archaeological evidence and a climatic event is identified, caution is required as correlation does not imply causation. It is equally important to bear in mind the resilience of human communities to changes in the climate and the environment, which is why it is instrumental to have a comprehensive, well-dated archaeological record that would enable us to identify potential adaption strategies that were adopted by societies to counter the impact of changes that occurred in the climate. The discussion also highlights the challenging task to discern and disentangle the impact of anthropogenic activity from that of climate change on the environment especially from the Holocene period onwards, emphasising the importance of using a multi-proxy approach to investigate human-environmental interrelationships in the past.

10 Conclusions and Recommendations

In this chapter we provide a synthesis of the key results of this PhD in the context of the research questions outlined in Chapter 1. This discussion will enable us to shed light onto human-environmental interactions that took place between ~17,700-2200 yrs BP in the Zagros region, which includes the impact of anthropogenic activity on the environment and resilience of human societies to climate change. Following this issue, the contribution to the wider knowledge and future research possibilities will be highlighted.

10.1 Key Contributions

Research Question 1: To what extent was anthropogenic activity responsible for the changes in vegetation composition and succession at Hashilan wetland and Lake Ganau?

Anthropogenic impact on the Late Pleniglacial and Lateglacial environment, which corresponds to the Epipalaeolithic period, is not visible in the pollen records of Hashilan wetland and Lake Ganau. This absence of anthropogenic signal indicates that although Epipalaeolithic communities were present in the landscape, based on archaeological investigations, and were utilising animal and plant resources, as evidenced for example by the faunal and macrobotanical data from the archaeological site of Palegawra (Asouti *et al.* 2020), the impact was not strong enough to leave an imprint in the pollen record of either site. Whether cereal cultivation in some form in the western Zagros region already started in the Epipalaeolithic, based on the low presence of *Centaurea solstitialis-type* and *Galium*, both weeds of cultivation, is uncertain until further archaeological work confirms this. The impact of human activities on the environment becomes visible at ~9800 yrs BP, during the Neolithic period, in the Hashilan wetland record, which is in agreement with the archaeological data from the Zagros region indicating that domestication of cereals had started by ~9800 yrs BP (Riehl *et al.* 2015). The presence of *Centaurea solstitialis-type* at ~9400 yrs BP in the Hashilan wetland record confirms that the cereal grains identified in the Neolithic period were not produced by their progenitor wild grass species or by naturally occurring grass species but are domesticated cereal grains. Identifying a human signal in the pollen record of Hashilan wetland as early as the Neolithic period reveals that humans were actively manipulating their environment from ~9800 yrs BP onwards, if not earlier. This finding opposes previous views that Neolithic activities were not intense enough to be visible in the pollen records and that human activities intensified from the Bronze Age onwards, which is when they start to become visible in the pollen records of the region (e.g. Djamali *et al.* 2009b; Djamali *et al.* 2009a; Djamali *et al.* 2010b; Djamali *et al.* 2016).

The use of fire also played an important part in the Early Holocene period with an increase in both microcharcoal and macrocharcoal at ~11,350 and ~9600 yrs BP, respectively, with the latter one overlapping with the start of the cultivation that began at 9800 yrs BP. It is, thus, a possibility that Neolithic societies were using fire to manipulate their surrounding environment, although the role of climate and natural fire cannot be entirely ruled out. Fire continued to play an important part in shaping the environment regardless of whether it was naturally or deliberately ignited with a strong human footprint on the local fire event between ~2700-2200 yrs BP, which corresponds to the Neo-Assyrian empire and subsequent Persian Achaemenid empire of the Iron Age. At Lake Ganau, the presence of fire events in the landscape increases over time which could be linked to both human activities and climate, however, at present it is not possible to disentangle these two agencies.

The signal for animal grazing and the presence of herbivores is very low at Hashilan wetland at the start of the Holocene and only increases slightly from ~6100 yrs BP onwards, corresponding to the latter half of the Chalcolithic period, which according to the increase in dust input and declining Poaceae/*Artemisia* values was a period of drier and dustier climate. Despite the presence of an animal grazing signal, as indicated by the presence of *Plantago lanceolata-type* and *Polygonum aviculare-type*, the signal is weak. Due to the poor preservation of pollen grains, possibly related to oxidisation, the identification of *Centaurea solstitialis-type* was not always possible, which makes it difficult to identify with confidence the presence of agricultural activities in the landscape from the Middle Holocene onwards. Despite this issue, the sporadic presence of *Centaurea solstitialis-type* and appearance of *Galium* during the Late Holocene indicates that agricultural activities continued in the region from ~5400 yrs BP onwards, peaking at ~4100 yrs BP. The presence of plant taxa associated with anthropogenic activities, such as agriculture and grazing activities, increases during the Late Holocene (Bronze and Iron Age) and included the following taxa: *Plantago lanceolata-type*, *Polygonum aviculare-type*, Poaceae >40micron, *Galium*, *Centaurea solstitialis-type*, *Centaurea undif.*, *Euphorbia* and *Carthamus.* No evidence, however, of arboriculture within the vicinity of Hashilan wetland has been found in the pollen record unlike at other sites of the region.

The Hashilan wetland data has also shed light onto the delayed *Quercus* woodland expansion debate. Due to the very low pollen percentage of *Quercus*, its presence suggests a regional signal. Despite it being a regional signal, the following observations have been made: 1) *Quercus* established itself at ~8600 years BP but it took approximately 2700 yrs for a *Quercus* woodland to form in the wider regional landscape at ~5900 yrs BP; 2) The very slow expansion of *Quercus* could be linked to both low moisture levels, related to the strengthening of the Indian Summer Monsoon and the northward movement of the ITCZ, and human activity; 3) The decline of *Quercus* woodland at ~4100 yrs BP could be related to both drier climatic conditions and intensification of human activity in the landscape. To conclude, it is apparent that it becomes increasingly difficult to disentangle the impact of human activity and climate change on the environment from the Early Holocene period onwards. To better understand human-environmental interactions it is essential to obtain more archaeobotanical data which will enable us to directly link the exploitation of plant resources with humans.

Research question 2: How resilient were human communities and ecosystems to climate change?

The Late Pleniglacial and Lateglacial were punctuated by intervals of enhanced dust input at Hashilan wetland and low lake levels at Lake Ganau. At Hashilan wetland, periods of enhanced dusty conditions were identified between 24,500-24,100 yrs BP, 23,400-22,800 yrs BP, 22,300-22,700 yrs BP, 21,100-19,200, 18,400-16,800 yrs BP, 15,300-14,200 yrs, and 13,200-12,700 yrs BP. The intervals between 18,400-16,800 yrs BP and 13,200-12,700 yrs BP correspond to drier climatic conditions, based on the pollen assemblage and fire record, with the former potentially corresponding to Heinrich event 1. Further radiocarbon dating of the Late Pleniglacial and Lateglacial sequence is, however, required to verify whether the dry interval between 18,400-16,800 yrs BP corresponds to Heinrich event 1. At Lake Ganau, by contrast, no evidence for Heinrich event 1 is visible. Low lake levels have been identified at Lake Ganau between 19,200-19,150 yrs BP, 18,500-18,400 yrs BP, 13,530-13,470 yrs BP, and 12,650-12,370 yrs BP, while high lake levels were identified between 19,950-19,350 yrs BP, 19,080-18,800 yrs BP, 17,650-17,300 yrs BP, and 12,900-12,650 yrs BP. These changes in water level could have been caused by several factors including a decline in precipitation, increased evaporation related to a rise in temperature, or a combination of both.

Despite the climate variability outlined above, the archaeological record indicates that human occupation largely continued in the region during the Late Pleniglacial and Lateglacial Interstadial, which was characterised by a broadening in the human subsistence that included both faunal and plant resources. As occupation continued at a majority of Epipalaeolithic sites, it suggests that human communities were resilient to these changes in climate.

The start of the Lateglacial Stadial at Lake Ganau was marked by a decline in plant diversity between 12,800-12,400 yrs and low lake levels between 12,650-12,400 yrs BP, while at Hashilan wetland tree populations declined. Despite the drier climatic conditions, which impacted on the vegetation composition, the archaeological data observes three sets of behaviours which are site abandonment, site continuity and the emergence of new sites during the latter half of the Lateglacial Stadial. These variations in the occupation histories suggest that some Epipalaeolithic communities may have adapted to the impact of adverse climatic conditions. However, as the archaeological record for the Epipalaeolithic suffers from chronological uncertainties, it is difficult to assess the impact of the Lateglacial Stadial on Epipalaeolithic communities with certainty until further archaeological work is carried out.

The geochemical record of Hashilan wetland also clearly indicates periods of climate adversity during the Holocene period between 10,700-10,200 yrs BP and 6000-3900 yrs BP, which were characterised by enhanced dust input and low/declining moisture availability. The 9.3 ka and 8.2 ka climatic events, which have been identified between 9430-9200 yrs BP and 8280-7700 yrs BP do not chronologically coincide with changes in the archaeological record. The abandonment of Neolithic sites occurred prior to the onset of the 9.3 ka event and, thus, there is no correlation between these climatic events and the site abandonments identified in the archaeological record. The dry climatic interval between ~10,700-10,200 yrs BP also does not correspond to any changes in the archaeological record, suggesting that Neolithic communities were resilient to the dry climatic conditions or that, alternatively, the magnitude of the dry conditions was not strong enough to affect the lifestyle of Neolithic communities.

The 4.2 ka event has been identified both in the dust record of Hashilan wetland and the Poaceae/*Artemisia* ratio. According to the dust record, drier climatic conditions started from ~6000 yrs BP onwards and within this long interval of dry condition, two periods of enhanced dust input are recorded between 5300-4100 yrs BP and 4050-3900 yrs BP. The Poaceae/*Artemisia* ratio, in contrast, indicates a decline in moisture availability between 4500-4100 yrs BP and 4035-3220 yrs BP. These dry climatic conditions, as identified in the geochemical and pollen record, overlap with the collapse of the Early Transcaucasian Culture in north-western and western Iran at ~4400 yrs BP as well as the Akkadian empire at ~4190 yrs BP. While the abandonment of archaeological sites during the Neolithic period seems to be unrelated to the 9.3 and 8.2 ka climatic events, the 4.2 ka event, which was stronger in magnitude, longer in duration, and superimposed on an already pre-existing drying climate trend, would have had an impact on rainfed agricultural communities to some extent. However, although the 4.2 ka event overlaps with the collapse of the Early Transcaucasian Culture and the

Akkadian empire, additional archaeological sites, located close to Hashilan wetland, need to be investigated to determine a correlation between these dry climatic conditions and the changes in settlement and subsistence strategies, if any.

Research question 3: To what extent did the environment of Hashilan wetland and Lake Ganau influence and impact human lifestyle including broadening of the human diet?

The results of the pollen analysis have helped to shed light onto the Broad Spectrum Revolution and the context in which it started. The environment around Lake Ganau was rich in plant resources that could have been exploited by hunter-gatherer populations and form part of their subsistence, including a great range of species of Brassicaceae (mustard family), Fabaceae (legume/pea family), Poaceae >40micron (cerealia type), Apiaceae (parsley family), as well as *Pistacia* (Pistachio) nuts and *Juniperus* (Juniper) fruits. At Hashilan wetland, Epipalaeolithic communities had, likewise, access to Apiaceae (parsley family), Fabaceae (legume/pea family), Brassicaceae (mustard family), Rhamnaceae (buckthorn family), and potentially *Pistacia* nuts. In contrast to Lake Ganau, wild cereal grains were not as readily available in the landscape around Hashilan wetland which, might reflect their minor role in the human diet in the eastern Zagros region.

Other differences that can be observed between the pollen records of the eastern and western Zagros is the presence of trees, which was higher and more diverse in the Lake Ganau area during both the Late Pleniglacial and Lateglacial periods. Both *Pistacia* and *Quercus* were present in the Lake Ganau area during these periods, which suggests that moisture availability and temperature were higher in the western Zagros compared to the eastern Zagros region. Epipalaeolithic communities living in the locality of the Lake Ganau environment thus had access not only to more diverse edible plant resources but also to a range of firewood sources including *Quercus*, *Salix*, *Fraxinus*, *Tamarix*, *Pistacia*, and *Acer*. At Hashilan wetland, firewood sources would have included *Salix*, *Fraxinus*, *Tamarix*, and potentially Amaranthaceae and *Artemisia* during the Epipalaeolithic. Wetland plant resources available to Epipalaeolithic communities would have been predominantly Cyperaceae with *Sparganium-type* more readily available from the Holocene period onwards. By producing two pollen records that are located on opposite sides of the Zagros mountains, we highlighted the differences in environment and availability of resources accessible to hunter-gatherers. This study has also clearly demonstrated that the broadening of the human diet took place in resource-rich environments during the Epipalaeolithic period, probably linked to the ameliorating climatic conditions associated with the Lateglacial Interstadial.

10.2 Additional Findings

In addition to the key research outputs, related to the research questions, other findings include:

- Based on the pollen, geochemical and radiocarbon results, the Lateglacial Interstadial started at ~15,200 yrs BP at Lake Ganau, while at Hashilan wetland it started at ~14,700 yrs BP. The Lateglacial Stadial started at ~12,650 yrs BP at Lake Ganau, and at Hashilan wetland at ~12,600 yrs BP. The onset of the Early Holocene is recorded at Hashilan wetland at ~11,500 yrs BP. As can be seen, the timing of the transition varies across both sites but also varies in some instances from the Greenland ice and Lake Zeribar data. These offsets could be the result of dating uncertainties and/or lags in climate response

- The geochemical data of Hashilan wetland has shed light onto the Early Holocene precipitation paradox debate. According to the geochemical record, the onset of the Early Holocene was characterised by warmer and wetter climatic conditions, which enabled grasses to spread rapidly, leading to the formation of a grass steppe environment. This interval of ameliorating climatic conditions, however, only lasted until ~10,700 yrs BP and was followed by drier and dustier climatic conditions that peaked at ~10,200 yrs BP, which were likely connected to the intensification of the Indian Summer Monsoon and the northward movement of the ITCZ (Fleitmann et al. 2003; Fleitmann et al. 2007; Djamali et al. 2010a). After ~9200 yrs BP, the Poaceae/*Artemisia* ratio indicates a gradual increase in moisture availability with major peaks identified between ~9000-8280 yrs BP and ~7150-6500 yrs BP. The results of this research, therefore, indicate that although the Early Holocene experienced ameliorating climatic conditions, a short interval of dry climatic conditions punctuated the wet interval.

- Climatic events 11.4 ka, 9.3 ka, and 8.2 ka were not visible in the dust record of Hashilan wetland. The Poaceae/*Artemisia* ratio has, on the other hand, identified periods of reduced moisture availability between 9430-9200 yrs BP and 8280-7700 yrs BP. Two intervals of reduced moisture availability, based on Poaceae/*Artemisia* ratio, have also been identified during the Middle and Late Holocene period between 4500-4100 yrs BP and 4035-3220 yrs BP, while episodes of enhanced dust input have been identified between 5300-4100 yrs BP and 4050-3900 yrs BP. Both intervals are part of an already pre-existing drying climate trend that started at 6000 yrs BP. The 4.2 ka event was probably superimposed on this drying event. The Holocene climate history of the Zagros region can, thus, be described as a wet Early Holocene, that was punctuated by a dry interval between 10,700-9400 yrs BP, followed by a wet Middle Holocene that transitioned into drier climatic conditions after 6000 yrs BP. Improvement in climatic conditions is noted to have occurred between 3200-2300 yrs BP, characterised by an increase in moisture availability, which drops slightly between 2780-2690 yrs BP, potentially linked to the 'Megadrought' event as identified by Sinha et al. (2019b).

- The vegetational changes that have been observed at both Hashilan wetland and Lake Ganau agree with the broader changes identified at other sites of the region and can be described as a dry steppe environment during the Late Pleniglacial and Lateglacial that was dominated by Amaranthaceae and *Artemisia*. The start of the Holocene witnessed a transition into a relatively open grass steppe environment at Hashilan wetland, which did not change significantly throughout the Holocene, with riparian trees growing on the edge of the wetland.

- All the peaks identified in the local fire record prior to the Holocene period correlate to periods of drier climate and, thus, it raises the possibility that these local burning events were related to climate-induced aridity rather than the activities of Pleistocene hunter-gatherers who were present in the close vicinity of Hashilan wetland. Fire events increased rapidly at the start of the Early Holocene, probably linked to the formation of grasslands that acted as a fuel source. Since there is, however, evidence of Neolithic sites dating to ~11,800 yrs BP (Matthews *et al.* 2013a), the role of human activities in igniting fires, whether accidentally or deliberately, cannot be ruled out for the Holocene period. It is difficult to disentangle the role of humans and climate change in causing fires in the landscape during the Holocene period as the data suggest that both agencies could have been responsible for shaping the environment.

10.2.1 Radiocarbon dating - challenges

It is important to mention here the challenges that were encountered during the radiocarbon dating process at both Hashilan wetland and Lake Ganau and what insights they have provided to us in this regard.

One of the objectives of this thesis was to produce chronologically well-constrained age-depth models for both Hashilan wetland and Lake Ganau, which is one of the limitations of some of the previous palaeoenvironmental studies carried out in Southwest Asia.

In an attempt to provide a chronology that is unaffected by the hard water effect, bulk samples were not radiocarbon dated. Radiocarbon dating macrofossils demonstrated, however, that there are also limitations associated with this approach. Besides the difficulty of retrieving sufficient amount of plant material for radiocarbon dating, age-reversals were visible at both sites with several radiocarbon dates not being in stratigraphic order (i.e. either too young or too old in age). This portrayed a challenge in determining which radiocarbon dates were reliable and which ones needed to be rejected from the age-depth model. To overcome these issues, ideally, humic, humin, and plant material should be radiocarbon dated to identify the more reliable type of sample. Alternatively, if only humic and humin dates are available then two age-depth models should be created, a minimum age-depth (humin) and a maximum age-depth model (humic) can be provided.

An in-depth discussion about potential factors that need to be considered before submitting samples for radiocarbon dating and how these issues were addressed at both sites can be found in Chapters 6-8. It is important to understand that while a specific radiocarbon dating strategy might produce reliable radiocarbon results at one site, it could well produce unreliable results at a different site. Each site needs to be assessed individually before deciding which strategy should be employed to produce a reliable age-depth model. Variables that should be considered include the study of the depositional environment of the site and how different processes can influence the movement of materials vertically in the sediment profile. For instance, the humic dates appeared to be more reliable than the plant material dates at Hashilan wetland, while a combination of bulk and macrocharcoal dates were used to produce a reliable age-depth model for Lake Ganau. This research, hence, demonstrates the complexity and challenges associated with radiocarbon dating as well as the importance of producing a reliable age-depth model, as it may ultimately obscure temporal changes and hinder precise temporal correlation between the archaeological and palaeoenvironmental records.

10.3 Wider significance of research

The aim of this research was to reconstruct the environmental history of Hashilan wetland and Lake Ganau between 17,700-2200 yrs BP to identify changes in the vegetation cover and correlate them with anthropogenic activity and climate change. To achieve the aim, a multi-proxy approach was adopted to produce two high-resolution palaeoenvironmental records, which provided contrasting views of the eastern and western Zagros environmental conditions through time and compared the impact of altitude on environmental conditions at the respective sites.

The research involved attempts to overcome previous limitations of palaeoenvironmental studies, which included low spatial variability of records, chronological issues, low-resolution data, and limited availability of records that go as far back in time as the Late Pleniglacial. Most of these limitations were successfully addressed by this research. The Lake Ganau pollen record, that has been presented in this thesis, is the first high-resolution pollen record of the western Zagros region, providing an extremely in-depth reconstruction of the palaeoenvironmental conditions that existed during the Late Pleniglacial and Lateglacial. When compared to the palaeoenvironmental data from the eastern Zagros region, primarily the Lake Zeribar data, it shows clear differences between both areas. The Hashilan wetland data also provides an uninterrupted high-resolution reconstruction of the palaeoenvironmental conditions that existed here, covering the last 24,500 years (pollen record covers ~17,700-1300 yrs BP).

The study of both sites has contributed to growth in our knowledge about key themes and debates associated with the study of human-environmental interactions in the Zagros region, including the Broad Spectrum Revolution, the Early Holocene precipitation paradox, the impact of anthropogenic activity on the environment (e.g. cereal cultivation), the delay in *Quercus* woodland formation, and the resilience of human societies to events of climatic change. Besides improving our understanding of human-environmental interactions, this research also provides a detailed and comprehensive account on the vegetation, climate, and fire history of the Zagros region. Furthermore, this research highlights and discusses some of the issues that can be encountered in the process of radiocarbon dating and how we may overcome or mitigate them in future studies.

10.4 Future research directions

- The mollusc and ostracod assessment carried out on the Hashilan wetland samples demonstrates the potential to perform an in-depth mollusc and ostracod analysis, which could improve our understanding of the palaeoenvironmental conditions as they developed through time. Other potential proxies such as phytoliths and diatoms can also be analysed to augment and strengthen palaeoenvironmental interpretations.

- Additional radiocarbon dates are needed for Hashilan wetland to make the age-depth model more robust and reliable, especially for the Lateglacial period as it is currently only constrained by one radiocarbon date.

- Similar to the Lake Neor dust provenance study (Sharifi *et al.* 2018), the ITRAX data of Hashilan wetland provides an opportunity to identify potential changes in dust sources, which would help to further our understanding about changes in the atmospheric systems of the past.

- The resolution of the Lake Ganau pollen record for the Lateglacial Stadial can be improved from 20cm to every 4cm. Improving the resolution to 4cm would provide greater detail into the vegetation composition and the impact of cold climatic conditions on the vegetation cover. Additionally, pollen analysis should be carried out for the depth 37.50-45.00m to shed light onto the environmental conditions that existed prior to 16,100 yrs BP. Pre-liminary results of the pollen analysis (three pollen samples taken at 39.70m, 42.50m and 44.60m) show the presence of a dry steppe environment dominated by Amaranthaceae and *Artemisia* with very low plant diversity.

- A macrocharcoal analysis should be carried out on the Lake Ganau samples to obtain a local fire history record, which may help us to further our understanding about the role of fire and how it shaped the environment of the Late Pleniglacial and Lateglacial.

- More palaeoenvironmental work is needed from the western Zagros region to better understand vegetation succession in the region and improve spatial coverage as at the moment only one high-resolution pollen study for this region exists, which has been presented in this research (Lake Ganau).

- The archaeological record also needs to be improved including better dating of archaeological sites and carrying out on-site macrobotanical analysis, which would enable us to improve our understanding of human interactions with their surrounding environment. It would allow us to conduct precise cross-comparative investigations between the archaeological and palaeoenvironmental records.

- The use of geochemical markers, such as ancient sedimentary DNA and coprostanol could also yield valuable information to improve our understanding of human-environmental relationships and the presence of animals in the landscape of the past.

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Appendix

Appendix 1: Organic matter and bulk carbonate data

See link: https://tinyurl.com/MRabbaniPhDData

Tabs:

- Hashilan LOI
- Ganau LOI

Appendix 2: Age-depth models

Hashilan wetland

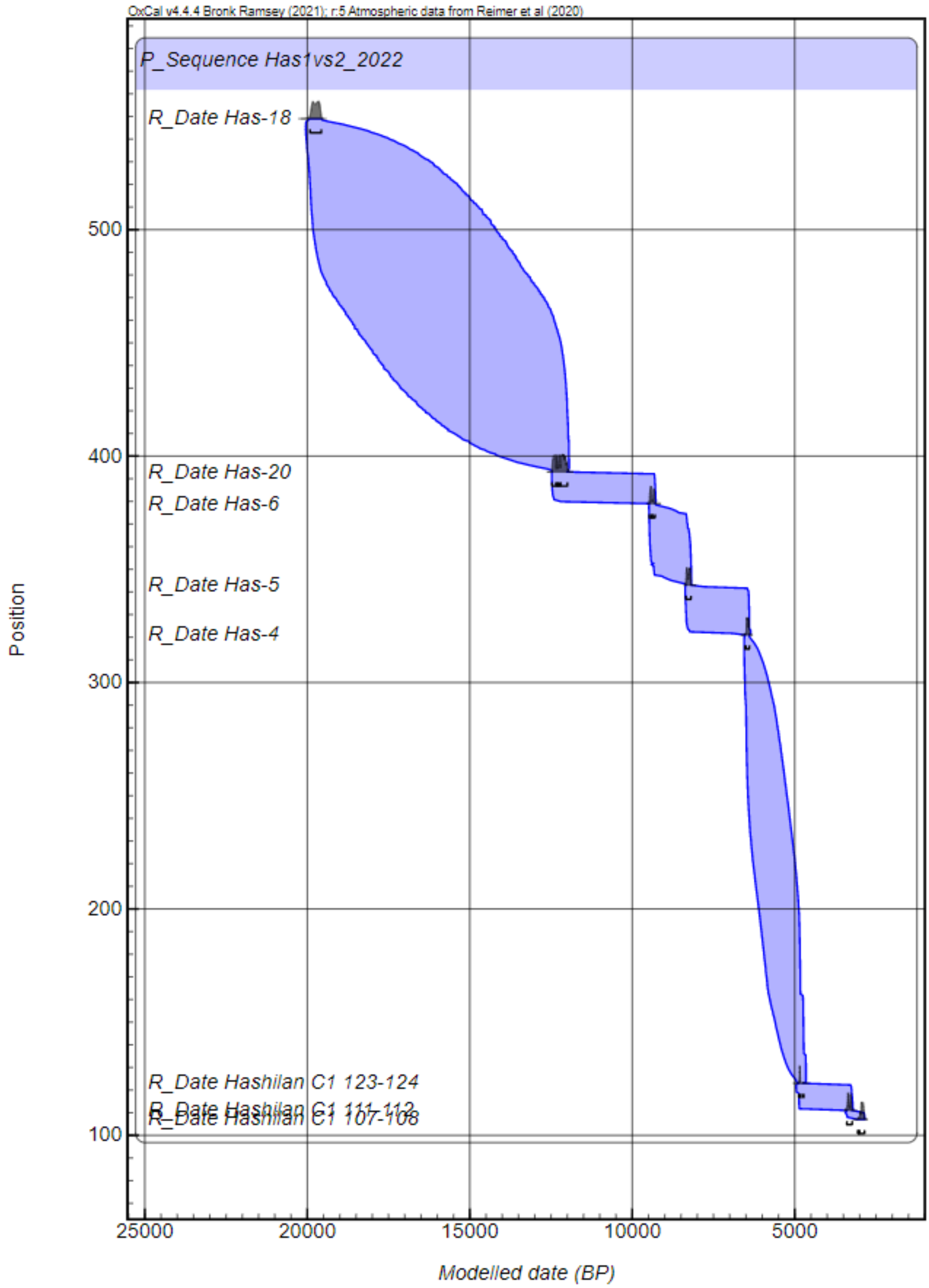
Age depth model Has-1

A combination of plant and humic dates were used to create an age-depth model. Radiocarbon dates derived from plant material that were recovered from silty clay units (Has-12, Has-14, Has-16 and Has-7) were rejected as they all yielded too young dates (highlighted yellow).

For this age-depth model it is assumed that Has-4, 5, 6 and 20, which are stratigraphically correct, are reliable dates to be used for the creation of the age-depth model. Based on this assumptions Hashilan C1 291-292 and Has-3 have been rejected because they are stratigraphically too old (highlighted blue). Has-13 has been rejected as being too young (highlighted orange). Based on the age-depth model created, the pollen record covers the last ca.19,800 cal. yrs BP.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (cm)	Sedimentary context	Reason for excluding
Has-12	202 ± 26	100	Silty clay	Plant not in-situ (too young)
Hashilan C1 107-108	2821 ± 30	107	Bulk peat	
Hashilan C1 111-112	3117 ± 30	111	Bulk peat	
Has-13	2390 ± 26	116	Peat	Too young
Hashilan C1 123-124	4273 ± 30	123	Bulk peat	
Has-14	941 ± 26	134	Silty clay	Plant not in-situ (too young)
Has-16	1182 ± 26	242	Silty clay	plant not in-situ (too young)
Hashilan C1 291-292	11,013 ± 32	291	Bulk peat	Stratigraphically too old
Has-3	9493 ± 26	294	Peat	Stratigraphically too old

Has-4	5678 ± 21	321	Peat	
Has-5	7459 ± 22	343	Peat	
Has-6	8371 ± 25	379	Peat	
Has-20	10,359 ± 29	393	Peat	
Has-7	2935 ± 18	397	At boundary between sandy clay and peat unit	Too young
Has-18	16,388 ± 53	549	Peat	


OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Has1vs2_2022
R_Date Has-18
R_Date Has-20
R_Date Has-6
R_Date Has-5
R_Date Has-4
R_Date Hashilan C1 123-124
R_Date Hashilan C1 111-112
R_Date Hashilan C1 107-108
Position
Modelled date (BP)
500
400
300
200
100
25000
20000
15000
10000
5000

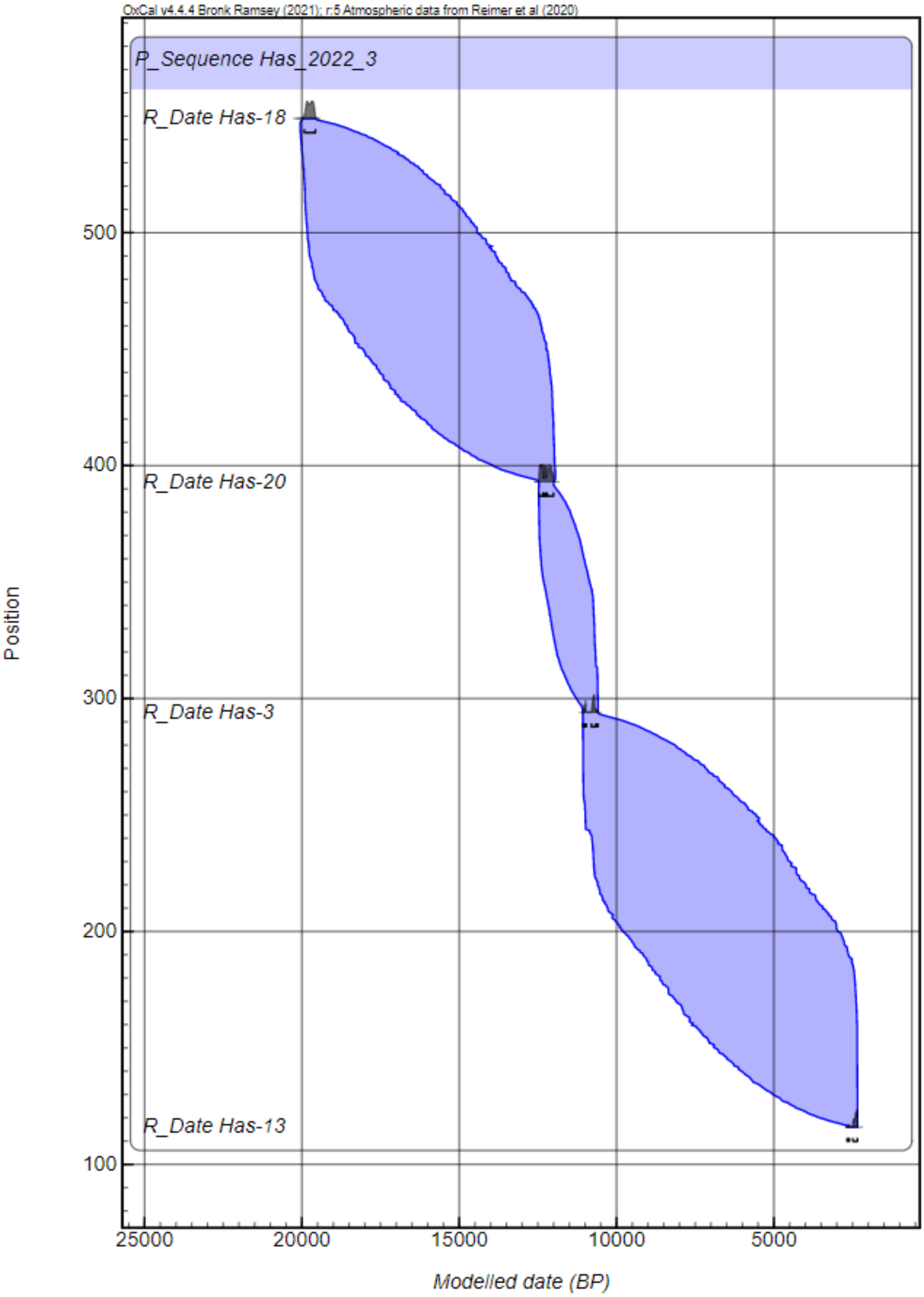
Age depth model Has-3

This age-depth model was created on the assumption that the bulk samples are erroneous, yielding older dates due to hard-water effect and the humic date being an average of all the organic material present in the sample (highlighted grey). Furthermore, the following radiocarbon dates were excluded:

- Has-12, Has-14, Has-16 and Has-7 (silty-clay context) = excluded because they are stratigraphically too young and probably represent non-in-situ plants (highlighted yellow)
- Has-4, Has-5 and Has-6 = excluded because they are stratigraphically too young (highlighted blue)

Based on the age-depth model created the pollen covers the last ca.19,800 cal. yrs BP.

Sample ID	**Conventional Radiocarbon Age (BP)**	**Depth (cm)**	**Sedimentary context**	**Reason for excluding**
Has-12	202 ± 26	100	Silty clay	Plant not in-situ (too young)
Hashilan C1 107-108	2821 ± 30	107	Bulk peat	Hard-water effect
Hashilan C1 111-112	3117 ± 30	111	Bulk peat	Hard-water effect
Has-13	2390 ± 26	116	Peat	
Hashilan C1 123-124	4273 ± 30	123	Bulk peat	Hard-water effect
Has-14	941 ± 26	134	Silty clay	Plant not in-situ (too young)
Has-16	1182 ± 26	242	Silty clay	Plant not in-situ (too young)
Hashilan C1 291-292	11,013 ± 32	291	Bulk peat	Hard-water effect
Has-3	9493 ± 26	294	Peat	
Has-4	5678 ± 21	321	Peat	Too young
Has-5	7459 ± 22	343	Peat	Too young
Has-6	8371 ± 25	379	Peat	Too young
Has-20	10,359 ± 29	393	Peat	
Has-7	2935 ± 18	397	At boundary between sandy clay and peat unit	Plant not in-situ (too young)
Has-18	16,388 ± 53	549	Peat	


OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Has_2022_3
R_Date Has-18
R_Date Has-20
R_Date Has-3
R_Date Has-13
Position
500
400
300
200
100
25000
20000
15000
10000
5000
Modelled date (BP)

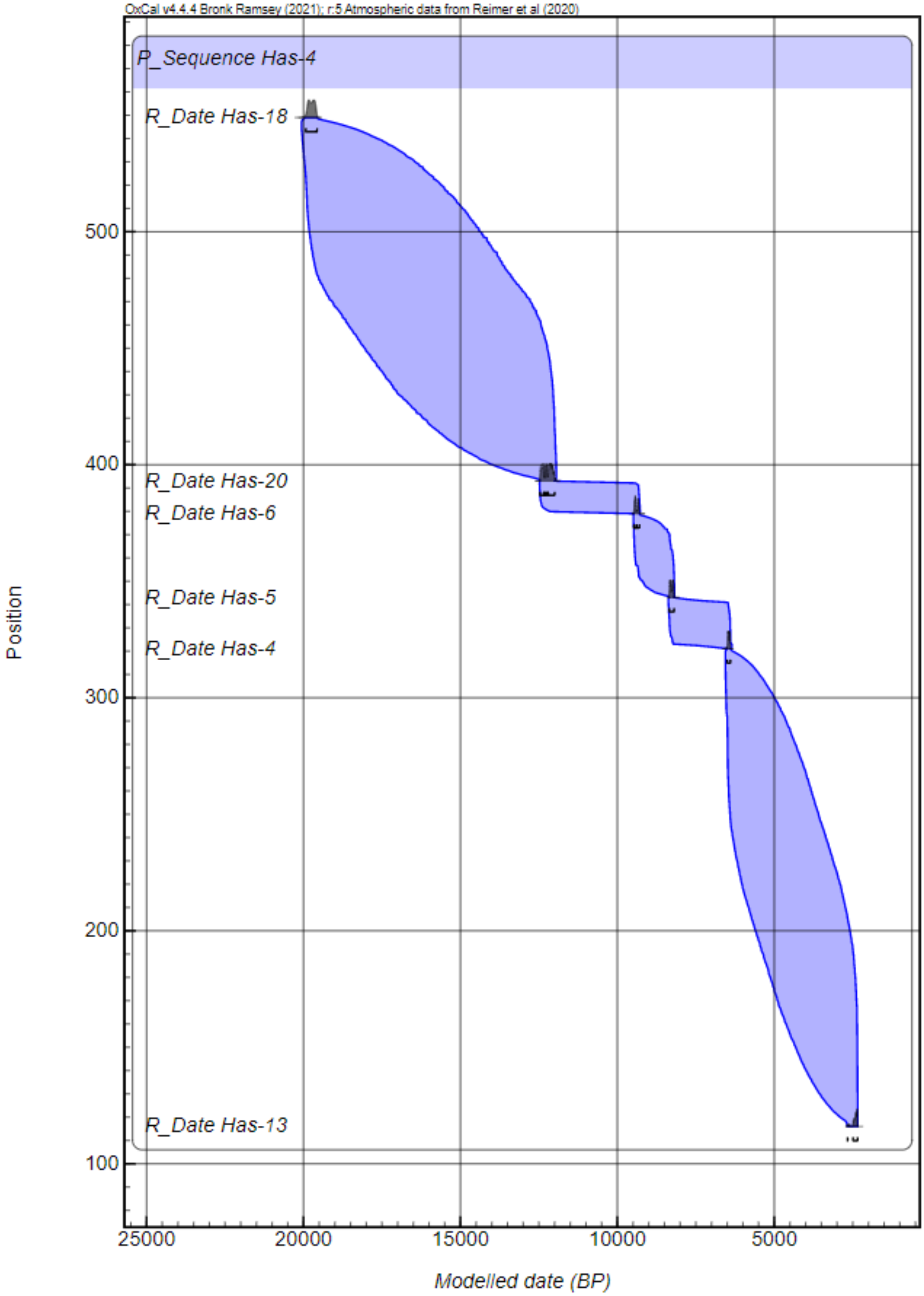
Age depth model Has-4

This age-depth model was created on the assumption that:

- Bulk samples were subject to hard-water effect so they were excluded (highlighted grey)
- Has-12, Has-14, Has-16 and Has- 7 (silty-clay context) = excluded because they are stratigraphically too young and probably represent non-in-situ plants (highlighted yellow)
- Has-3 is stratigraphically too old (highlighted blue)

Based on the age-depth model created the pollen covers the last ca.19,800 cal. yrs BP.

Sample ID	**Conventional Radiocarbon Age (BP)**	**Depth (cm)**	**Sedimentary context**	**Reason for excluding**
Has-12	202 ± 26	100	Silty clay	Plant not in-situ (too young)
Hashilan C1 107-108	2821 ± 30	107	Bulk peat	Old carbon effect
Hashilan C1 111-112	3117 ± 30	111	Bulk peat	Old carbon effect
Has-13	2390 ± 26	116	Peat	
Hashilan C1 123-124	4273 ± 30	123	Bulk peat	Old carbon effect
Has-14	941 ± 26	134	Silty clay	Plant not in-situ (too young)
Has-16	1182 ± 26	242	Silty clay	Plant not in-situ (too young)
Hashilan C1 291-292	11,013 ± 32	291	Bulk peat	Old carbon effect
Has-3	9493 ± 26	294	Peat	Too old
Has-4	5678 ± 21	321	Peat	
Has-5	7459 ± 22	343	Peat	
Has-6	8371 ± 25	379	Peat	
Has-20	10,359 ± 29	393	Peat	
Has-7	2935 ± 18	397	At boundary between sandy clay and peat unit	Plant not in-situ (too young)
Has-18	16,388 ± 53	549	Peat	



OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Has-4
R_Date Has-18
R_Date Has-20
R_Date Has-6
R_Date Has-5
R_Date Has-4
R_Date Has-13
500
400
300
200
100
Position
25000
20000
15000
10000
5000
Modelled date (BP)

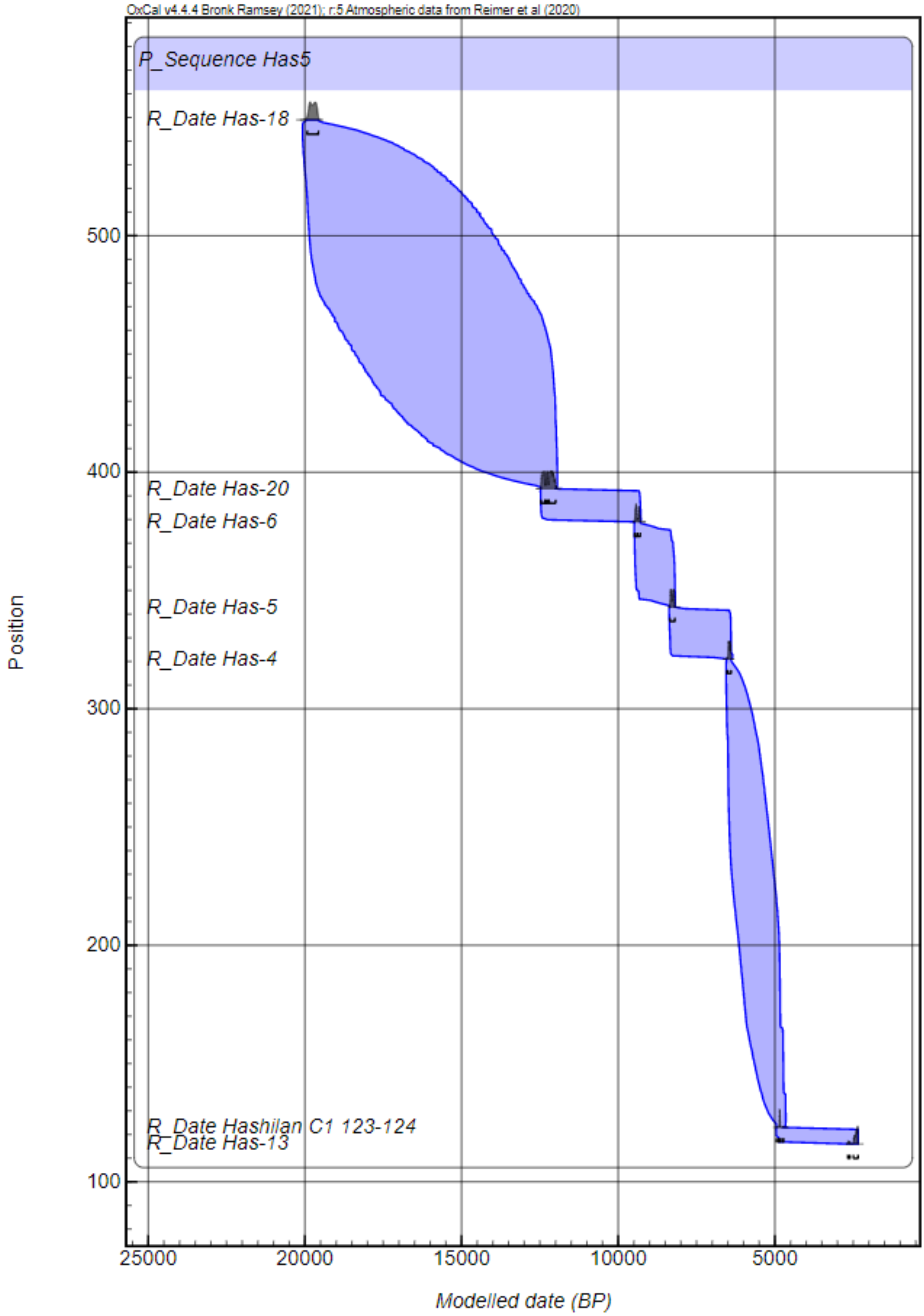
Age depth model Has-5

This age-depth model was created on the assumption that:

- Has-12, Has-14, Has-16 and Has- 7 (silty-clay context) = excluded because they are stratigraphically too young and probably represent non-in-situ plants (highlighted yellow)
- Has-13 is stratigraphically correct which makes the following dates too old: Hashilan C1 107-108, Hashilan C1 111-112, Hashilan C1 291-292, Has-3 (highlighted blue)

Based on the age-depth model created the pollen covers the last ca.19,800 cal. yrs BP.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (cm)	Sedimentary context	Reason for excluding
Has-12	202 ± 26	100	Silty clay	Plant not in-situ (too young)
Hashilan C1 107-108	2821 ± 30	107	Bulk peat	Too old
Hashilan C1 111-112	3117 ± 30	111	Bulk peat	Too old
Has-13	2390 ± 26	116	Peat	
Hashilan C1 123-124	4273 ± 30	123	Bulk peat	
Has-14	941 ± 26	134	Silty clay	Plant not in-situ (too young)
Has-16	1182 ± 26	242	Silty clay	Plant not in-situ (too young)
Hashilan C1 291-292	11,013 ± 32	291	Bulk peat	Too old
Has-3	9493 ± 26	294	Peat	Too old
Has-4	5678 ± 21	321	Peat	
Has-5	7459 ± 22	343	Peat	
Has-6	8371 ± 25	379	Peat	
Has-20	10,359 ± 29	393	Peat	
Has-7	2935 ± 18	397	At boundary between sandy clay and peat unit	Too young
Has-18	16,388 ± 53	549	Peat	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R_Date Has-18
R_Date Has-20
R_Date Has-6
R_Date Has-5
R_Date Has-4
R_Date Hashilan C1 123-124
R_Date Has-13
Position
500
400
300
200
100
25000
20000
15000
10000
5000
Modelled date (BP)

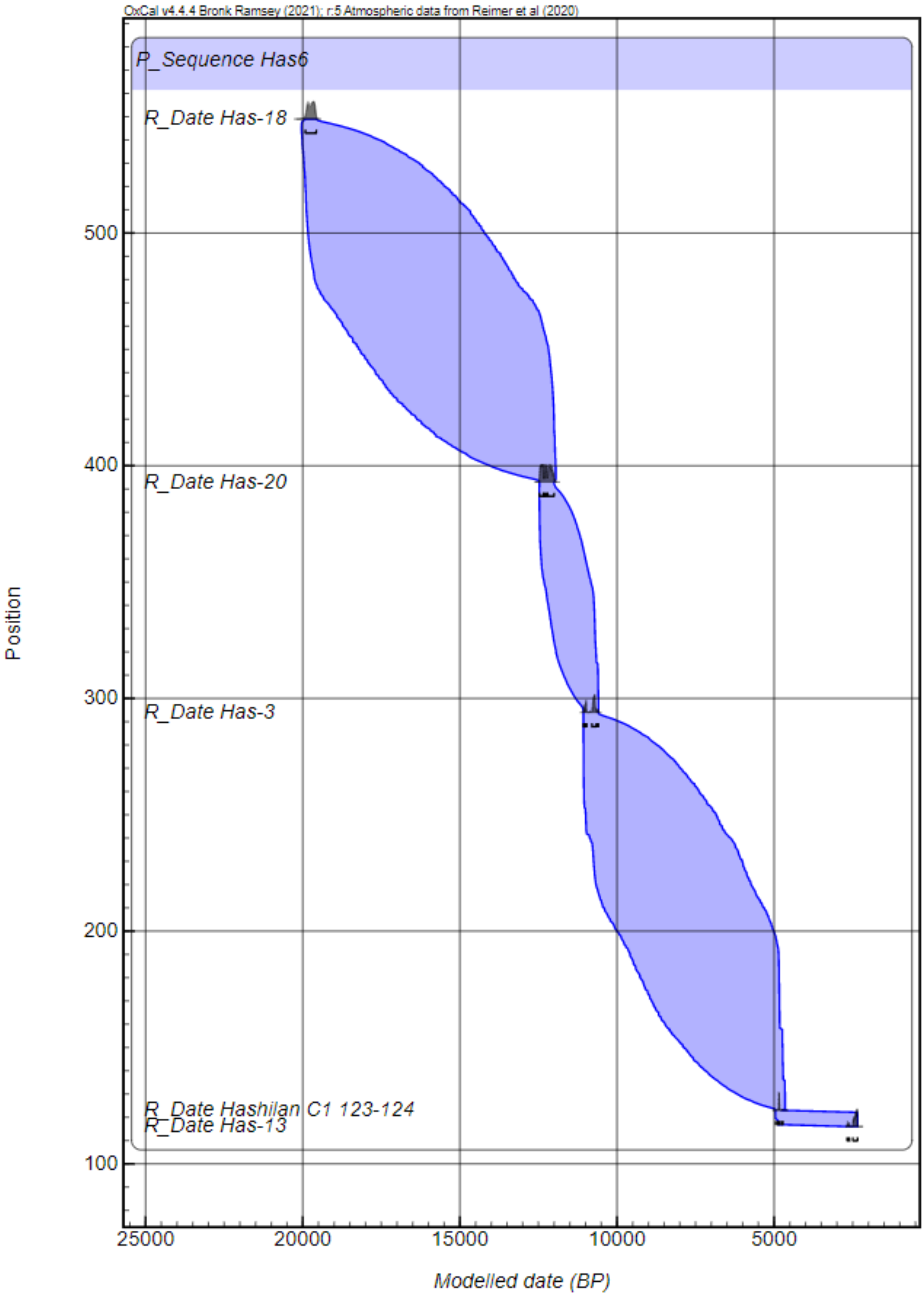
Age depth model Has-6

This age-depth model was created on the assumption that:

- Has-12, Has-14, Has-16 and Has-7 (silty-clay context) = excluded because they are stratigraphically too young and probably represent non-in-situ plants (highlighted yellow)
- Has-13 is stratigraphically correct which makes the following dates too old: Hashilan C1 107-108, Hashilan C1 111-112, Hashilan C1 291-292 (highlighted blue)
- Has-4, Has-5 and Has-6 = are stratigraphically too young (highlighted orange)

Based on the age-depth model created the pollen covers the last ca.19,800 cal. yrs BP.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (cm)	Sedimentary context	Reason for excluding
Has-12	202 ± 26	100	Silty clay	Plant not in-situ (too young)
Hashilan C1 107-108	2821 ± 30	107	Bulk peat	Too old
Hashilan C1 111-112	3117 ± 30	111	Bulk peat	Too old
Has-13	2390 ± 26	116	Peat	
Hashilan C1 123-124	4273 ± 30	123	Bulk peat	
Has-14	941 ± 26	134	Silty clay	Plant not in-situ (too young)
Has-16	1182 ± 26	242	Silty clay	Plant not in-situ (too young)
Hashilan C1 291-292	11,013 ± 32	291	Bulk peat	Too old
Has-3	9493 ± 26	294	Peat	
Has-4	5678 ± 21	321	Peat	Too young
Has-5	7459 ± 22	343	Peat	Too young
Has-6	8371 ± 25	379	Peat	Too young
Has-20	10,359 ± 29	393	Peat	
Has-7	2935 ± 18	397	At boundary between sandy clay and peat unit	Too young
Has-18	16,388 ± 53	549	Peat	


OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Has6
R_Date Has-18
R_Date Has-20
R_Date Has-3
R_Date Hashilan C1 123-124
R_Date Has-13
500
400
300
200
100
Position
25000
20000
15000
10000
5000
Modelled date (BP)

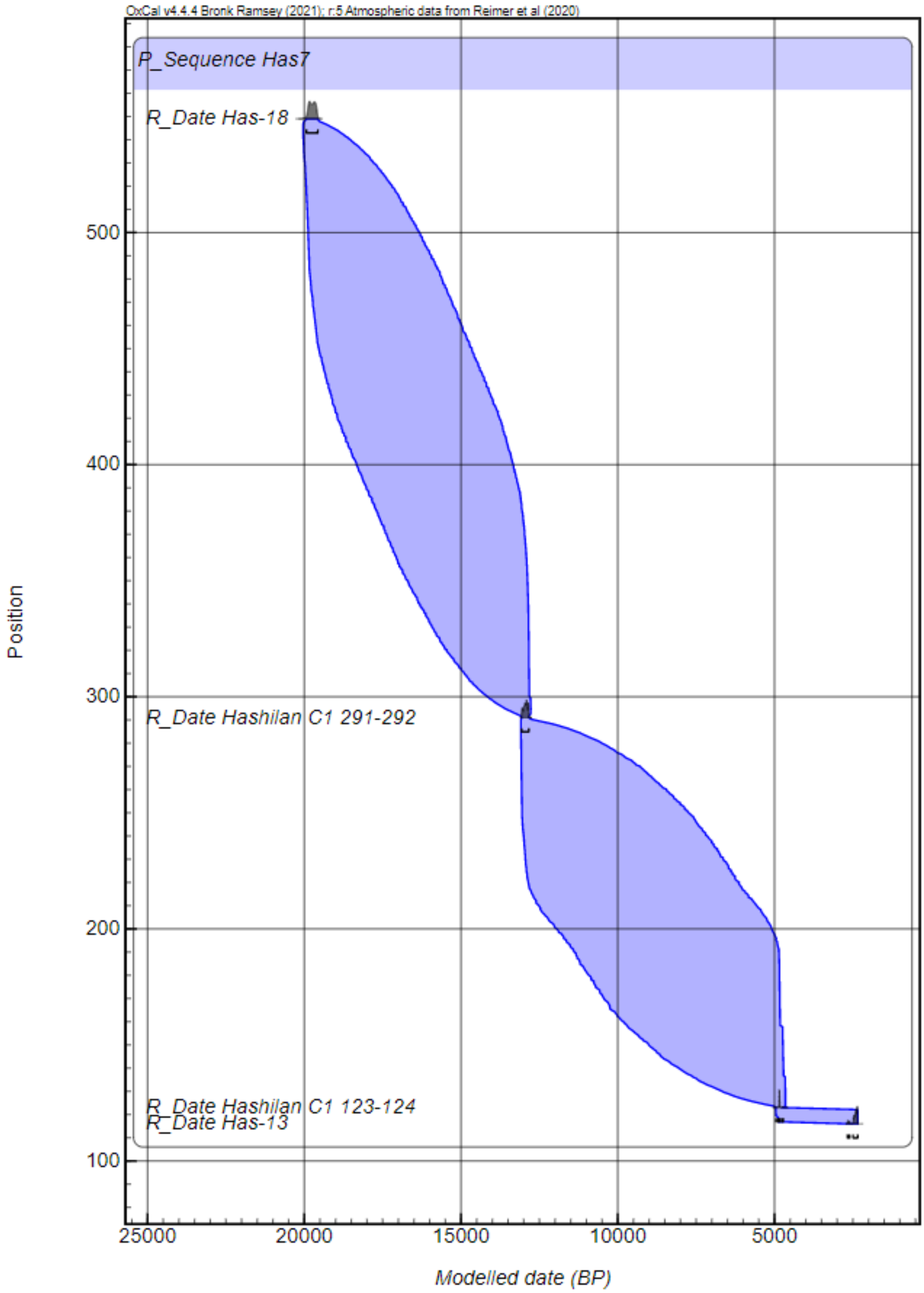
Age depth model Has-7

This age-depth model was created on the assumption that:

- Has-12, Has-14, Has-16 and Has-7 (silty-clay context) = excluded because they are stratigraphically too young and probably represent non-in-situ plants (highlighted yellow)
- Has-13 is stratigraphically correct which makes the following dates too old: Hashilan C1 107-108, Hashilan C1 111-112 (highlighted blue)
- Has-3, Has-4, Has-5, Has-6, and Has-20 = are stratigraphically too young (highlighted orange)

Based on the age-depth model created the pollen covers the last ca.19,800 cal. yrs BP.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (cm)	Sedimentary context	Reason for excluding
Has-12	202 ± 26	100	Silty clay	Plant not in-situ (too young)
Hashilan C1 107-108	2821 ± 30	107	Bulk peat	Too old
Hashilan C1 111-112	3117 ± 30	111	Bulk peat	Too old
Has-13	2390 ± 26	116	Peat	
Hashilan C1 123-124	4273 ± 30	123	Bulk peat	
Has-14	941 ± 26	134	Silty clay	Plant not in-situ (too young)
Has-16	1182 ± 26	242	Silty clay	Plant not in-situ (too young)
Hashilan C1 291-292	11,013 ± 32	291	Bulk peat	
Has-3	9493 ± 26	294	Peat	Too young
Has-4	5678 ± 21	321	Peat	Too young
Has-5	7459 ± 22	343	Peat	Too young
Has-6	8371 ± 25	379	Peat	Too young
Has-20	10,359 ± 29	393	Peat	Too young
Has-7	2935 ± 18	397	At boundary between sandy clay and peat unit	Too young
Has-18	16,388 ± 53	549	Peat	


OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Has7
R_Date Has-18
R_Date Hashilan C1 291-292
R_Date Hashilan C1 123-124
R_Date Has-13
500
400
300
200
100
25000
20000
15000
10000
5000
Position
Modelled date (BP)

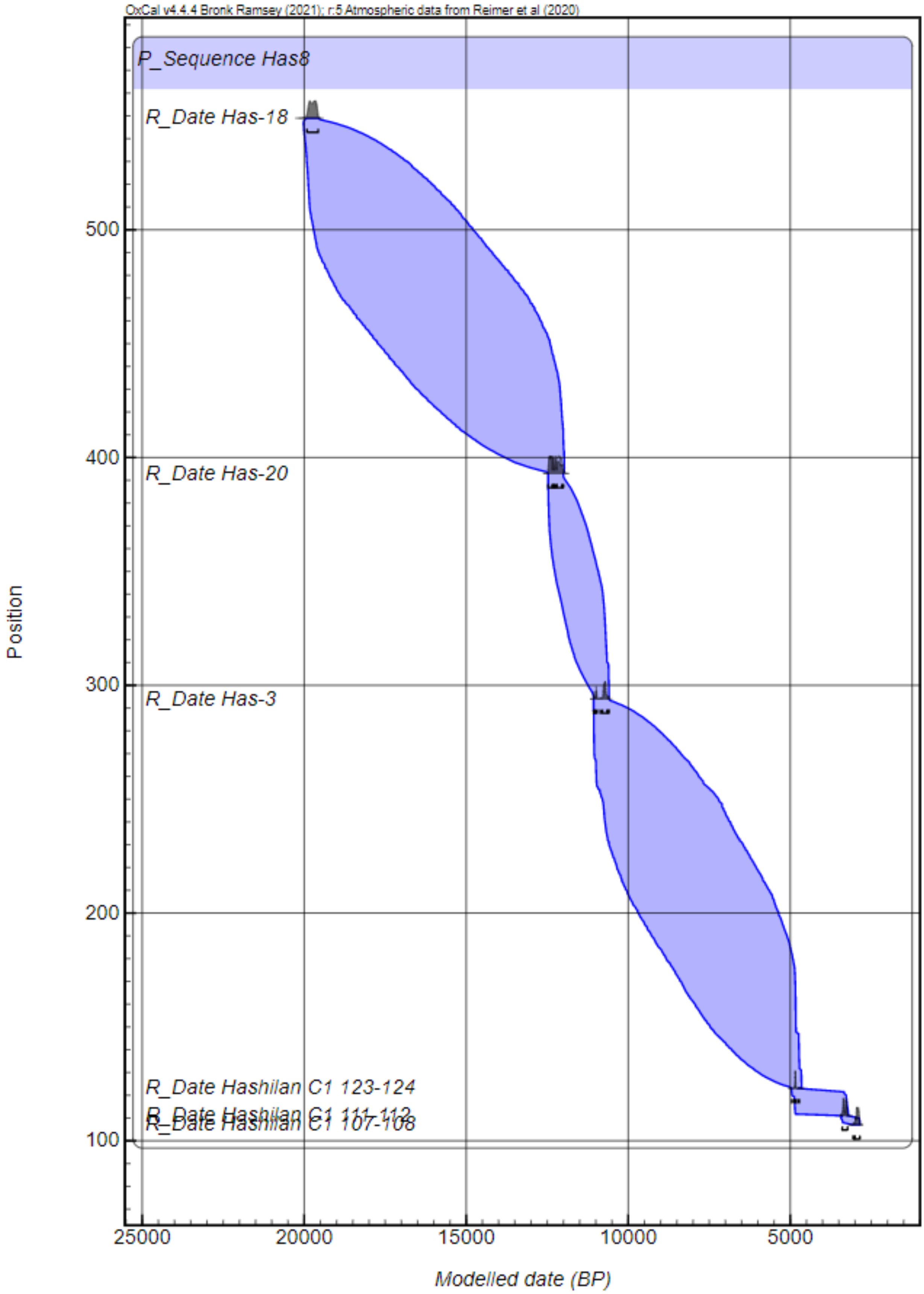
Age depth model Has-8

This age-depth model was created on the assumption that:

- Has-12, Has-14, Has-16 and Has-7 (silty-clay context) = excluded because they are stratigraphically too young and probably represent non-in-situ plants (highlighted yellow)
- Hashilan C1 107-108 is correct which makes Has-13 Hashilan C1 291-292, Has-4, Has-5 and Has-6 stratigraphically incorrect (highlighted blue and orange)

Based on the age-depth model created the pollen covers the last ca.19,800 cal. yrs BP.

Sample ID	**Conventional Radiocarbon Age (BP)**	**Depth (cm)**	**Sedimentary context**	**Reasons for excluding**
Has-12	202 ± 26	100	Silty clay	Plant not in-situ (too young)
Hashilan C1 107-108	2821 ± 30	107	Bulk peat	
Hashilan C1 111-112	3117 ± 30	111	Bulk peat	
Has-13	2390 ± 26	116	Peat	Too young
Hashilan C1 123-124	4273 ± 30	123	Bulk peat	
Has-14	941 ± 26	134	Silty clay	Plant not in-situ (too young)
Has-16	1182 ± 26	242	Silty clay	Plant not in-situ (too young)
Hashilan C1 291-292	11,013 ± 32	291	Bulk peat	Too old
Has-3	9493 ± 26	294	Peat	
Has-4	5678 ± 21	321	Peat	Too young
Has-5	7459 ± 22	343	Peat	Too young
Has-6	8371 ± 25	379	Peat	Too young
Has-20	10,359 ± 29	393	Peat	
Has-7	2935 ± 18	397	At boundary between sandy clay and peat unit	Too young
Has-18	16,388 ± 53	549	Peat	



OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Has8
R_Date Has-18
R_Date Has-20
R_Date Has-3
R_Date Hashilan C1 123-124
R_Date Hashilan C1 111-112
R_Date Hashilan C1 107-108
500
400
300
200
100
Position
25000
20000
15000
10000
5000
Modelled date (BP)

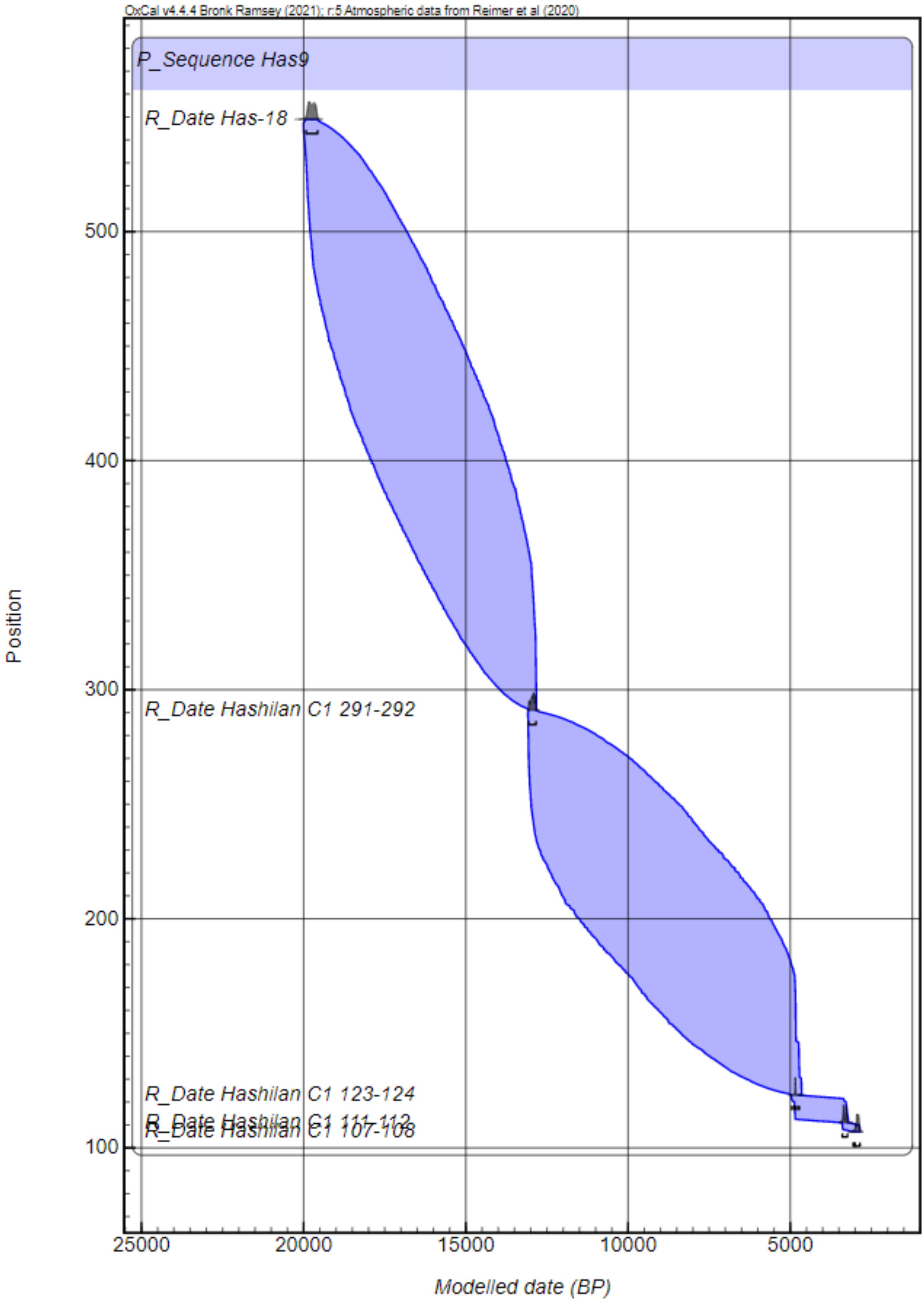
Age depth model Has-9

This age-depth model was created on the assumption that:

- Has-12, Has-14, Has-16 and Has-7 (silty-clay context) = excluded because they are stratigraphically too young and probably represent non-in-situ plants (highlighted yellow)
- All humic dates are stratigraphically correct
- Has-13, Has-3, Has-4, Has-5, Has-6 and Has-20 are stratigraphically too young (highlighted orange)

Based on the age-depth model created the pollen covers the last ca.19,800 cal. yrs BP.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (cm)	Sedimentary context	Reason for excluding
Has-12	202 ± 26	100	Silty clay	Plant not in-situ (too young)
Hashilan C1 107-108	2821 ± 30	107	Bulk peat	
Hashilan C1 111-112	3117 ± 30	111	Bulk peat	
Has-13	2390 ± 26	116	Peat	Too young
Hashilan C1 123-124	4273 ± 30	123	Bulk peat	
Has-14	941 ± 26	134	Silty clay	Plant not in-situ (too young)
Has-16	1182 ± 26	242	Silty clay	Plant not in-situ (too young)
Hashilan C1 291-292	11,013 ± 32	291	Bulk peat	
Has-3	9493 ± 26	294	Peat	Too young
Has-4	5678 ± 21	321	Peat	Too young
Has-5	7459 ± 22	343	Peat	Too young
Has-6	8371 ± 25	379	Peat	Too young
Has-20	10,359 ± 29	393	Peat	Too young
Has-7	2935 ± 18	397	At boundary between sandy clay and peat unit	Too young
Has-18	16,388 ± 53	549	Peat	


OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Has9
R_Date Has-18
R_Date Hashilan C1 291-292
R_Date Hashilan C1 123-124
R_Date Hashilan C1 111-112
R_Date Hashilan C1 107-108
Position
500
400
300
200
100
25000
20000
15000
10000
5000
Modelled date (BP)

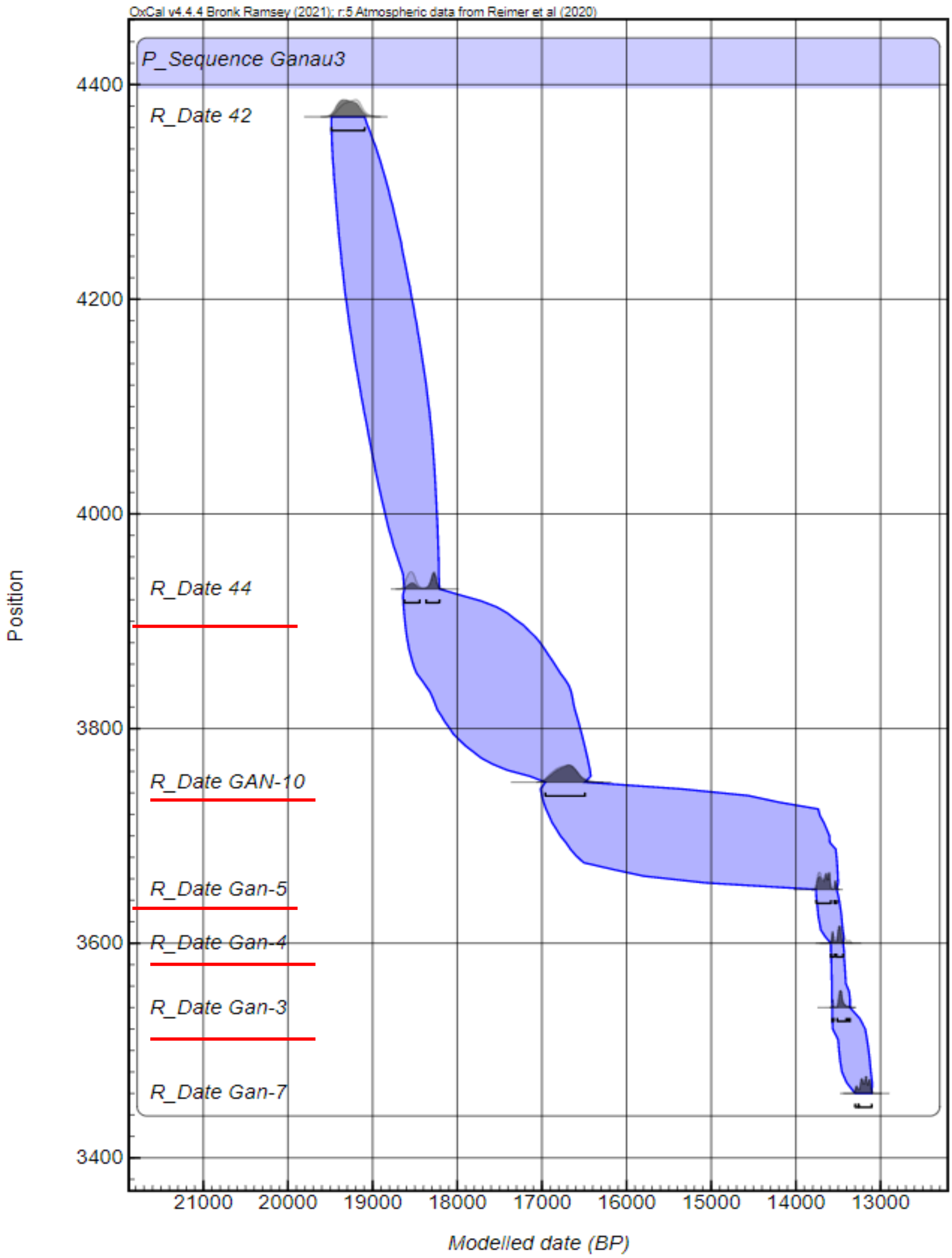
Lake Ganau

Age depth model Gan3

Rows highlighted in yellow (too young) and blue (too old) have been excluded. As it is difficult to determine whether radiocarbon date 43 or 42 is stratigraphically correct, two age-depth models have been created, one that treats 43 as stratigraphically too old and one that treats 42 as stratigraphically too young (see age-depth model 4).

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.20	Holocene date
Gan-2	11,922 ± 32	33.80	Stratigraphically too old
Gan-7	11,294 ± 49	34.60	
Gan-8	6606 ± 24	34.90	Holocene date
Gan-3	11,611 ± 28	35.40	
Gan-4	11,611 ± 38	36.00	
Gan-5	11,799 ± 31	36.50	
Gan-6	7785 ± 48	37.00	Holocene date
GAN-10	13,784 ± 58	37.50	
44	15,068 ± 61	39.30	
43	18,410 ± 80	41.70	Stratigraphically too old
42	15,941 ± 66	43.70	

Based on the age-depth model created the pollen records spans the time interval between **ca.12,100-16,700 cal. yrs BP**



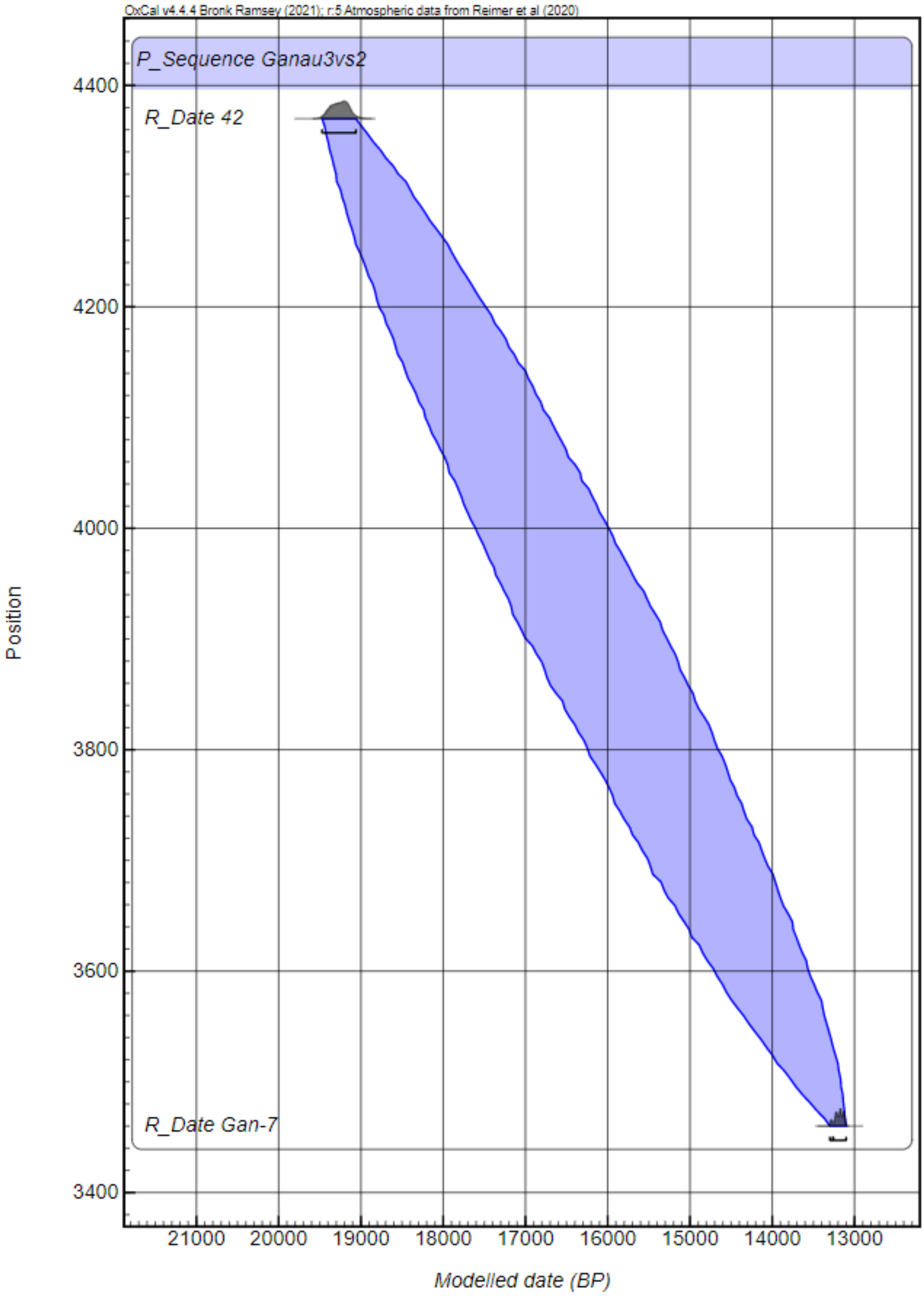
Based on the shape of the age-depth model curve, I decided to remove **Gan-5, Gan-4, Gan-3, Gan-10 and Gan-44** (see Gan3 vs2)

Age-depth model Gan3 vs2

Rows highlighted in yellow (too young), blue (too old), green and orange have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.20	Holocene date
Gan-2	11,922 ± 32	33.80	Stratigraphically too old
Gan-7	11,294 ± 49	34.60	
Gan-8	6606 ± 24	34.90	Holocene date
Gan-3	11,611 ± 28	35.40	Excluded because the ages are located too close to each other despite the distance at which they were sampled. Very high sedimentation rate or movement of charcoal? Unsure
Gan-4	11,611 ± 38	36.00	
Gan-5	11,799 ± 31	36.50	
Gan-6	7785 ± 48	37.00	Holocene date
GAN-10	13,784 ± 58	37.50	Stratigraphically incorrect
44	15,068 ± 61	39.30	Stratigraphically incorrect
43	18,410 ± 80	41.70	Stratigraphically too old
42	15,941 ± 66	43.70	

Based on the age-depth model created the pollen records spans the time interval between **ca.12,100-15,100 cal. yrs BP**



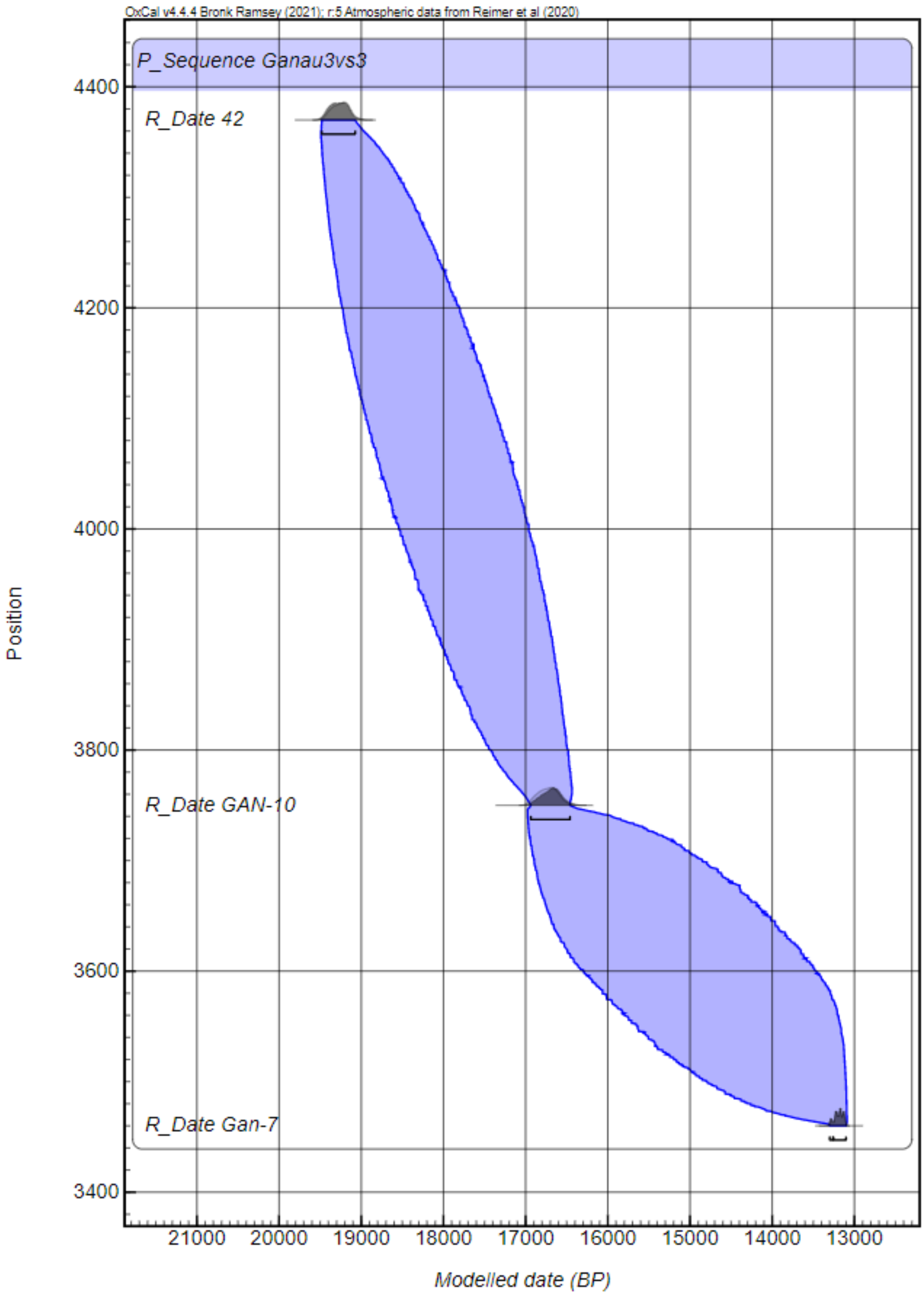
Another age-depth model was created including **Gan-10 (see Gan3 vs3)**

Age-depth model Gan3 vs3

Rows highlighted in yellow (too young), blue (too old), green and orange have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	Stratigraphically too old
Gan-7	11,294 ± 49	34.6	
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Excluded because the ages are located too close to each other despite the distance at which they were sampled. Very high sedimentation rate or movement of charcoal? Unsure
Gan-4	11,611 ± 38	36	
Gan-5	11,799 ± 31	36.5	
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	
44	15,068 ± 61	39.3	Stratigraphically incorrect
43	18,410 ± 80	41.7	Stratigraphically too old
42	15,941 ± 66	43.7	

Based on the age-depth model created the pollen records spans the time interval between **ca.12,100-16,700 cal. yrs BP**

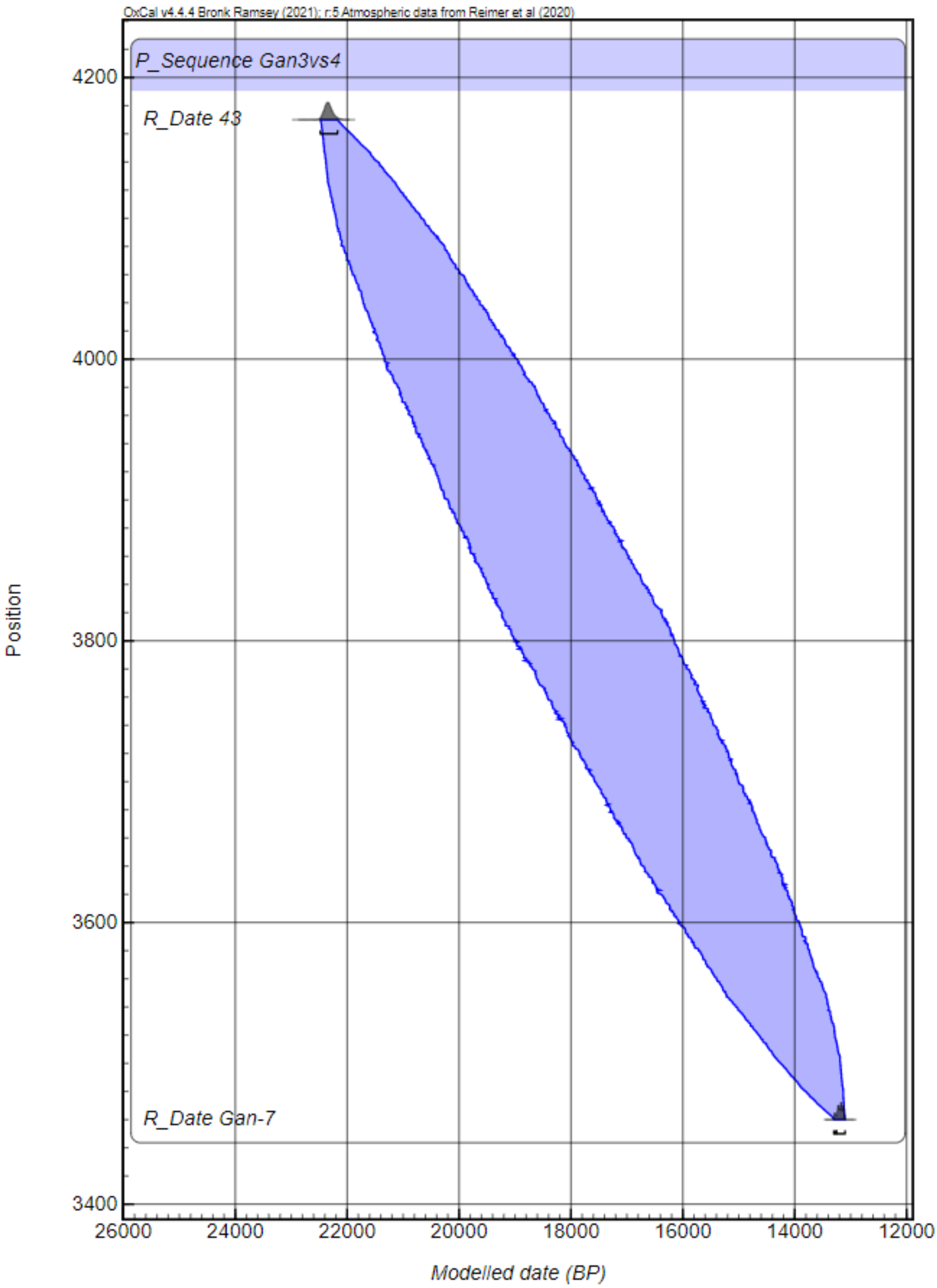

OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Ganau3vs3
R_Date 42
R_Date GAN-10
R_Date Gan-7
Position
4400
4200
4000
3800
3600
3400
21000
20000
19000
18000
17000
16000
15000
14000
13000
Modelled date (BP)

Age-depth model Gan3 vs4

Rows highlighted in yellow (too young), blue (too old), green and orange have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	Stratigraphically too old
Gan-7	11,294 ± 49	34.6	
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Excluded because the ages are located too close to each other despite the distance at which they were sampled. Very high sedimentation rate or movement of charcoal? Unsure
Gan-4	11,611 ± 38	36	
Gan-5	11,799 ± 31	36.5	
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	Stratigraphically incorrect
44	15,068 ± 61	39.3	Stratigraphically incorrect
43	18,410 ± 80	41.7	
42	15,941 ± 66	43.7	Stratigraphically too young

Based on the age-depth model created the pollen records spans the time interval between **ca.11,100 -16,900 cal. yrs BP**

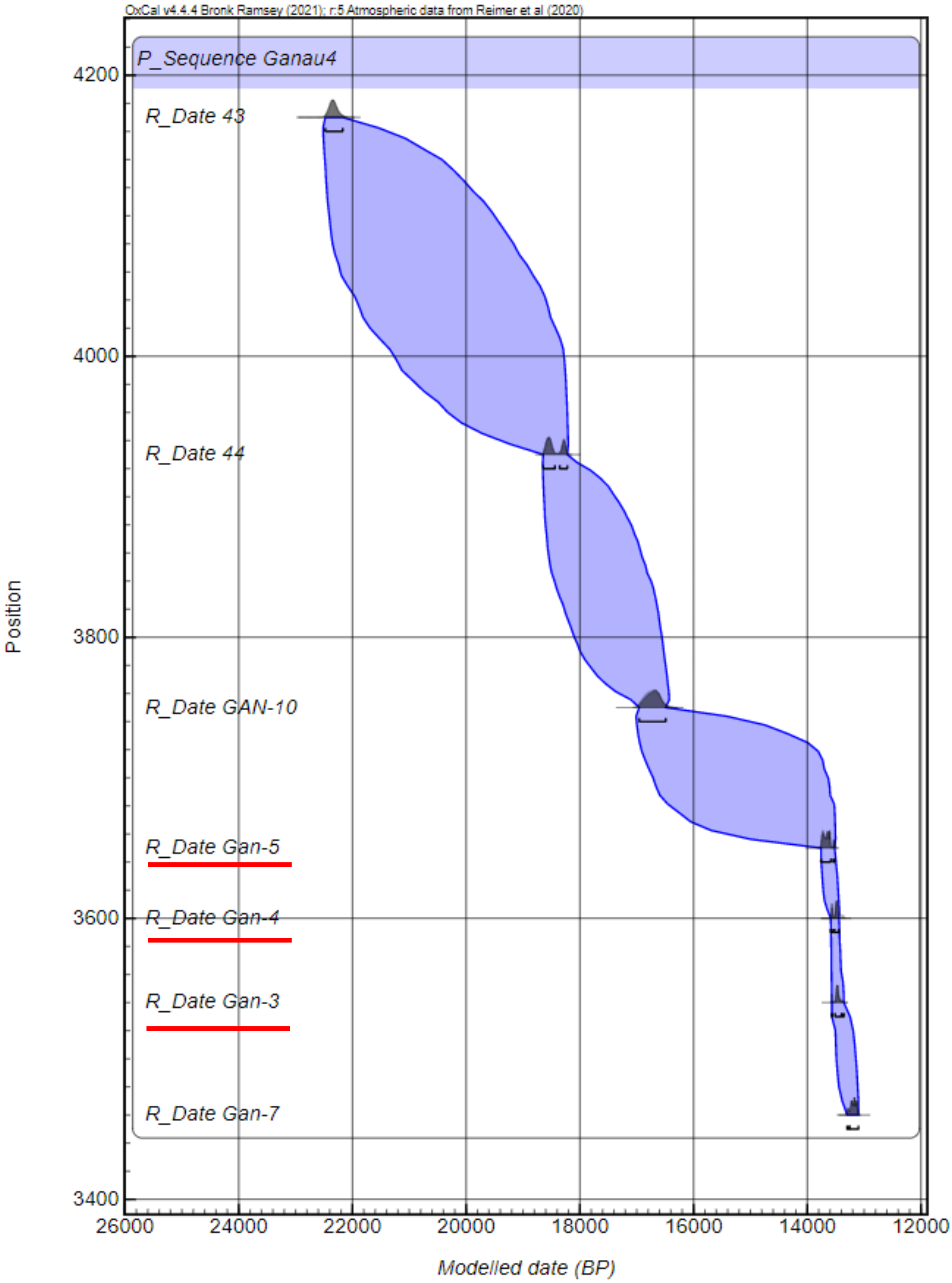

OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Gan3vs4
R_Date 43
R_Date Gan-7
Position
4200
4000
3800
3600
3400
26000
24000
22000
20000
18000
16000
14000
12000
Modelled date (BP)

Age-depth model 4

Rows highlighted in yellow (too young) and blue (too old) have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	Stratigraphically too old
Gan-7	11,294 ± 49	34.6	
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	
Gan-4	11,611 ± 38	36	
Gan-5	11,799 ± 31	36.5	
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	
44	15,068 ± 61	39.3	
43	18,410 ± 80	41.7	
42	15,941 ± 66	43.7	Stratigraphically too young

Based on the age-depth model created the pollen records spans the time interval between **ca.11,100-16,700 cal. yrs BP.**



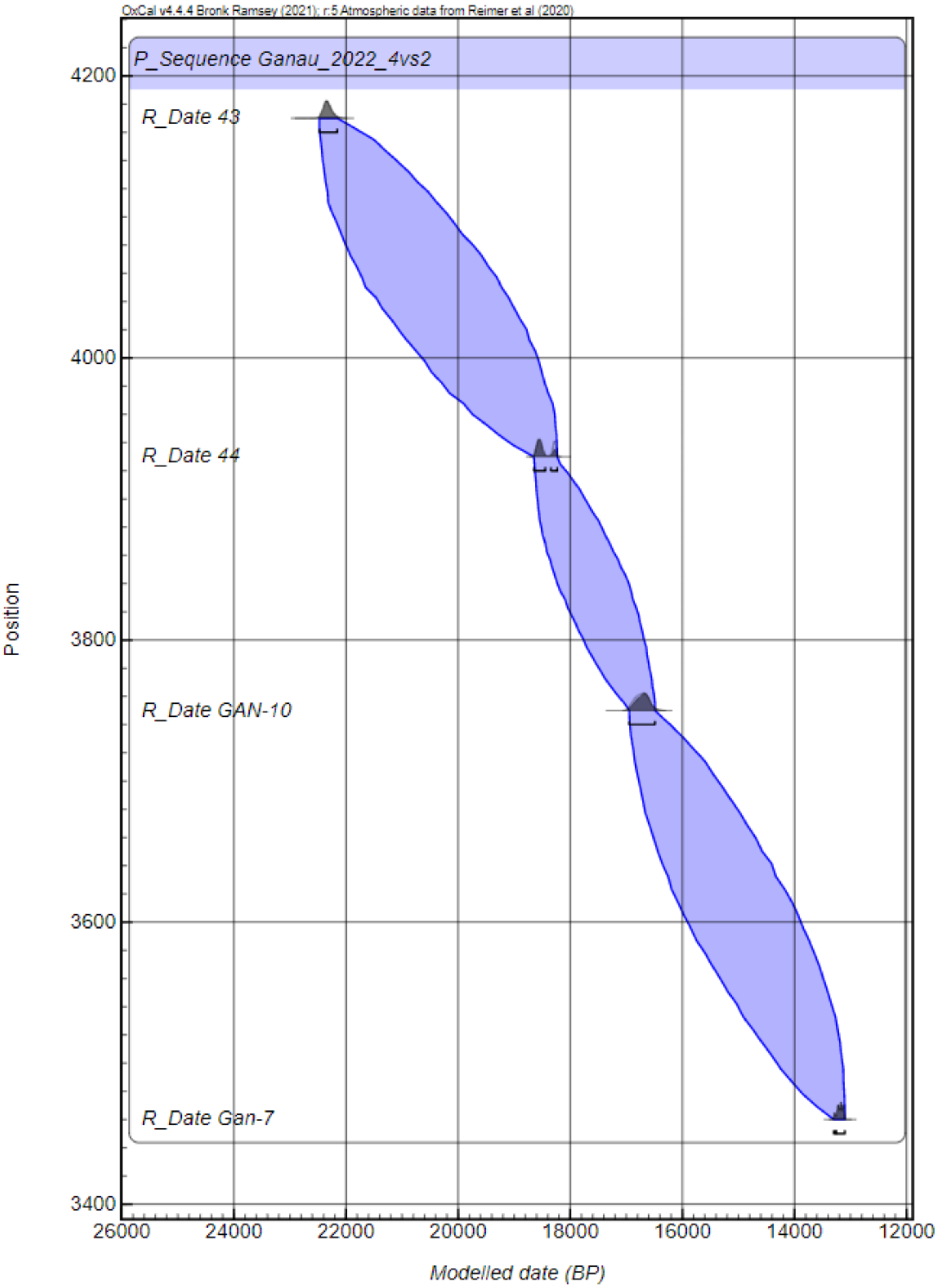
Based on the shape of the age-depth model curve, it was decided to remove **Gan-5, Gan-4, Gan-3** (see Gan4 vs2)

Age-depth model Gan4 vs2

Rows highlighted in yellow (too young), blue (too old) and green have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	Stratigraphically too old
Gan-7	11,294 ± 49	34.6	
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Excluded because the ages are located too close to each other despite the distance at which they were sampled. Very high sedimentation rate or movement of charcoal? Unsure
Gan-4	11,611 ± 38	36	
Gan-5	11,799 ± 31	36.5	
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	
44	15,068 ± 61	39.3	
43	18,410 ± 80	41.7	
42	15,941 ± 66	43.7	Stratigraphically too young

Based on the age-depth model created the pollen records spans the time interval between **ca.11,100-16,700 cal. yrs BP.**



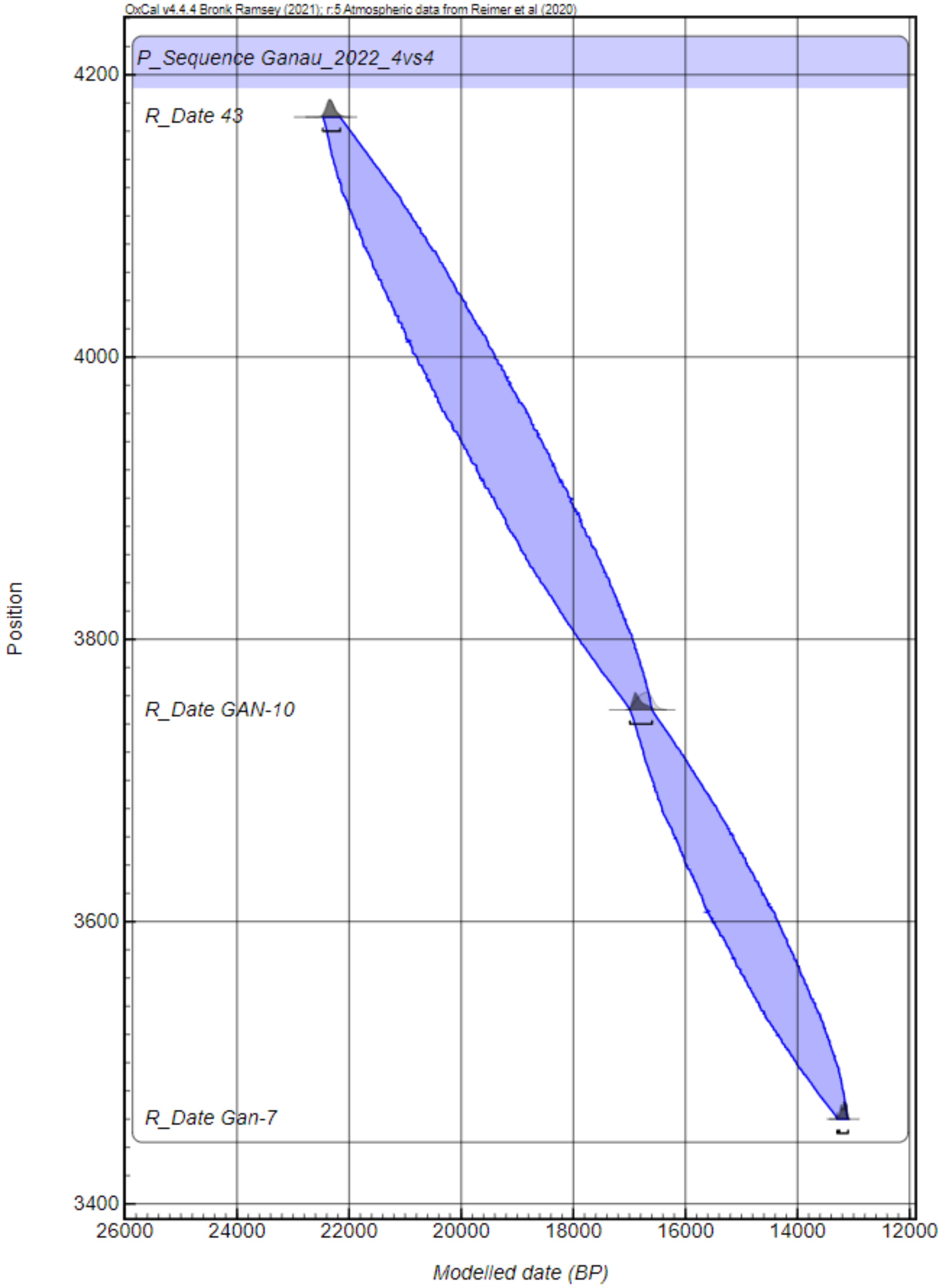
Another age-depth model was created by removing **<u>44 (see Gan vs4)</u>**

Age-depth model Gan4 vs4

Rows highlighted in yellow (too young), blue (too old), green and orange have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	Stratigraphically too old
Gan-7	11,294 ± 49	34.6	
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Excluded because the ages are located too close to each other despite the distance at which they were sampled. Very high sedimentation rate or movement of charcoal? Unsure
Gan-4	11,611 ± 38	36	
Gan-5	11,799 ± 31	36.5	
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	
44	15,068 ± 61	39.3	Stratigraphically not correct
43	18,410 ± 80	41.7	
42	15,941 ± 66	43.7	Stratigraphically too young

Based on the age-depth model created the pollen records spans the time interval between **ca.11,100-16,800 cal. yrs BP.**



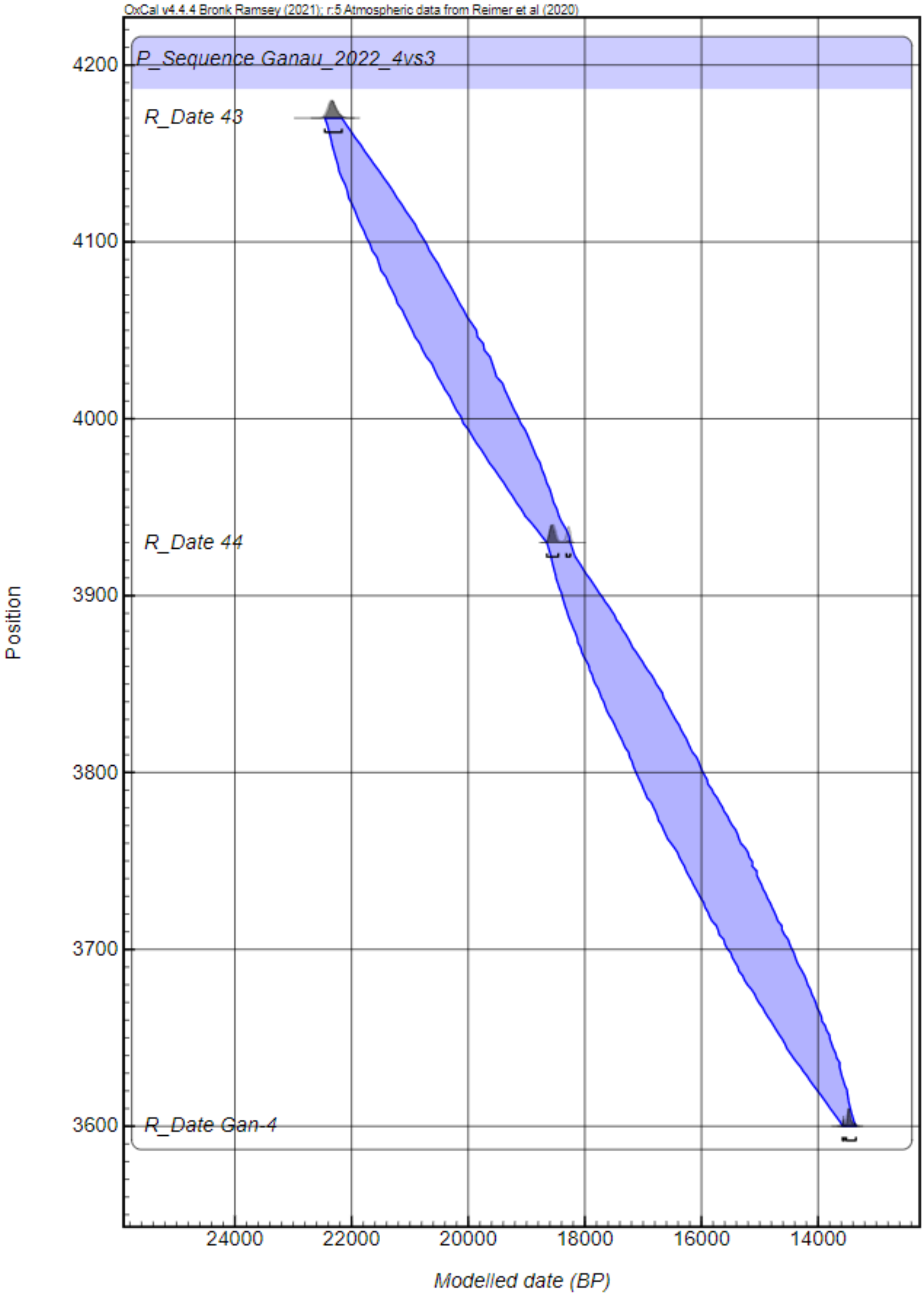
Another age-depth model was created to see what would happen **if Gan 4 (11,611) was correct (see Gan4 vs3)**

Age-depth model Gan4 vs3

Rows highlighted in yellow (too young), blue (too old), green and orange have been excluded. However, **I cannot justify the selection of Gan4 and not Gan3 and Gan-5. I can also not justify the removal of Gan7 and Gan10.**

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	Stratigraphically too old
Gan-7	11,294 ± 49	34.6	Stratigraphically not correct
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Excluded because the ages are located too close to each other despite the distance at which they were sampled. Very high sedimentation rate or movement of charcoal? Unsure
Gan-4	11,611 ± 38	36	
Gan-5	11,799 ± 31	36.5	
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	Stratigraphically not correct
44	15,068 ± 61	39.3	Stratigraphically not correct
43	18,410 ± 80	41.7	
42	15,941 ± 66	43.7	Stratigraphically too young

Based on the age-depth model created the pollen records spans the time interval between **ca.8800-15,400 cal. yrs BP.** Since based on the pollen record I do not have the Holocene sequence, this **age-depth model is rejected** with confidence.



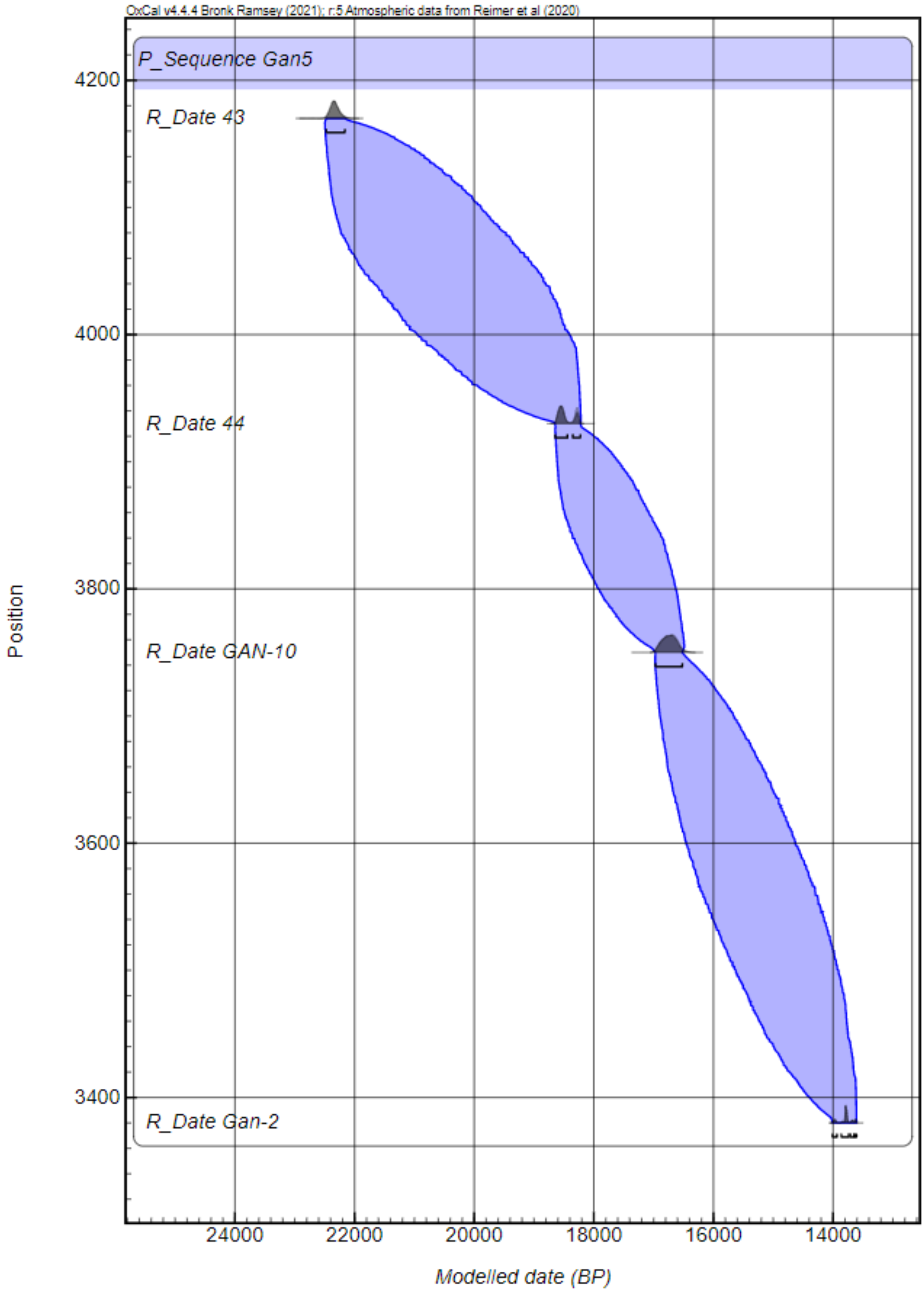
OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Ganau_2022_4vs3
R_Date 43
R_Date 44
R_Date Gan-4
Position
4200
4100
4000
3900
3800
3700
3600
24000
22000
20000
18000
16000
14000
Modelled date (BP)

Age-depth model 5

Rows highlighted in yellow (too young) and blue (too old) have been excluded. Another ag-depth model was created assuming that Gan-2 is stratigraphically correct

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	
Gan-7	11,294 ± 49	34.6	Stratigraphically too old
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Stratigraphically too old
Gan-4	11,611 ± 38	36	Stratigraphically too old
Gan-5	11,799 ± 31	36.5	Stratigraphically too old
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	
44	15,068 ± 61	39.3	
43	18,410 ± 80	41.7	
42	15,941 ± 66	43.7	Stratigraphically too young

Based on the age-depth model created the pollen records spans the time interval between **ca.12,900-16,700 cal. yrs BP**



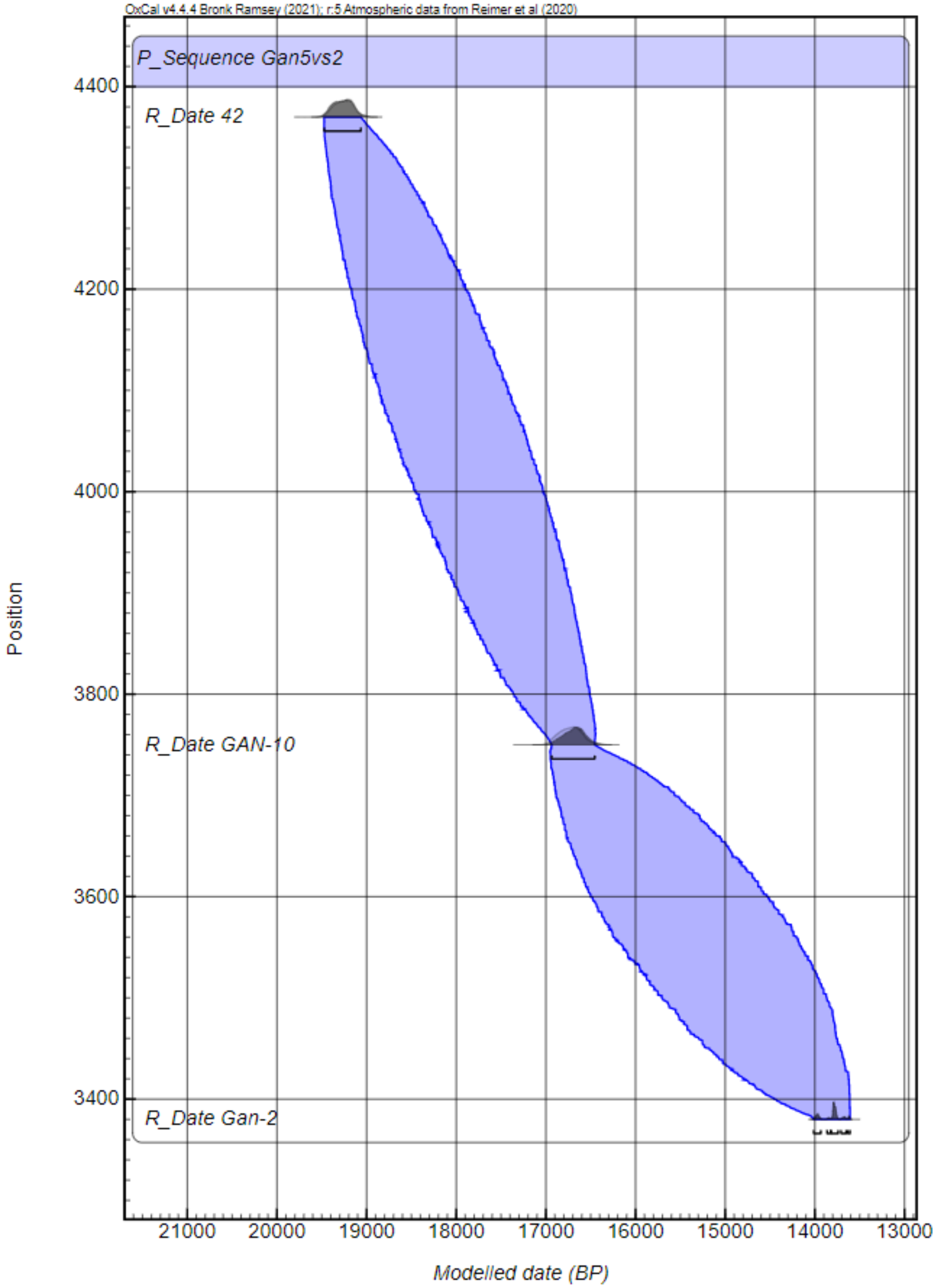
Another age-depth model was created assuming **43 is stratigraphically too old and 44 is stratigraphically incorrect (see Gan5 vs2).**

Age-depth model Gan5 vs2

Rows highlighted in yellow (too young) and blue (too old) and orange have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	
Gan-7	11,294 ± 49	34.6	Stratigraphically too old
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Stratigraphically too old
Gan-4	11,611 ± 38	36	Stratigraphically too old
Gan-5	11,799 ± 31	36.5	Stratigraphically too old
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	
44	15,068 ± 61	39.3	Stratigraphically incorrect
43	18,410 ± 80	41.7	Stratigraphically too old
42	15,941 ± 66	43.7	

Based on the age-depth model created the pollen records spans the time interval between **ca.13,400-16,700 cal. yrs BP**



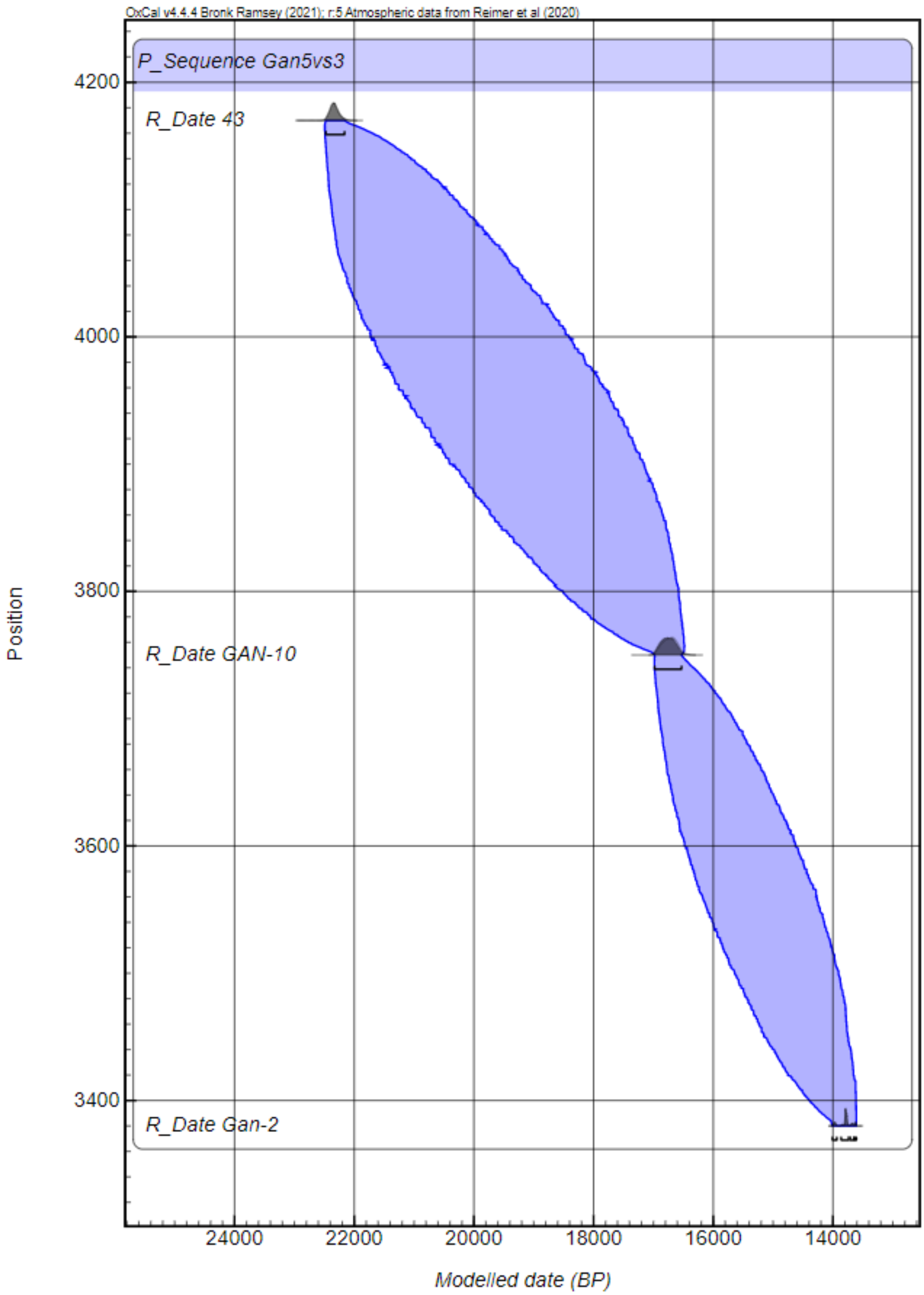
A final age-depth model was created assuming **44 and 42 are not correct stratigraphically (see Gan5 vs3)**

Age-depth model Gan5 vs3

Rows highlighted in yellow (too young) and blue (too old) and orange have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	
Gan-7	11,294 ± 49	34.6	Stratigraphically too old
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Stratigraphically too old
Gan-4	11,611 ± 38	36	Stratigraphically too old
Gan-5	11,799 ± 31	36.5	Stratigraphically too old
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	
44	15,068 ± 61	39.3	Stratigraphically incorrect
43	18,410 ± 80	41.7	
42	15,941 ± 66	43.7	Stratigraphically too young

Based on the age-depth model created the pollen records spans the time interval between **ca.12,900-16,800 cal. yrs BP**



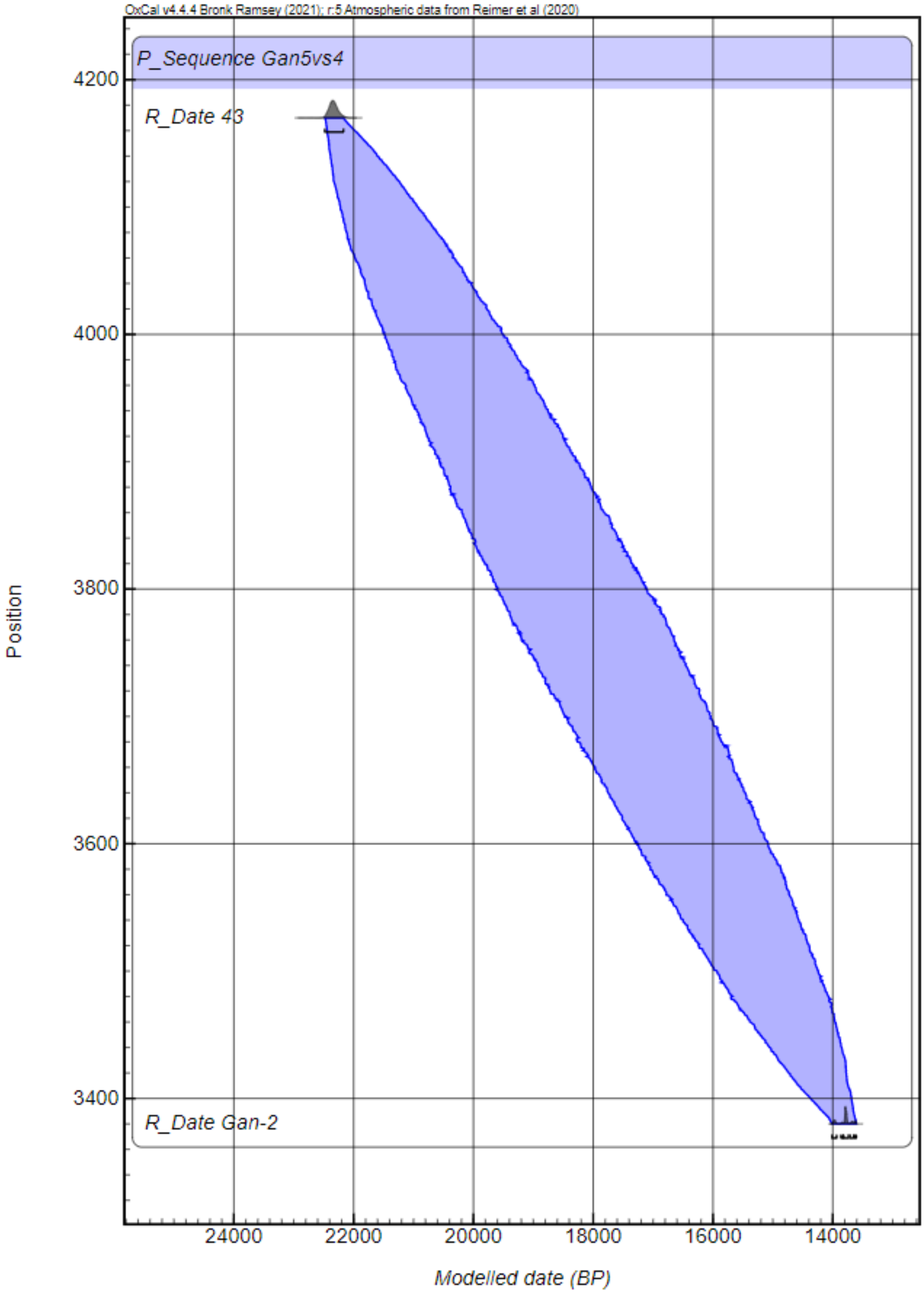
OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Gan5vs3
R_Date 43
R_Date GAN-10
R_Date Gan-2
4200
4000
3800
3600
3400
Position
24000
22000
20000
18000
16000
14000
Modelled date (BP)

Age-depth model Gan5 vs4

Rows highlighted in yellow (too young) and blue (too old) and orange have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ± 32	33.8	
Gan-7	11,294 ± 49	34.6	Stratigraphically too old
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Stratigraphically too old
Gan-4	11,611 ± 38	36	Stratigraphically too old
Gan-5	11,799 ± 31	36.5	Stratigraphically too old
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	Stratigraphically incorrect
44	15,068 ± 61	39.3	Stratigraphically incorrect
43	18,410 ± 80	41.7	
42	15,941 ± 66	43.7	Stratigraphically too young

Based on the age-depth model created the pollen records spans the time interval between **ca.12,900-17,800 cal. ysr BP**

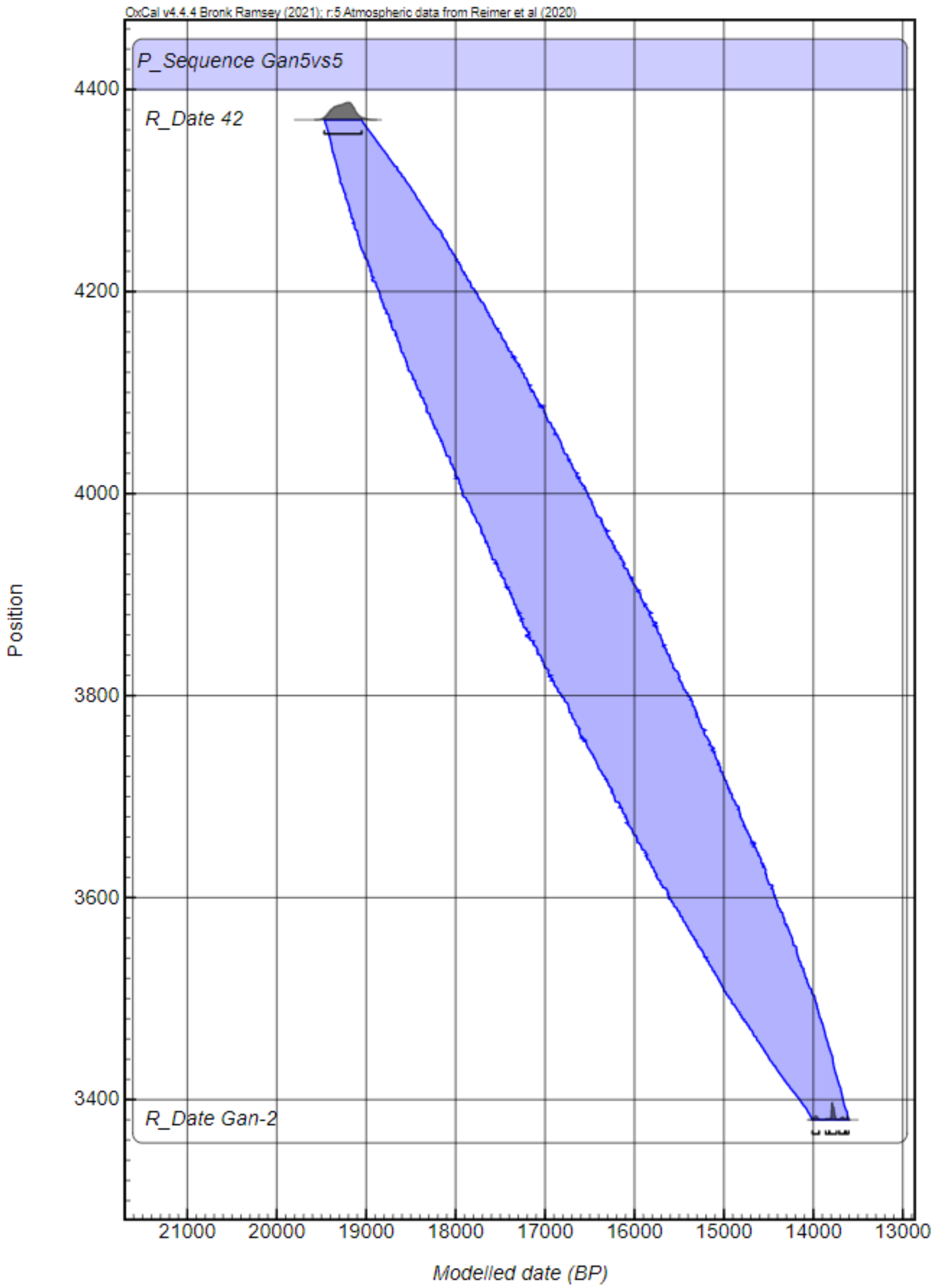

OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Gan5vs4
R_Date 43
R_Date Gan-2
4200
4000
3800
3600
3400
Position
24000
22000
20000
18000
16000
14000
Modelled date (BP)

Age-depth model Gan5 vs5

Rows highlighted in yellow (too young) and blue (too old) and orange have been excluded.

Sample ID	Conventional Radiocarbon Age (BP)	Depth (m)	Reason for excluding
Gan-9.1	15530 ± 29	33.03	Stratigraphically too old – Top of sequence
Gan-1	3772 ± 18	33.2	Holocene date
Gan-2	11,922 ±32	33.8	
Gan-7	11,294 ± 49	34.6	Stratigraphically too old
Gan-8	6606 ± 24	34.9	Holocene date
Gan-3	11,611 ± 28	35.4	Stratigraphically too old
Gan-4	11,611 ± 38	36	Stratigraphically too old
Gan-5	11,799 ± 31	36.5	Stratigraphically too old
Gan-6	7785 ± 48	37	Holocene date
GAN-10	13,784 ± 58	37.5	Stratigraphically incorrect
44	15,068 ± 61	39.3	Stratigraphically incorrect
43	18,410 ± 80	41.7	Stratigraphically too old
42	15,941 ± 66	43.7	

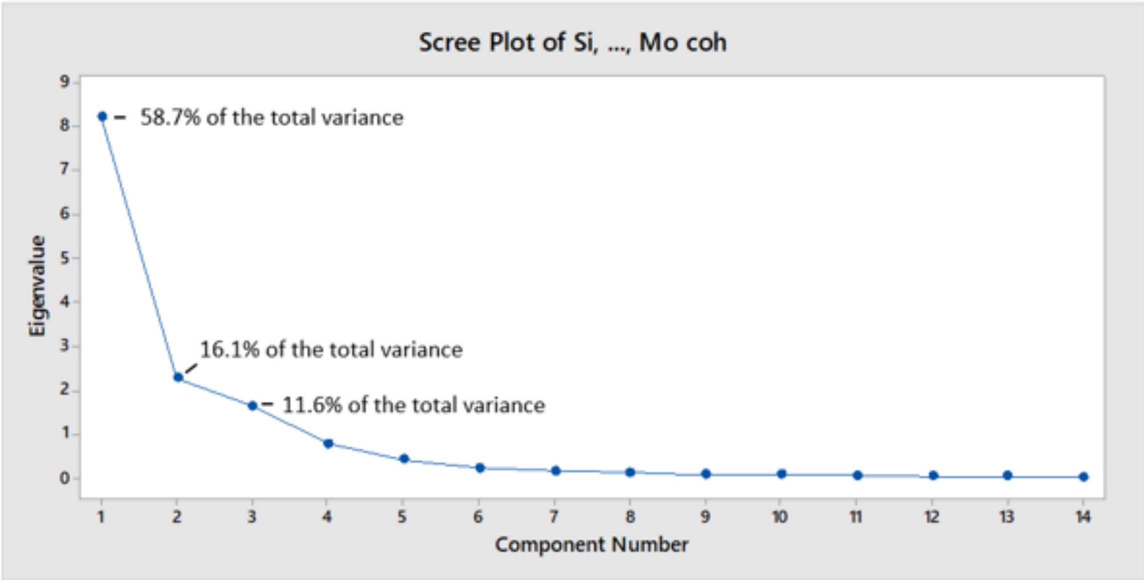
Based on the age-depth model created the pollen records spans the time interval between **ca.13,400-15,800 cal. yrs BP**



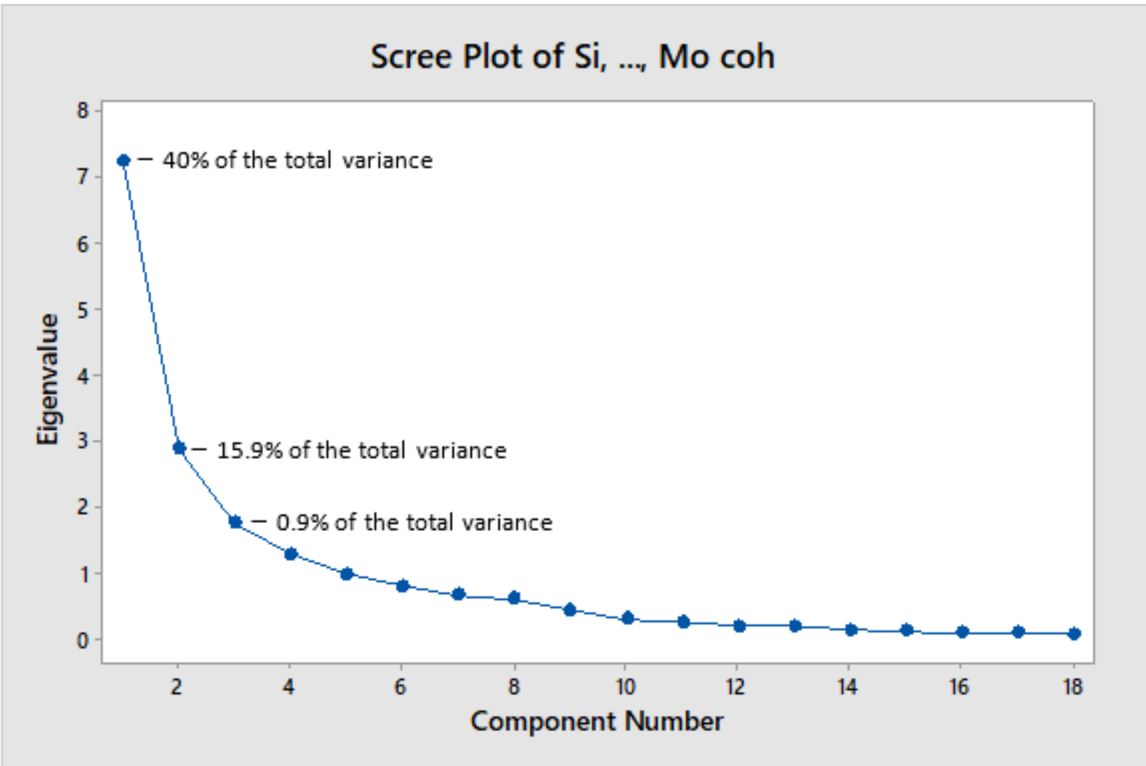
OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al (2020)
P_Sequence Gan5vs5
R_Date 42
R_Date Gan-2
Position
4400
4200
4000
3800
3600
3400
21000
20000
19000
18000
17000
16000
15000
14000
13000
Modelled date (BP)

Appendix 3: Principal component analysis

Hashilan wetland scree plot - *Eigenvalues of correlation matrix*



Lake Ganau scree plot - *Eigenvalues of correlation matrix*



Appendix 4: ITRAX data and Magnetic Susceptibility

See link: https://tinyurl.com/MRabbaniPhDData

Tabs:

- Hashilan ITRAX
- Ganau ITRAX
- Hashilan magnetic susc.

Appendix 5: Pollen, non-pollen palynomorph, microcharcoal data

See link: https://tinyurl.com/MRabbaniPhDData

Tabs:

- Hashilan pollen %
- Hashilan influx
- Hashilan concentration
- Hashilan pollen ratio
- Ganau pollen %
- Ganau concentration
- Ganau influx
- Ganau pollen ration

Appendix 6: Macrocharcoal data – Hashilan wetland

See link: https://tinyurl.com/MRabbaniPhDData

Tabs:

- Hashilan macrocharcoal

Appendix 7: Radiocarbon dates of sites in the region

Site name	Depth (cm) and mean depth (cm)	Material dated	Uncalibrated date	Error	Calibrated date using IntCal20 (BP)	Notes
Arasbaran protected areas	92	Bulk sediment	1258	37	1283-1172 (66.5%) 1165-1113 (21.4%) 1105-1073 (7.6%)	
	182	Bulk sediment	1542	28	1425-1355 (55%) 1517-1430 (40.4%)	
	212	Bulk sediment	2785	30	2959-2840 (80.2%) 2831-2784 (15.2%)	
Caspian sea (Leroy et al. 2014)	69.5 (67-72)	Ostracods	3550	35	3929-3812 (59.8%) 3804-3716 (32.1%) 3968-3946 (3.5%)	
	424.5 (422-427)	Ostracods	8300	140	9545-8983 (95%) 8910-8901 (0.2%) 8825-8813 (0.2%)	
	535.5 (533-538)	Ostracods	9960	120	11,837-11,189 (94.7%) 11,875-11,852 (0.7%)	
	595 (593-597)	Ostracods	10,610	130	12,769-12,045 (95.4%)	
	725 (720-730)	Ostracods	11330	60	13,316-13,111 (95.4%)	
	853 (851-854)	Ostracods	12,260	60	14,456-14,043 (87%) 14,805-14,710 (8.4%)	
Ganli-Gol wetland	256-254	Wood?	2424	17	2495-2357 (85.7%) 2675-2651(5.9%) 2613-2600 (3.8%)	

	446-444	Plant material?	2483	22	2719-2486 (93.7) 2481-2466 (1.7%)	
	500-497	Bulk sediment	2863	20	3065-2924 (90.2%) 2903-2883 (5.3%)	
Gomishan area	250	Gastropoda	1497	15	1401-1346 (95.4%)	
	475	Broken: bivalves	2012	24	2001-1878 (95.4%)	
	890	Gastropoda: Theodoxus	3392	15	3646-3573 (71.7%) 3689 - 3660 (23.8%)	
	1010	Ostracoda: Cyprideis	3529	25	3805-3715 (55%) 3892-3811 (40.1%) 3706-3703 (0.3%)	
	1170	Gastropoda	3644	28	4011-3878 (75%) 4084-4030 (20.4%)	
	1610	Many Ostracoda & Foraminifera	7121	62	8034-7791 (95.4%)	
	1660	Foraminifera: Ammonia beccarii	7248	50	8175-7970 (95.4%)	
	2380	One bovalve	8663	42	9725-9536 (95.4%)	
	2560	Gastropoda: Ps. brusiniana	9717	45	11,240-11,071 (83.2%) 10,946-10,873 (11.5%) 10,836-10,825 (0.7%)	
	2700	Ostracoda: Cyprideis	17,367	65	21,181-20,786 (95.4%)	
Hashilan wetland	80	?	2100	25	2126-1993 (94.4%) 2143-2136 (1.1%)	Paper written in Farsi language
	755	?	31,500	300	36,410-35,275 (95.4%)	
	1193	?	39,500	700	44,195-42,340 (95.4%)	
Konar Sandal	34-35	Bulk sediment	1125	30	1075-956 (90.6%) 1119-1100 (2.5%) 1177-1165 (2.3%)	

	63-64	Bulk sediment	1700	35	1640-1529 (73.7%) 1700-1655 (21.8%)	
	94-95	Bulk sediment	2130	30	2154-2000 (84.6%) 2295-2265 (10.9%)	
	113-114	Bulk sediment	2405	30	2496-2348 (84.2%) 2684-2644 (7.6%) 2613-2598 (3.6%)	
	142-143	Bulk sediment	3010	35	3269-3074 (79%) 3338-3286 (16.5%)	
	194-195	Bulk sediment	3400	35	3724-3558 (89.6%) 3821-3795 (3.8%) 3525-3511 (1.1%) 3762-3755 (0.5%) 3503-3496 (0.5%)	
	234-235	Bulk sediment	3655	35	4090-3877 (95.4%)	
	244-245	Bulk sediment	3570	30	3932-3824 (76.7%) 3972-3942 (8.5%) 3793-3770 (6.5%) 3746-3727 (3.7%)	
Kongor Lake	12–16	Charred vegetative grass remains	845	30	791-684 (95.4%)	
	36–40	Rubus seeds	865	30	798-688 (87.2%) 900-870 (8.3%)	
	49	Bulk sediment	1150	30	1127-962 (88%) 1177-1161 (7.5%)	
	99	Bulk sediment	3900	30	4417-4243 (95.4%)	
	149	Bulk sediment	4200	30	4763-4620 (68.4%) 4844-4792 (27.1%)	

	172-176	Charred vegetative grass remains	4465	35	5290-4969 (95.4%)	
	198	Bulk sediment	5085	35	5913-5743 (95.4%)	
	249	Bulk sediment	3830	30	4304-4146 (80.6%) 4357-4323 (7.2%) 4402-4368 (4.6%) 4118-4097 (3.1%)	
	297	Bulk sediment	5285	35	6126-5988 (64.1%) 6188-6135 (23.3%) 5970-5940 (8.1%)	
Lake Almalou	24.5	Peat	105.84	0.33	???	
	99.5	Peat	830	30	784-681 (95.4%)	
	160.5	Peat	1340	30	1305-1243 (64.6%) 1215-1176 (30.9%)	
	239.5	Peat	1960	50	1995-1745 (95.4%)	
	311.5	Peat	2285	30	2352-2300 (56.1%) 2241-2158 (39.3%)	
	373.5	Peat	2450	30	2543-2361 (54.1%) 2703-2631 (26%) 2619-2558 (15.3%)	
	459.5	Gyttja	3110	30	3391-3235 (95.4%)	
	469.5	Gyttja	3465	30	3833-3681 (83.9%) 3670-3640 (11.6%)	
Lake Maharlou (Djamali et al. 2009)	35.25 (34.5-36)	Bulk sediment	1815	30	1798-1692 (64.3%) 1670-1621 (28%) 1821-1805 (3.1%)	
	73.2 (72.5-74)	Bulk sediment	3075	35	3372-3207 (93.1%) 3194-3179 (2.4%)	

	113 (112.5-113.5)	Bulk sediment	4110	40	4731-4520 (69.2%) 4821-4747 (24.3%) 4465-4450 (1.9%)	
	145 (144.5-145.5)	Bulk sediment	4560	35	5192-5051 (51.3%) 5324-5231 (39.5%) 5439-5417 (3.6%) 5225-5215 (1.0%)	
Lake Maharlou (Brisset et al. 2019; Saeidi Ghavi Andam et al. 2020)	43	Charcoal, Coleoptera, seed	390	30	509-426 (67.1%) 379-320 (28.4%)	
	88	Plant fragment	655	35	607-555 (48.9%) 671-622 (46.5%)	
	159	Charcoal, Coleoptera, seed	2450	50	2622-2358 (71.7%) 2708-2627 (23.8%)	Rejected age due to insufficient weight of carbon
	193	Charcoal	1950	50	1992-1741 (95.4%)	
	237	Charcoal, Coleoptera	2820	90	3171-2756 (95.4%)	
	269	Charcoal, Coleoptera, seed	3800	180	4650-3698 (93%) 4806-4756 (1.6%) 4700-4672 (0.8%)	
	321	Charcoal, Coleoptera, seed	3370	35	3693-3490 (95.4%)	
Lake Mirabad (Van Zeist and Bottema 1977)	479 (475-483)	White shelly marl	10,790	150 **or** 200	13,090-12,480 (95.4%) **or** 13,124-12,426 (87%) 12,401-12,166 (6.9%) 12,131-12,102 (0.7%) 13,160-13,135 (0.6%) 12,157-12,123 (0.4%)	Too old because of 14C-depleted carbonates
	721.5 (720-723)	Dark peaty sediment	10,370	120	12,625-11,816 (94.7%) 12,666-12,642 (0.8%)	Ommited from age-depth model
	90	Charcoal	350	50	496-309 (95.4%)	

Lake Mirabad (Griffiths et al. 2001)	390	Charcoal	4400	50	5067-4853 (76.1%) 5278-5169 (15.9%) 5134-5103 (3.5%)	
	676	Charcoal	7970	60	9000-8638 (95.4%)	
Lake Neor (Alinezhad et al. 2021)	52.5cm	Peat bulk	920	30	915-770 (88.8%) 762-741 (6.6%)	
	152.5cm	Peat bulk	2285	30	2352-2300 (56.1%) 2241-2158 (39.3%)	
	252.5cm	Peaty gyttja bulk	3085	30	3371-3216 (95.4%)	
	372.5cm	Peat bulk	4775	35	5590-5461 (91%) 5375-5358 (2.5%) 5346-5332 (2%)	
	472.5cm	Peat bulk	5990	40	6945-6733 (95.4%)	
Lake Neor core B (Aubert et al. 2017)	602.5	Peaty gyttja	5285	35	6126-5988 (64.1%) 6188-6135 (23.3%) 5970-5940 (8.1%)	
	652.5	Peaty gyttja	7290	40	8179-8018 (95.4%)	
	702.5	Dark gyttja	9300	50	10,596-10,292 (91%) 10,653-10,620 (4.4%)	
	752.5	Brown gyttja	10,630	60	12,735-12,598 (79.3%) 12,543-12,490 (16.2%)	
	777.5	Brown gyttja	12,300	60	14,530-14,068 (80.8%) 14,819-14,698 (14.7%)	
	798	Wood (Salix root)	12,270	70	14,525-14,041 (83.9%) 14,817-14,699 (11.6%)	Not used in the age-depth model
Lake Parishan	225.5		3745	90	4405-3889 (95.4%)	230Th date Calendar years BP
	?	Mud	1705	30	1630-1533 (73.5%) 1698-1660 (21.9%)	

	125.5	Mud	2685	35	2854-2748 (95.4%)	
	225.5	Mud	3750	30	4160-4063 (60.3%) 4050-3986 (23.3%) 4233-4198 (9.7%) 4183-4167 (2.1%)	
Lake Urmia (Bottema 1986)	207.5 (205-210)	Fine aragonite pellets	7505	125	44,195-42,340 (95.4%)	
	297.5 (295-300)	Pellet (*artemisia*)	9540	130	11,204-10,510 (95.4%)	
	1.5	Pellet (*artemisia*)	2690	105	3076-2490 (94.9%) 3105-3097 (0.3%) 3137-3129 (0.2%)	Rejected
Lake Urmia (Djamali et al. 2008)	8500	Aragonit	?	2400		Uranium series -Calendar years BP . 230Th date given by the author Morteza Djamali in 2009 and is not published.
	800	Bulk sediment	10,345	40	12,206-11,967 (51.1%) 12,467-12,344 (25.6%) 12,277-12,218 (10.6%) 12,333-12,293 (7.4%) 11,958-11,949 (0.8%)	
	1850	Bulk sediment	24,750	200	29,350-28,578 (93.7%) 29,502-29,371 (1.7%)	
Lake Urmia (Talebi et al. 2016)	30	Bulk sediment	110.1	0.37	???	
	48	Bulk sediment	845	30	791-684 (95.4%)	
	151	Bulk sediment	875	30	825-720 (79.2%) 904-866 (13.8%) 708-693 (1.8%) 854-848 (0.6%)	
	183	Bulk sediment	2715	30	2864-2757 (95.4%)	

Lake Zeribar	1415 (1410-1420)	Sediment	8100	160	9435-8596 (95.4%)	Core 63-J
	1715 (1710-1720)	Sediment	11,480	160	13,612-13,093 (93.2%) 13,741-13,706 (1.3%) 13,657-13,630 (0.9%)	Core 63-J
	1895 (1890-1900)	Sediment	13,650	160	17,009-16,053 (95.4%)	Core 63-J
	2540 (2535-2545)	Sediment	22,000	500	27,294-25,326 (95.4%)	Core 63-J
	670-700	Cladium fruit	4010	75	4655-4246 (84.7%) 4814-4752 (7.0%) 4713-4666 (3.8%)	Core 63-J (unpublished H.E. Wright)
	1610-1620	Plant macroremain	11,850	120	14022-13,493 (95.4%)	Core 63-J (unpublished H.E. Wright)
	1675-1680	Plant macroremain	10,300	50	12,198-11,875 (67.2%) 12,462-12,348 (16.8%) 12,272-12,223 (5.6%) 12,330-12,298 (4.1%) 11,858-11,833 (1.7%)	Core 63-J (unpublished H.E. Wright)
	1745-1750	Plant macroremain	12,050	55	14,050-13,800 (95.4%)	Core 63-J (unpublished H.E. Wright)
	1790-1800	Plant macroremain	12,750	110	15,601-14,868 (95.4%)	Core 63-J (unpublished H.E. Wright)
	700-710	Sediment	2240	150	2712-1920 (94.6%) 1910-1890 (0.8%)	Core 63-B
	3422.5 (3415-3430)	Sediment	37,350	1250	43,953-40,081 (95.4%)	Core 70-A
	4021 (4015-4027)	Sediment	29,780	1400	38,195-31,216 (95.4%)	Core 70-A
	22.1	Plant macroremain	17,729	98	21,885-21,091 (95.4%)	Core 70-A (unpublished H.E. Wright)
	23.3	Plant macroremain	19,360	130	23,475-23,023 (64.3%) 23,742-23,485 (31.2%)	Core 70-A (unpublished H.E. Wright)

	24	Plant macroremain	21,900	150	26,433-25,885 (95.4%)	Core 70-A (unpublished H.E. Wright)
	4022.5 (4015-4030)	Sediment	42,600	3600	52,822-42,532 (87.4%) 54,989-53,340 (8.1%)	Core 70-A-2. Left out of consideration in the paper by van Zeist and Bottema (1977) because it was not in accordance with the other data
	990-1010	Calcareous gyttja	5460	120	6490-5988 (93.8%) 5969-5941 (1.6%)	Core I-13
	1625	Calcareous gyttja	14,800	300	18,754-17,332 (95.4%)	Core I-12
	978-993	Calcareous gyttja	5640	70	6565-6295 (92.4%) 6621-6585 (3.1%)	Core 70-B
	1100-1115	Calcareous gyttja	6890	80	7866-7586 (91.8%) 7923-7898 (3.7%)	Core 70-B
	1360-1375	Calcareous gyttja with shells	10,600	100	12,755-12,431 (85%) 12,395-12,321 (3.4%) 12,239-12,171 (3.4%) 12,310-12,250 (3.3%) 12,118-12,104 (0.4%)	Core 70-B