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LATE QUATERNARY FIRE HISTORIES IN THE EASTERN MEDITERRNEAN REGION FROM LAKE SEDIMENTARY MICRO-CHARCOALS

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LATE QUATERNARY FIRE HISTORIES IN THE EASTERN MEDITERRNEAN REGION FROM LAKE SEDIMENTARY MICRO-CHARCOALS

By

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Late Quaternary fire histories in the Eastern Mediterranean region from lake sedimentary micro-charcoals.

The Eastern Mediterranean has a long history of human occupation, which spans the transition from hunter-gatherers to the establishment of early agro-pastoralist communities, coinciding with the Last Glacial: Interglacial transition. Over the same timeframe a delay in postglacial woodland recolonisation in the region has been identified. Fire has long been used by people to manage and manipulate the landscape, and has been hypothesised to have played a role in this delay. This thesis employed lacustrine microcharcoal (particles less than 180 µm) remains to reconstruct Late Quaternary fire histories for Central Turkey and the Levant, and examine the possible role that fire may have played in retarding woodland development in the region. Microcharcoals were analysed in cores taken from four sites in Central Turkey (Akgöl, Eski Acıgöl, Çatalhöyük and Nar Gölü) and one site in Israel (Lake Hula) that cover varying time intervals from the Last Glacial through to the Late Holocene.

In order to develop a standardised analytical procedure for microcharcoals, a series of published extraction and quantification techniques along with a new approach using heavy liquid separation were rigorously tested on "control" samples that contained a known volume of microscopic charcoal. As a result of this investigation a novel, two step extraction procedure based on the use of heavy liquid separation was developed and applied alongside a contiguous high resolution sampling strategy.

Using this approach, fire activity was reconstructed based on cores from each of the sites and these data were compared with existing multi-proxy data (stable oxygen isotopes, pollen and archaeological data). Results show clear links between climate, biomass, people and fire, although these relationships changed over time. Regional fire activity during the Last Glacial: Holocene transition was apparently controlled by climate through the influence it exerted on biomass availability, whereas links between people and fire activity are most evident during the Late Holocene. Humans do not seem to have retarded the Early Holocene spread of woodland through the use of fires, although it is possible that natural fire activity served to maintain the open parkland vegetation communities may have played a role. During the Mid Holocene a mixture of climatic and anthropogenic controls apparently influenced regional fire activity. Evidence was also identified of a ca.1,500 year periodicity in fire history from Central Turkey which may reflect teleconnections to climatic changes in the North Atlantic. This research also highlighted the potential of using microscopic charcoal to infer the spatial resolution of fire history reconstructions from lake basins of different sizes and types through comparisons of influx values.

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For Kathleen Priestley – This is it Grandma I am all finished now.

Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

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Roberts, N., Reed, J.M., Woodbridge, J., Turner, R., Leng, M.J. & Eastwood, W.J. (2006). Replicating proxy-climate records: a lake sediment based study from the East Mediterranean. *10th International Paleolimnology Symposium.* Duluth, Minnesota, USA. June 25th to 29th 2006.
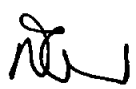
Seminars were also presented to the School of Geography, University of Plymouth (March, 2004; May 2006).

Publications

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Introduction

(1.1) Late Quaternary environmental change in the Eastern Mediterranean

The Last Glacial in the Eastern Mediterranean was characterised by cold, arid conditions (Bar-Matthews *et al.*, 1997; COHMAP Members, 1988; Roberts & Wright, 1993; Robinson *et al.*, 2006) (an overview of the inferred regional climate adapted from Bar-Matthews *et al.*, 1997 is presented in Table 1.1). Evaporation rates fell which resulted in high lake levels throughout Africa, Arabia and the Eastern Mediterranean (Bar-Matthews *et al.*, 1997; COHMAP Members, 1988; Roberts & Wright, 1993). The Last Glacial (hereafter Greenland Stadial 2, 21,200 to 14,700 years BP (GS-2) – see section 1.8 for a detailed explanation of the chronostratigraphic framework applied in this thesis) peaked in the so-called Last Glacial Maximum at ca.21,000 ± 3,000 cal. years BP ca. years BP (Mix *et al.*, 2001). In the northern hemisphere ice sheets then started to retreat with a warming of global climates (Greenland Interstadial 1, 14,700 to 12,650 (GI-1), see section 1.8), synchronous with the Bølling-Alleröd in Europe (Bar-Mathews *et al.*, 1997; COHMAP Members, 1988). Climatic amelioration was interrupted by the Younger Dryas (hereafter Greenland Stadial 1 12,650 to 11,500 years BP (GS-1), see section 1.8) a widespread cooling event that saw the reversion to "quasi-glacial" conditions of a cold, arid climate and the re-expansion of ice sheets (Alley *et al.*, 1993; Rossignol-Strick, 1995). GS-1 ended very rapidly with the onset of the Holocene ca.11,500 cal. years BP (Alley *et al.* 1993; Becker *et al.*, 1991). The Early Holocene is hypothesised to have experienced the most favourable climatic conditions of the Holocene, whereby winters became frost-free and summer precipitation occurred, as evidence from speolothems has demonstrated (Bar-Matthews *et al.*, 1997; Robinson *et al.*, 2006).

Climatic episode	Overview of regional climate
GS-2	Cold, arid climate with low precipitation and evaporation.
GI-1	Climatic warming; increasing rainfall (speleotherm estimates ca 550 to 750 mm/year) and temperatures (ca.14.5 to 18.0°C).
GS-1	Reversion to quasi-glacial conditions; reduced temperatures and precipitation leading to climatic aridity,
Early Holocene	Rapid climatic amelioration; increased temperatures (14.5 to 19.0°C) and precipitation (675 to 950 mm/year) resulting in higher summer precipitation and frost-free winters.
Mid Holocene onwards	Establishment of contemporary climatic conditions characterised by summer drought, an increase in average temperatures (18.0 to 22.0°C) and reduced rainfall (450 to 580 mm/year), the majority of which falls during the winter and spring months. The trend of climatic aridification continued, exacerbated by anthropogenic impacts of the landscape.

Table 1.1: Inferred regional climate for the Eastern Mediterranean from the Last Glacial through to the Holocene (adapted from Bar-Matthews *et al.*, 1997; 1999; Robinson *et al.*, 2006)

Pollen records from lakes located in the Eastern Mediterranean (Figure 1.1), have demonstrated that these climatic changes exerted a direct impact on the vegetation communities of the region. The cold, arid climate of GS-2 was characterised by open, desert-steppe vegetation in which only plants tolerant of extreme aridity e.g. Chenopodiaceae and *Artemisia* spp. occurred (Robinson *et al.*, 2006). For example, at

Lake Zeribar (Iran) steppic herbs accounted for 50 to 80% of the vegetation cover and a similar level of steppic herb abundance has been recorded in numerous sites throughout the region e.g. Eski Acıgöl (Central Turkey) and Lake Van[1], (southeast Turkey) (Figures 1.2a, 1.2b & 1.2c) ((El-Moslimany, 1987; van Zeist & Bottema, 1991; Wasylikowa, 2005)). Trees were restricted to sheltered pockets of favourable climatic conditions in the eastern and western Taurus, Zagros, Levantine and Balkan Mountain ranges, which served as glacial refugia for woodland taxa (Bennett *et al.*, 1991; Roberts 1982; van Zeist & Bottema, 1991; Wasylikowa, 2005). The climatic warming (GI-1) following the end of the GS-2 saw the replacement of desert-steppe with grass-steppe and the initial migration of trees from glacial refugia (Rossignol-Strick, 1995). However, the reversal back to glacial conditions during the GS-1 halted the spread of trees and resulted in the re-expansion of steppic herbs (Rossignol-Strick, 1995; van Zeist & Bottema, 1991). With the onset of the Holocene, and the associated increase in the precipitation: evaporation balance, the steppic herb community was again replaced by grass steppe and trees again began to recolonise from glacial refugia.

However, woodland recolonisation throughout the Eastern Mediterranean region was not synchronous. In Greece, e.g. Gramousti, Ioannina, Rezina and Tenaghi Philippon, and Northern Turkey maximum tree pollen values were reached several thousand years earlier than in Central Turkey and Western Iran (Lawson *et al.*, 2004; Roberts, 1982; 2002; Willis, 1992; 1994; Wijmstra, 1969). For example, the pollen record from Lake Zeribar (Iran), shows a rapid reduction in steppic herbs which were replaced by Gramineae steppe, yet arboreal pollen remained below 10% during the Early Holocene (Figure 1.2a) (El-Moslimany, 1987; Rossignol-Strick, 1993; van Zeist & Bottema, 1991; Wasylikowa, 2005). Maximum arboreal pollen values in Lake Zeribar were not reached until ca.6,500 cal. years BP (Figure 1.2c) (Wasylikowa, 2005). Likewise, at Eski Acıgöl and Lake Van, maximum arboreal pollen values were not reached until ca.5,500 cal. years BP and ca.6,000 varve years BP respectively (Figure 1.2a and 1.2b) (Wick *et al.*, 2003; Woldring & Bottema,

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[1] The chronology of this site is based on varve counts and therefore dates are expressed as varve years BP.
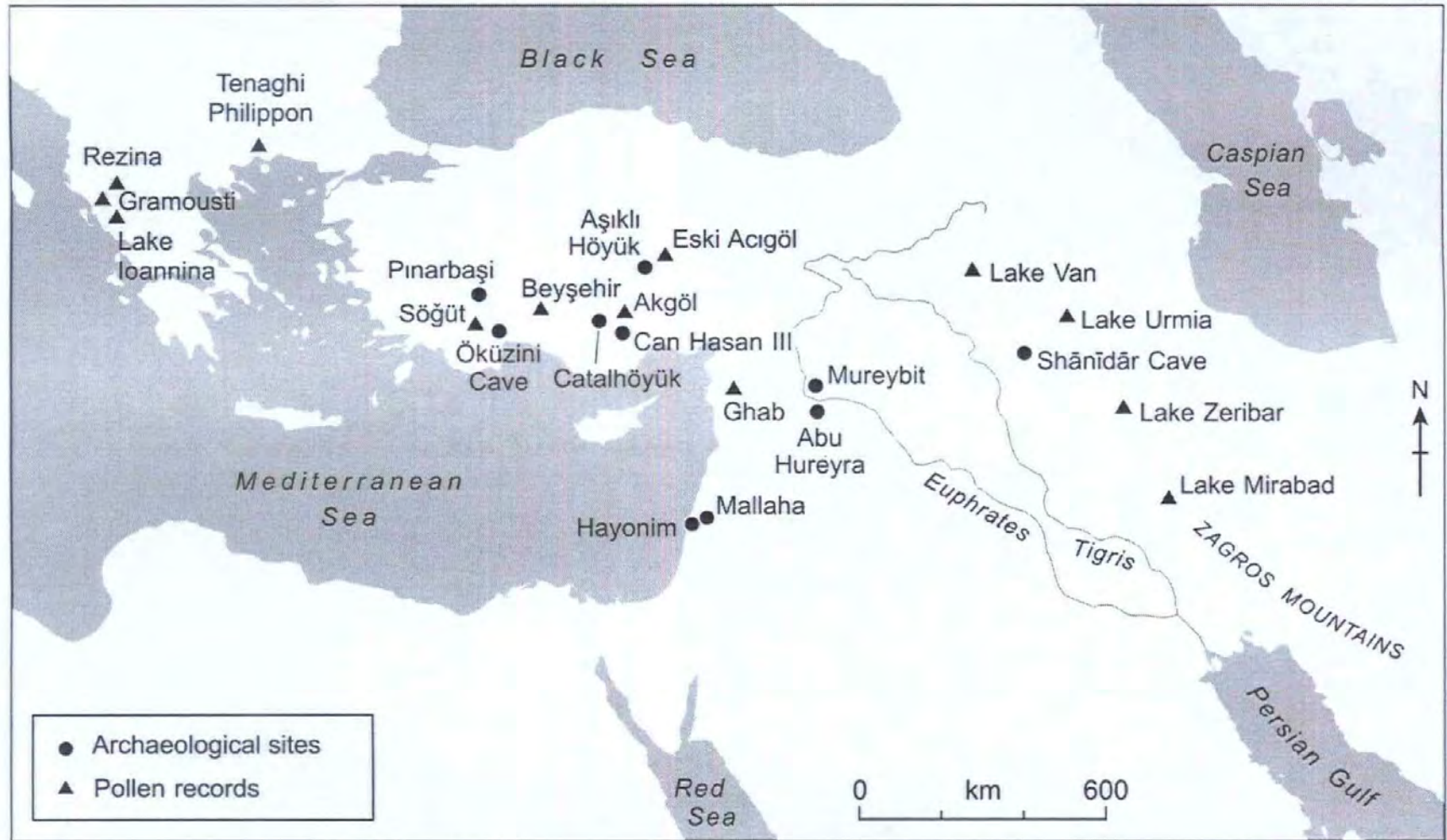
Figure 1.1: Map of the lake and archaeological sites mentioned in this Chapter.
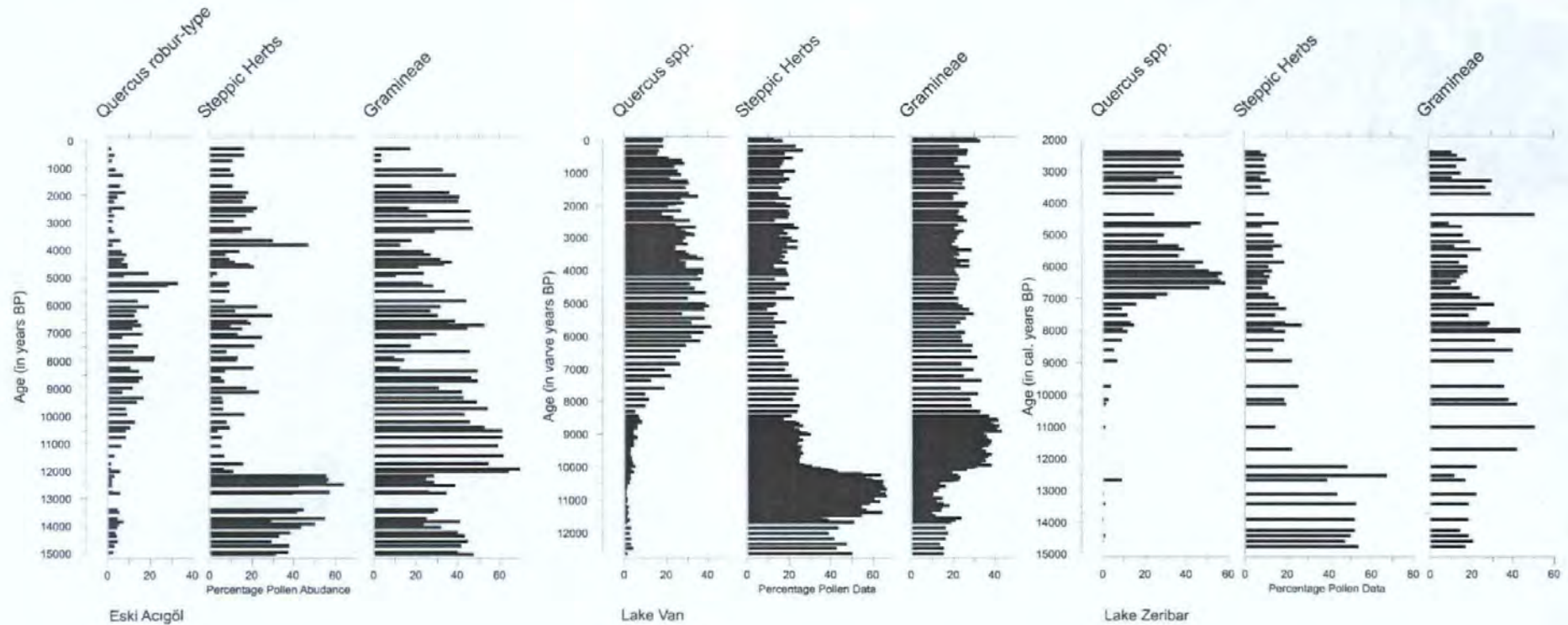
Figure 1.2a: Pollen diagram from Eski Acigol, Cappadocia, Central Turkey (Woldring & Bottema, 2001); **1.2b:** Pollen diagram from Lake Van, Turkey (Wick *et al.*, 2003); **1.2c:** Pollen diagram from Lake Zeribar, Iran (van Zeist & Bottema, 1977). Steppic herbs include both *Artemisia* spp. and Chenopodiaceae

2001). A further six pollen records also show a delay in woodland recolonisation. These include Akgöl (Konya, Turkey), Beyşehir, Söğüt (southwest Turkey) and Mirabad (Iran) (Bottema & Woldring, 1986; van Zeist & Bottema, 1977) (Figure 1.1). A delay in the timing of woodland recolonisation of approximately 5,000 years has been identified in sites from interior areas of the Eastern Mediterranean and Iran compared to coastal areas which experienced the recolonisation of woodland soon after the onset of the Holocene (Roberts, 2002; Roberts & Wright, 1993; van Zeist & Bottema, 1991; Wick *et al.*, 2003; Woldring & Bottema, 2001).

(1.2) Why was there a delay in woodland recolonisation?

The delay in woodland recolonisation between interior and coastal areas has long been recognised in the palaeoenvironmental record (e.g. van Zeist & Bottema, 1977; Roberts, 1982), but, the cause of this delay remains unclear. Several theories have been proposed to explain the delay in woodland recolonisation. These include climatic unsuitability (Roberts & Wright, 1993), the time taken for trees to migrate from refugia in the Taurus, Zagros and Balkan Mountains and the Levant (migration lag - Wright, 1976), and edaphic factors. The delay in woodland recolonisation was originally interpreted by palynologists as being a function of relative climatic aridity at the beginning of the Holocene (e.g. Roberts & Wright, 1993). As discussed above, however, other proxy records have shown that the Early Holocene was characterised by rapid increases in the amount of precipitation falling in the region (Bar-Matthews *et al.*, 1997; 1999; Rossignol-Strick, 1999). Evidence for these optimal climatic conditions were derived from lake level reconstructions using isotopic measurements and diatom analyses and have now been widely accepted (e.g. Bar-Matthews *et al.*, 1997; Goodfriend, 1999; Snyder *et al.*, 2001; Roberts *et al.*, 2001). Therefore climatic factors are not likely to have been responsible for the delayed spread of woodland.

Using pollen data the rates of dispersal from areas of refugia have been modelled. These models have demonstrated that each taxon responds independently to the environmental and climatic improvements, therefore migration rates vary (Huntley, 1990). However, estimates of 50 to 500 metres per year were identified for most species (Birks, 1989; Huntley, 1990). These relatively rapid dispersal rates demonstrate that although the spread of tree species was time-transgressive, as soon as the climate became favourable trees did begin to spread to areas they retreated from when the climate deteriorated (Bennett *et al.*,

1991). It seems highly likely that the same would have occurred in the Eastern Mediterranean.

Roberts (2002) also suggested woodland recolonisation may be retarded by the need for postglacial soil development. Whilst such an argument may apply to glaciated and periglaciated areas particularly at high elevations, it remains unclear what role edaphic factors played elsewhere in this region. Likewise, although soil development is a highly complex process which is controlled by the interaction of numerous factors, (e.g. mechanical and chemical weathering agents, plant roots, mycorrhizae and the organic content of the soil), in many Mediterranean areas woodlands are known to develop over a range of soil types of differing depths and composition (Colinvaux, 1993; Grove & Rackham, 2001). Therefore it is highly likely that soil developmental factors did not hinder the recolonisation of woodlands (Grove & Rackham, 2001).

An alternative, as yet untested hypothesis that may explain the delay in woodland recolonisation relates to human activity at the time of the climatic shifts occurring during the GS-2: Holocene transition. There is archaeological evidence of the presence of people in the Levant from GI-1 and Central Turkey from the Early Holocene (Asouti, 2003; Bar-Yosef, 1998; Asouti & Hather, 2001; Esin, 1991; Roberts, 2002). As well as significant changes taking place in the climate and environment of the Eastern Mediterranean at this time, there was a change in human behaviour that saw the gradual shift from nomadic hunter-gatherer communities to the adoption of a sedentary way of life associated with the onset of agriculture and domestication of wild plants.

(1.3) Plant and animal domestication in the Eastern Mediterranean
South-west Asia has long been recognised alongside Africa, China, Mesoamerica, the Andes and the Eastern United States as one of the main centres where early agricultural domestication occurred (Blumler, 1991; Diamond, 1997; Harris, 1998; Zohary & Hopf, 2000). In the Eastern Mediterranean domestication was located in the area defined by Hillman *et al.* (2001) as the Fertile Crescent where the wild progenitors of domesticated crops occurred naturally.

The climatic warming following GS-2 provided the optimal conditions for plant growth (i.e. sufficient moisture availability) as exemplified by the initial expansions of open parkland steppe (Hillman *et al.,* 2001; Emery-Barbier & Thiébault, 2005; Zohary, 1973).

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The open parkland steppe, which is characterised by scattered trees and a diverse grass dominated ground cover, provided a large resource base for hunter-gatherers due to the natural occurrence of wild wheat, rye, legumes, lentils and other potential crop plants (Bottema, 2002; Zohary & Hopf, 2000). This widely available resource base is believed to have led to an increase in population and allowed the subsequent adoption of a more sedentary way of life. The shift to the adoption of sedentary settlements has been recorded in archaeological sites in the southern Levant e.g. Ein Mallaha, and Hayonim Cave (Figure 1.1) (Bar-Yosef & Goren, 1973). They show that with the shift to sedentary settlements there was the adoption of complex social rituals such as burial practices (Mithen, 2003). These settlements were generally located at the junction between dense woodland and open parkland which may have maximised the resource base for the community (Mithen, 2003).

The onset of the GS-1 saw a crash in the availability of this wild resource base as those species that were intolerant of drought became locally extinct (van Zeist & Bottema, 1991). However, this loss of wild plant resources, driven by climatic and environmental changes during the GS-1 is widely believed to have provided a trigger for the development of agriculture in the region (Cappers *et al.*, 1998; Harris, 1998; Hillman *et al.*, 2001; Wright, 1976*)*. Therefore at some point during GS-1 the shift to cultivation occurred. Abu Hureyra (Euphrates Valley) has a continuous record of occupation throughout GS-1 and at this site archaeobotanical evidence points to the cultivation of rye throughout the GS-1, at a time when wild stands of these species had become locally extinct (Hillman *et al.*, 2001; Moore *et al.*, 2000).

Therefore by the onset of the Holocene plant domestication was underway and soon followed by animal domestication (Diamond, 1997). It is unlikely that it was adopted immediately, as it has been hypothesised that it took approximately a thousand years for the shift from a hunter-gathering to a farming economy to occur (Hillman *et al.*, 2001). By the onset of the Neolithic at the start of the Holocene, a shift in settlement pattern occurred that saw the occupation of fertile floodplains and alluvial fans and the subsequent spread of farming from its origins in the Levant into Greece, the southern Balkans and beyond (Bottema & Woldring, 1990; van Andel & Runnels, 1995; Zohary & Hopf, 2000).

Areas that were the focus of human activity, e.g. the open parklands, coincide with the areas that exhibited a delay in woodland recolonisation. As mentioned, the open-parklands hosted the diverse grass communities that included the wild cereals. Therefore the

expansion of woodland would have had a negative effect on the availability of these resources, and it is possible that the hunter-gatherer or early agro-pastoralist communities artificially retarded the spread of woodland to maintain the open-parklands (Emery-Barbier & Thiébault, 2005; Lewis, 1972). A mechanism by which hunter-gatherer and early agro-pastoral communities could have retarded the spread of woodlands and managed the vegetation is through the use of fire.

(1.4) Natural and anthropogenic fire in parklands

Under natural conditions, climate, vegetation/biomass (fuel) and fire are inextricably linked (Carrión et al., 2001; Pausas, 2004; Whelan, 1995) (Figure 1.3). This relationship is not surprising based on the dominant control climate exerts on many aspects of the natural environment (Zolitschka & Negendank, 1999). The nature of the climate (e.g. humid vs. arid) influences the basic composition of a vegetation community and therefore fuel availability (Brown et al., 2005; Camill et al., 2003; Carrión et al., 2001). For example, in the North American prairies clear links have been identified throughout the Holocene between phases of increased humidity which has promoted vegetation growth, increasing fuel load and fire occurrence (Briggs & Knapp, 1995; Brown et al., 2005; Camill et al., 2003; Lynch et al., 2004). Climate also exerts an overriding control on the fire regime in terms of the seasonality of fire occurrence, as well as providing the ignition source (Carcaillet et al., 2001a; 2002; Carrión et al., 2001; Figure 1.3). People modify the natural patterns of biomass burning through their manipulation and management of vegetation communities, and practices of either fire suppression or promotion (Carcaillet et al., 2002; Clark & Royall, 1995). In vegetation communities where fire has played an integral role in the community for thousands of years, regular burning of the landscape may have promoted the spread of fire tolerant vegetation such as that found in the Mediterranean Basin today (Carcaillet et al., 2002; Grove & Rackham, 2001). Therefore in many ecosystems fire is essential to the maintenance and regeneration of the ecosystem (Naveh, 1974; Scholes & Archer, 1997). Eastern Mediterranean parklands are a classic example of an ecosystem where under natural conditions fire is fundamental to the maintenance of the community and of an ecosystem where people have used fire to manage to landscape (Naveh & Carmel, 2003).
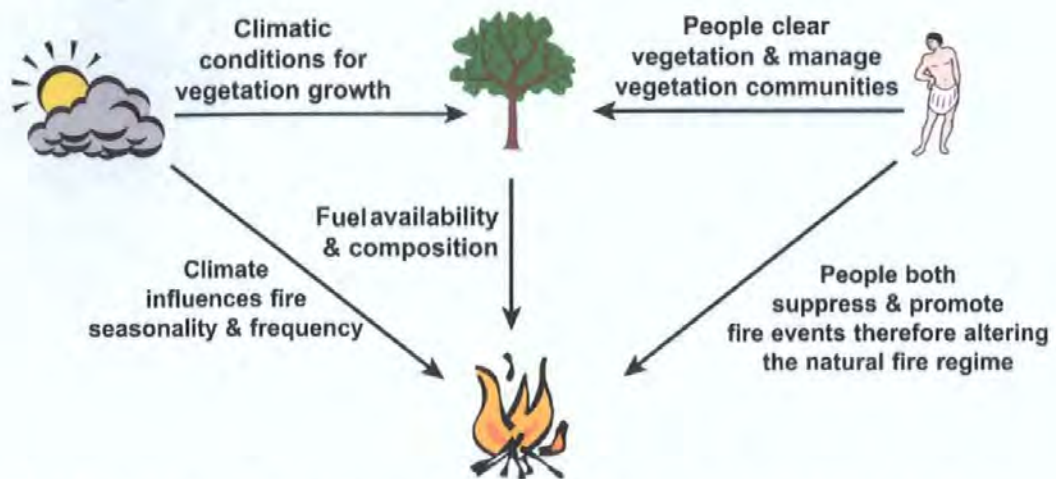
Figure 1.3: The relationship between climate, biomass availability, people and fire occurrence

Fire acts as a significant disturbance mechanism operating within Eastern Mediterranean parklands and therefore has a central role in stimulating the regeneration of vegetation (Naveh, 1974; Pausas, 2004; Trabaud, 1994). Eastern Mediterranean parklands are associated with semi-arid climates which experience a long summer drought (Naveh, 1974; Van Zeist & Bottema, 1991). During the summer drought, high temperatures and low humidity dries out the vegetation and enhances its flammability (Naveh, 1974; Pausas, 2004; Riggan *et al.*, 1998). Toward the end of the summer drought, lightning storms occur, providing an ignition source, resulting in low-intensity, stand replacement ground fires (Komerak, 1967). These stand-replacement fires occur periodically when the vegetation has grown dense and unproductive. Globally in mediterranean-type vegetation communities, prairies and in Eastern Mediterranean parkland close links have been established between grasses and the susceptibility of the ecosystem to fire (e.g. Brown *et al.*, 2005; Clark *et al.*, 2001; Vilà *et al.*, 2001). Grasses are not only an important constituent of overall biomass of these ecosystems they are also an important fuel source (Camill *et al.*, 2003; Grove & Rackham, 2001). Grasses are highly combustible and produce extensive, fast moving fires due to their low moisture content and a high proportion of biomass that is readily available to burn (Brown *et al.*, 2005; Vilà *et al.*, 2001). Regular burning of grasses impedes the encroachment of woody vegetation and trees, serves to release nutrients trapped in old lignified woody stems, reduces resource competition and maintains a diverse vegetation community (Riggan *et al.*, 1998; Vilà *et al.*, 2001). Research has shown that as the woody plant and tree density increases within

grasslands there is a fall in the incidence of fires as the availability of fine, readily combustible fuel declines (Camill *et al.,* 2003; Clark *et al.,* 2001).

After a fire event, parkland ecosystems exhibit a rapid recovery, whereby plant species present prior to the fire gradually redevelop following an auto-successional pathway (Mutch, 1970). The resources released by the fire event are quickly utilised by seeds that have lain dormant within the soil, the fire event serving to stimulate their germination. The subsequent growth of the plant community coincides with the autumnal and spring rainfall associated with semi-arid climates (Naveh, 1974). The early post-fire community is diverse, including numerous species of grasses, tubers and legumes, all of which were important to hunter-gatherer and early agro-pastoralist communities (Komerak, 1967; Naveh, 1990; Naveh & Carmel, 2003; Pyne, 1993). As the time from the fire events passes, the grasses are gradually replaced by herbaceous vegetation and trees, resulting in the gradual closing of the canopy and the loss of the diverse grass community. It is once the community has reached this stage that the likelihood of another fire event increases. Therefore, within parkland ecosystems natural fire events have not only strong seasonal pattern (i.e. following the summer drought) but also they demonstrate a fixed periodicity or return interval.

As discussed, Eastern Mediterranean parkland ecosystems host many of the plant species utilised by hunter-gatherer and early agro-pastoralist communities. Fire promotes the growth of some but not all (e.g. wild barley is intolerant of fire) of these plant species (Zohary & Hopf, 2000). However, fire does maintain the open grassland communities where these species occur naturally. Therefore, it is not coincidental that in the Eastern Mediterranean and south-west Asia, plant domestication took place within these vegetation communities (Pyne, 1993). It is also likely that fire played a role delaying the recolonisation of woodlands. The use of fire, as acknowledged by Lewis (1972) and Naveh & Carmel (2003), would have maintained the open grasslands, promoted their growth and prevented the encroachment of woodland. There are numerous documented examples of the use of fire by the Native Indians in America and the Aborigines in Australia (e.g. Clark, 1983; Day, 1953; Keeley, 2002; Kershaw, *et al.* 1997; Lewis, 1985; Woodcock & Wells, 1994). Therefore it is highly likely that fire played a role in both agricultural domestication and delayed woodland recolonisation.

(1.5) Charcoal as a palaeoenvironmental tool

The occurrence of fire events can be recorded within the palaeoenvironmental and archaeological record. The products of fire events include charred plant remains (e.g. seeds) and micro and macroscopic charcoal particles, of which microscopic charcoal particles are to be the main focus of this thesis. Charcoal particles are the product of the incomplete combustion of plant material (Patterson *et al.*, 1987). Under suitable conditions, the products of fire, particularly microscopic charcoal, can be incorporated in depositional environments e.g. lakes or bogs, where they are readily preserved and can remain undisturbed for thousand of years.

Microscopic charcoal particles in particular have been widely used to reconstruct records of natural and anthropogenic fire events throughout the world. Iverson (1941) first used charcoal to reconstruct the history of land clearance in Denmark that marked the arrival of agriculture to the region. Since then, microscopic charcoal analysis has been central in enhancing understanding vegetation change in the North American forests (e.g. Clark & Royall, 1995; 1996) and forest succession in the Western Mediterranean (e.g. Carrión & van Geel, 1999; Múgica *et al.*, 1998; 2001; Valero-Garcés *et al.*, 2000), the (long) history of human fire use e.g. in Australia by aboriginal populations and the Americas by hunter-gatherers (Clark, 1983; Clark & Royall, 1995; Kershaw *et al.* 1997; Trabaud *et al.*, 1993) and understanding changes in the global carbon cycle with increased biomass burning (e.g. Carcaillet *et al.*, 2002; Crutzen & Andreae, 1990). This widespread use of microscopic charcoal analysis has led to the development of a range of analytical techniques to extract microscopic charcoal (see Chapter 3). Therefore, through the analysis of charcoal preserved, in lake sediments, in the Eastern Mediterranean the role fire played in delaying woodland recolonisation may be identified.

(1.6) Existing research into the role of fire in the Eastern Mediterranean

The potential role of fire in agricultural domestication has long been recognised, (e.g. Lewis, 1972). To date, however, the level of research into regional fire histories of the Eastern Mediterranean has been limited. Lewis discussed the presence of charcoal in the pollen records of Lake Zeribar and Lake Mirabad (later published in van Zeist & Bottema, 1977), and evidence of the use of fire at the archaeological sites of Shanidar Cave, Northern Iraq and Mureybit along the banks of the Euphrates (see Figure 1.1). The Iranian lake records showed changes in vegetation that were due to the occurrence of fire and the presence of charcoal particles, yet it was unknown as to whether the fire was natural or

anthropogenic in origin (Lewis, 1972). At the archaeological sites ash layers were found that were attributed to the people inhabiting the sites. For example, at Shanidar Cave analysis of the vegetation record showed that change in the vegetation community at this site occurred independently of climatic stimuli, therefore Lewis concluded that it was a result of the use of fire (Solecki, 1963).

Thorough investigation has since been conducted into the on-site charred (e.g. wood and seeds) remains at archaeological sites in the region e.g. Çatalhöyük (Konya, Turkey), Öküzini Cave (south-west Anatolia) and in the area of the Euphrates (Syria) (Asouti & Hather, 2001; Emery-Barbier & Thiébault, 2005; Willcox, 1996). These records have been subsequently used to infer the vegetation community around the site as the charred seed and wood remains will represent what was available in the surrounding area (e.g. Asouti & Hather, 2001). Such studies are scattered and site specific, however, and do not provide details of fire histories in the region in general. As mentioned, analysis of charcoal record preserved within lake sediments could provide a region-wide measure of fire activity, and to date, only two such studies have been conducted.

Wick *et al.* (2003) & Yasuda *et al.* (2000) conducted fire history reconstructions into Lake Van (Turkey) and the Ghab Valley (Syria). These studies both demonstrate changes in fire occurrence throughout the Holocene, however, a full discussion of these fire history records will be reserved until Chapter 10 when these studies will be discussed in detail in relation to the fire history reconstructions presented in this thesis.

Although these studies do acknowledge the occurrence of fire over the GS-2: Early Holocene transition, their spatial extent and temporal-resolution are not known. Furthermore, there are many published methods of microscopic charcoal extraction and analysis, and although there is not universal agreement on an extraction protocol, these studies used a technique that will be demonstrated as not the most appropriate method of charcoal extraction (see Chapter 3). Therefore through research into both methods of charcoal analysis and an investigation into the fire histories of a greater range of lake sites located throughout the Eastern Mediterranean, our understanding of both the regional fire history and the role of fire within the landscape can be enhanced.

(1.7) Aims & Objectives

This study aims to reconstruct the fire history of the Eastern Mediterranean region; this will be achieved through the following objectives:

i. The development and application of a robust laboratory procedure and sampling protocol for the analysis of microscopic charcoal preserved in lake sediments, following a comprehensive investigation into different methods of charcoal extraction and analysis.

ii. Examination of the influence of site type on fire history reconstruction, and in particular the detection of local and regional scale burning events.

iii. A reconstruction of Eastern Mediterranean fire activity from GS-2 to the present day based on microscopic charcoal records from a range of different site types.

iv. An evaluation of the role of natural and anthropogenic activities on past burning regimes, through comparison with existing multi-proxy (pollen, isotopic) and archaeological data, including potential effects on the delayed woodland recolonisation of parts of South West Asia during the Early Holocene.

(1.8) Note on the chronological terminology used in this thesis

As discussed, the Late Glacial to Holocene transition is comprised of a series of stepwise climatic shifts which have been clearly identified in palaeoenvironmental records throughout the North Atlantic region and beyond (Alley *et al.*, 1993; COHMAP Members, 1988). The traditional terminology applied to these climatic shifts is the scheme developed by Mangerud *et al.* (1974) based on palaeobotanical evidence from northwest Europe, which has subsequently been applied throughout Europe and beyond (Björck *et al.*, 1998). This terminology is problematic due to a number of factors including the time-transgressive nature of vegetation community response to climatic changes and also the potentially limited geographic range of this scheme (Björck *et al.*, 1998; Lowe & Gray, 1980). Björck *et al.* (1998) developed the Greenland Event Stratigraphy based the Greenland ice core stratigraphy (see Table 1.2). Subsequent work by Asioli *et al.* (1999) demonstrated a close correspondence between the Greenland Event Stratigraphy and therefore the North Atlantic, to climate records obtained from the Mediterranean region. Therefore throughout this thesis the Greenland Event Stratigraphy, as defined in Table 1.2, will be applied to climatic changes occurring during the Last Glacial to Holocene transition.

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Mangerud *et al.*, 1974 terminology	Greenland Event stratigraphy terminology	Greenland Event stratigraphy timeframes (in GRIP years BP which are equivalent to cal. years BP)
Last Glacial	GS-2	21,200 – 14,700
Bølling-Alleröd	GI-1*	14,700 – 12,650
Yonger Dryas	GS-1	12,650 – 11,500
Holocene	Holocene	11,500 onwards

Table 1.2: The Greenland Event Stratigraphy as devised by Björck *et al.*, 1998.

* Björck *et al.* (1998) divided GI-1 into a series of phases (a to e) however, this thesis is only focusing on the whole of GI-1 rather then the individual climatic shifts that occurred during GI-1.

(1.9) Thesis outline

Chapters 2 and 3 will present a review of issues associated with the production, dispersal and preservation of microscopic charcoal alongside a comprehensive investigation into charcoal extraction and analysis. An introduction into the environmental setting and human history of the sites selected to reconstruct regional fire history is presented in Chapter 4 along with the sampling strategies applied to the study sites. Chapters 5 to 8 present the results and a discussion of the fire history of each of the study sites in relation to available multi-proxy data. A regional synthesis of Eastern Mediterranean fire activity from GS-2 through to the Late Holocene is presented in Chapter 9 along with the conclusions drawn from this research.

Charcoal production, dispersal and preservation

This Chapter will focus on the main literature surrounding issues of charcoal production, dispersal and preservation. This information is central to a comprehensive interpretation of the stratigraphic records of fire history preserved within lake sediments.

(2.1) Charcoal production

Fires release different gaseous and particulate products. The majority of biomass that is burnt is converted to carbon dioxide, whereas only 10% of biomass is turned into Black Carbon (Carcaillet *et al.*, 2002). Charcoal is one of the two measurable forms of Black Carbon produced as a bi-product of fire events, the second being soot (Gelinas *et al.*, 2001; Schmidt & Noack, 2000). Black carbon represents a continuum of carbon based compounds that are produced at different stages of a fire. Black Carbon is formed at temperatures between 280 to 500°C (Schmidt & Noack, 2000). Charcoal is produced by the incomplete combustion of plant matter whereas soot results from the condensation of hot combustible gases (Patterson *et al.*, 1987). Several factors interact during a fire event to determine the amount and type of Black Carbon that is produced, these include; the nature of the fire (intensity and severity), the type, amount and condition of the fuel burnt (e.g. wood vs. grasses), the duration and temperature of the fire, and the weather conditions during the fire (Moore, 2000b; Schmidt & Noack, 2000; Whelan, 1995). Of these factors fuel moisture has been cited as exerting a direct control on the degree of carbonization that occurs during a fire event (Carcaillet *et al.*, 2002; Stocks & Kaufman, 1997). If fuel is very dry the degree of mineralization will be intense with high levels of gaseous emissions and ash produced but with low levels of charcoal (Stocks & Kaufman, 1997).

Black Carbon as coal has been recorded in terrestrial sediments dating back to the Devonian period, and as charcoal in glacial and lacustrine sediments beyond the Late Quaternary (Schmidt & Noack, 2000). The longevity of Black Carbon within terrestrial systems indicates its resistance to biological degradation, which in turn plays a fundamental role in the global biogeochemical carbon cycle (Carcaillet *et al.*, 2002; Thevenon *et al.*, in press). Consequently, sediments act as a vital sink for Black Carbon at times of increased biomass burning.

(2.2) Charcoal Preservation

During, and for an unknown period of time after a fire event, charcoal is transported from the fire site (Gifford, 1981). If charcoal reaches a depositional environment, e.g. a lake, it can be preserved forming a record of past fire activity. From the time of the fire until the time charcoal particles are deposited, taphonomic processes may alter the record of past fire activity. Although charcoal is inert and therefore not prone to the usual processes of chemical and biological degradation, it is mechanically fragile. Consequently processes that may affect the stratigraphic record of fire events need to be considered to ensure that a robust reconstruction of past fire activity is produced.

(2.2.1) Lakes as archives of palaeofire history

There are two main types of lake basin; closed and open. Open basins have surface in/outflows such as rivers, whereas closed lake basins do not have such in/outflows. Instead, water enters and leaves the lake by precipitation, evaporation and groundwater flux. In closed lake basins a delicate balance exists between evaporation and precipitation ratios which exert strong controls on the chemical and biological status of the lake. Therefore, closed lakes are very sensitive to climatic changes that alter the ratio of evaporation: precipitation. Lakes record fluctuations in the wider environment by the preservation of evidence in lake sediments. Over time, sediments are deposited and accumulate within the lake into a stratigraphic sequence that can provide a record of past climatic and environmental changes including fire.

(2.2.2) Processes by which charcoal enters lake basins

Charcoal is transported to lake basins via air and waterborne transport mechanisms that operate over a range of spatial scales (e.g. local, extra-local and regional) and catchment-specific processes (e.g. redeposition or focusing) (Figure 2.1). A combination of these transport processes determines the stratigraphic record of fire events within lake sediments. Unfortunately, research into charcoal transport processes has been limited. However, due to the similarity in the size ranges of pollen grains and microscopic charcoal particles there is an assumed analogy between pollen and charcoal taphonomy (Gajewski *et al.*, 1985; MacDonald *et al.*, 1991; Odgaard, 1992; Rhodes, 1996; Swain, 1978). Therefore, research on pollen transport and deposition in lake environments is used to infer similar processes for charcoal. A second possible analogy to charcoal is tephra. Unlike pollen, which is constantly present in the environment, charcoal and tephra are both produced in pulses

when a fire burns or a volcano erupts. Both of these palaeoenvironmental proxies will be discussed alongside existing information concerning charcoal taphonomy.
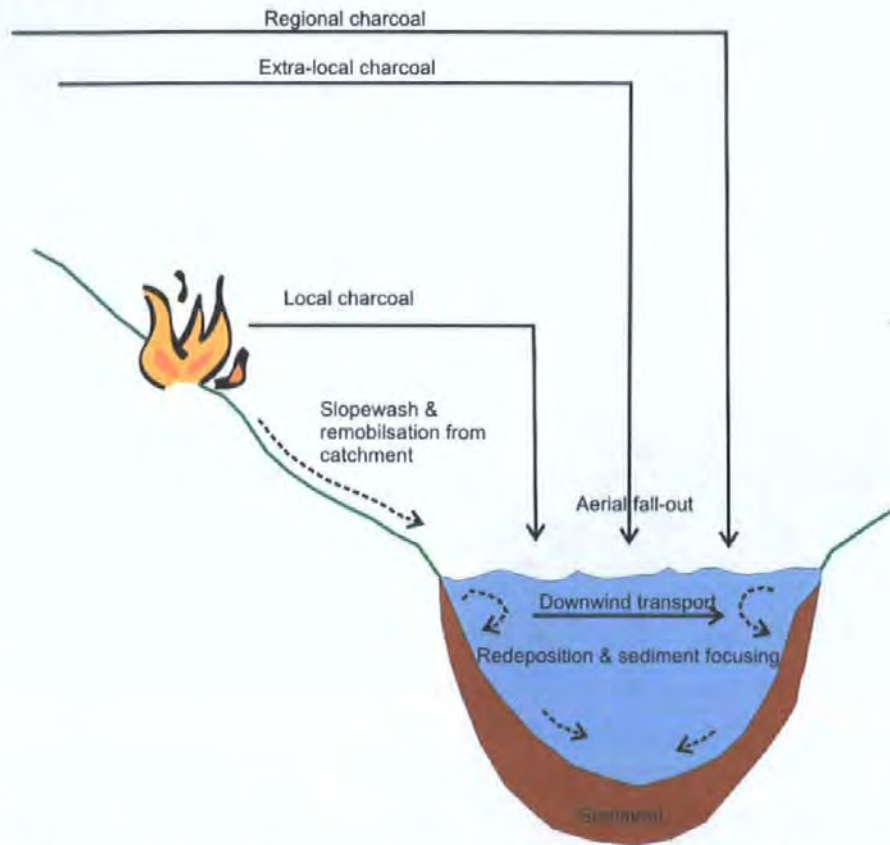
Figure 2.1: Schematic of the taphonomic processes acting upon charcoal particles from the point of origin until they are incorporated into sediments within closed lake basins (adapted from Whitlock & Larsen, 2001).

(2.2.3) Charcoal particle sizes, transport potential and source areas

Charcoal particles vary massively in size and therefore also in their transport potential (Figure 2.1). This has been identified through Gaussian plume models and investigations into the contemporary charcoal inputs to lake basins in North America (e.g. Clark, 1988a; Clark *et al.,* 1998; Gardner & Whitlock, 2001; Whitlock & Millspaugh, 1996). These investigations have been used to infer the transport potential of charcoal particles preserved in lake sediments. Larger particles (e.g. >100 µm) have a low critical velocity in terms of the wind speed necessary for entrainment to occur; instead, due to their size, larger particles are transported primarily by traction and are deposited near the fire site (Clark, 1988a; Whitlock & Anderson, 2004). Hence they are hypothesised to be of local origin. Microscopic charcoal (10 to 100 µm) experiences high cohesive forces due to its small size and therefore requires a significant entrainment velocity to be lifted into suspension (Clark,

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1988a). However, once entrained it can be transported considerable distance in suspension and therefore is more likely to represent a regional or extra-local source area (Clark & Patterson, 1997; Whitlock & Larsen, 2001). The smallest charcoal particles (<10 μm) exhibit similar behaviour but have a greater transport potential (Figure 2.2a; Clark, 1988a). This is due to the height at which they can be elevated to in the atmosphere which can result in particles being transported vast distances in suspension. Therefore these particles are believed to represent a global to sub-continental source area and are often referred to as background charcoal levels (Clark & Patterson, 1997).

The abundance of each size category of charcoal is determined by numerous factors e.g. the nature of the fire, fuel consumed and the taphonomic processes exerted on charcoal particles (Moore, 2000a; Stott, 2000; Whelan, 1995). Charcoal analysts (e.g. Ohlson & Tryterud, 2000) have repeatedly cited the high abundance of microscopic compared to macroscopic particles (Figure 2.2a). This is a function of the temperature of the fire and the contrasting transport mechanisms of each size fraction (Clark, 1988a; Lynch et al. 2004). For example, smaller particles are produced in greater abundance then larger particles, especially in hotter fires. Due to the contrasting transport potential and mechanisms of each size fraction i.e. microscopic charcoal is readily transported away from a fire site and is subsequently under-represented locally, it is likely that the majority of microscopic charcoal is extra-local/regional in origin (Clark, 1998; Ohlson & Tryteurd, 2000). Microscopic charcoal can also originate from the fragmentation of larger particles due to the physical stress that can be experienced by charcoal during transport (Clark, 1984; Patterson et al., 1987). Hence, microscopic charcoal can only reliably give an indication of fire occurrence; no firm inferences can be made from this size fraction concerning the precise location of the fire. In contrast, the abundance of larger charcoal particles, compared to microscopic particles, is generally low. Although this can indicate a local source area of the charcoal, the importance of a few macroscopic charcoal particles should not be overemphasised (Ohlson & Tryterud, 2000).

(2.2.4) Airborne transport

Airborne transport of charcoal particles has received the greatest level of attention as a mechanism of transport although empirical research has been limited. As a result, models of charcoal transport have been derived primarily from existing theory of atmospheric

transport of aerosols, dust, pollen and sand transport (Patterson *et al.,* 1987; Whitlock & Larsen, 2001).

Charcoal enters the air column either through entrainment or is lifted into the air column by thermal plumes and convection currents generated whilst a fire is burning (Clark, 1988a). The height of thermal plumes is determined by the intensity of the fire and the thermal structure of the atmosphere (Clark, 1988a; Garstang *et al.,* 1997). Once entrained, particles are transported from the fire site. The distance that particles are transported depends not only on their size but also the height and wind speed when entrainment occurs.

Deposition of charcoal particles from suspension occurs when the wind speed falls below the critical velocity necessary to transport particles or when they are washed out with precipitation. Precipitation can remove between 50-100% of charcoal particles travelling in suspension and is the main factor responsible for the deposition of microscopic charcoal (Garstang *et al.,* 1997).

(2.2.5) Theoretical and empirical research into airborne charcoal transport
Two basic models have been developed to explain airborne transport and deposition of charcoal particles. These models are briefly described and their applicability assessed based on the results of experimental burns conducted by Lynch *et al.* (2004), Clark *et al.* (1998), Gardner & Whitlock (2001) and Ohlson & Tryterud (2000).

Patterson et al. (1987): The Distance Decay Hypothesis
Patterson *et al.* applied the Distance Decay Hypothesis (hereafter DDH) of Byrne *et al.* (1977) to explain charcoal transport from a fire site. This hypothesis states as the distance from a fire increases the size of charcoal particles decreases (Figure 2.2b) (Patterson *et al.,* 1987). This model does not consider the effects of wind action and therefore assumes that charcoal particles are deposited equally in all directions. However, the direction and strength of the wind do determine the pattern of deposition (Gardner & Whitlock, 2001). Charcoal is generally deposited downwind of the fire site creating a debris trail of decreasing particle size from the fire (Figure 2.2c). Depending on the location of a lake basin one basin could receive a large quantity of charcoal whereas another may not receive any (Figure 2.2c).
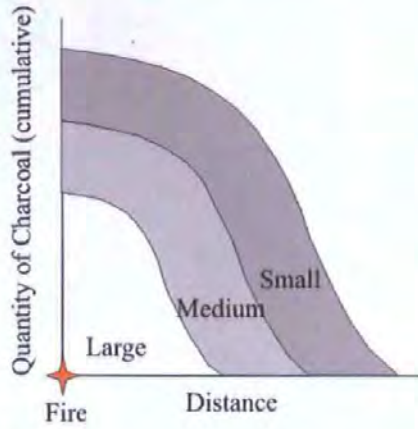
Figure 2.2a: The transport potential of different sized charcoal particles emitted from a fire (Patterson *et al.*, 1987).
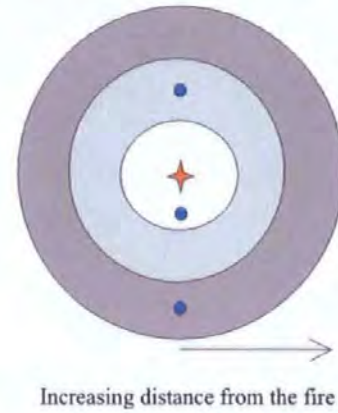
Figure 2.2b: Idealised model of charcoal transport and deposition from a fire site (Patterson *et al.*, 1987).
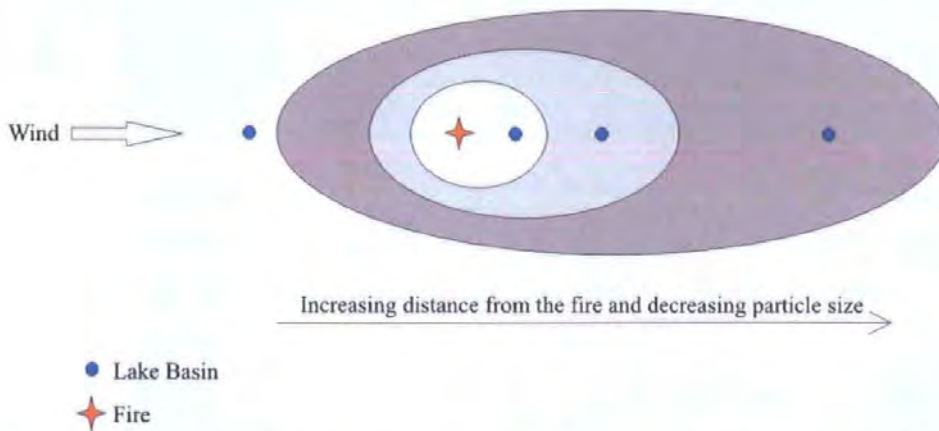
Figure 2.2c: Model of charcoal transport and deposition considering the effect of wind. (Patterson *et al.*, 1987).

Clark (1988a): The Skip Distance Model

The Skip Distance Model (hereafter the SDM) relates to the distance between the point of suspension of charcoal particles and the point of deposition from the air column (Figure 2.3). It is based on the varying transport potential of the different size fractions of charcoal and addresses the contrasting abundance of macroscopic vs. microscopic particles. Macroscopic charcoal particles have a finite skip distance that rarely exceeds tens of metres from the fire site, whereas microscopic charcoal can be elevated hundreds of metres in the atmosphere and potentially transported thousands of kilometres away from the source (Clark, 1988a).
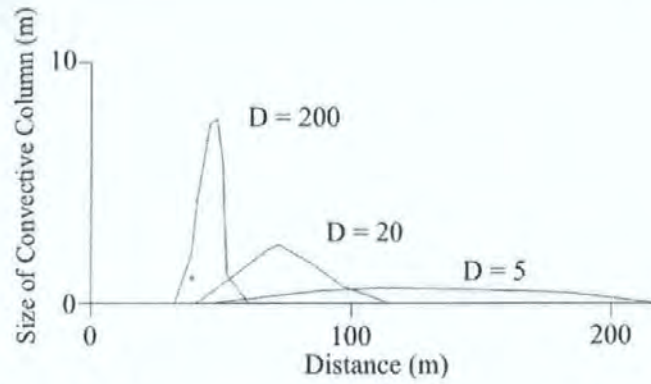
Figure 2.3: The effect of skip distances on charcoal transport (Clark, 1988a). Three different sized charcoal particles are represented (e.g. D = 5 μm) to demonstrate theoretical skip distances. The graph models transport from a 10 metre convective column and the effect this has upon transport potential.

(2.2.6) Empirical research into the airborne transport of charcoal

Empirical research into the transport of charcoal particles greater then 125μm has been conducted by Clark *et al.* (1998), Gardener & Whitlock (2001), Ohlson & Tryterud (2000) and Lynch *et al.*, (2004). Each of these studies investigated the transport potential of charcoal particles produced during contemporary forest fires. These investigations produced similar results and support the models of Patterson *et al.* (1987) and Clark (1988a).

Lynch *et al.* (2004) took their research a stage further by comparing the results from their experimental burn to stratigraphic records of fire events preserved within lake basins located within the surrounding environment. The sedimentary records did contain significantly less charcoal then was recorded in the immediate area of the experiment burn. This contrast is hypothesised to reflect the effect of localised catchment factors, e.g. vegetation and topography, serving to "filter" charcoal before it reaches the lake. However, charcoal recorded from the area outside of the controlled burn was comparable to that analysed in the lake records. Therefore Lynch *et al.* (2004) demonstrated that fire events are effectively recorded within lake sediments.

These investigations do raise questions concerning charcoal production and the effects this has on the stratigraphic charcoal record. Ohlson & Tryterud (2000) recognised that not all fuels produce charcoal e.g. lichens, and charcoal production depends on the intensity and conditions e.g. weather conditions on the day of the fire, that are specific to each fire event.

Garstang *et al.* (1997), Clark *et al.* (1998) and Lynch *et al.* (2004) all acknowledged the effect of fire intensity on charcoal production and therefore the stratigraphic charcoal signal. Charcoal production is outside the scope of this review but it is important to be aware of such issues when analysing or interpreting a palaeofire signal.

However, these models and experiments only focused on transport distances. None of the experiments thoroughly considered the smaller size fractions. This is where existing research concerning mechanisms of pollen transport and deposition within lake basins may be informative.

(2.2.7) Models of pollen transport

Tauber (1965; 1977): Components of pollen transport

Tauber identified four main mechanisms of pollen transport (Figure 2.4), these are; surface runoff (Cw), through the trunk space (Ct), above the tree canopy (Cc) and by rainfall (Cr) (Tauber, 1965; Tauber, 1977). Tauber also stated that sites of different size or source areas would experience varying levels of transport by these mechanisms.
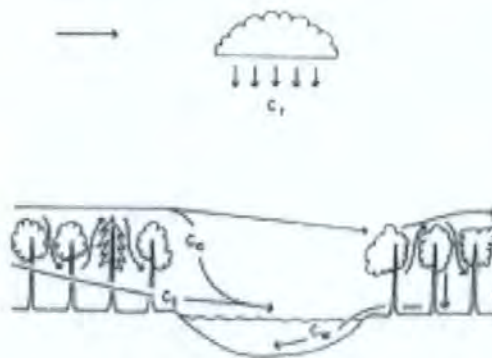
Letters identify the different transport mechanisms: Cw – surface run-off, Ct – through trunk space, Cr – by rainfall and Cc – above the canopy.

Figure 2.4: Mechanisms of pollen transport to a lake basin (Prentice, 1985)

Jacobson & Bradshaw (1981): Basin size model

Jacobson & Bradshaw focused on the relationship between lake size and pollen source areas. They base their model on the transport mechanisms identified by Tauber and also considered the varying dispersal properties of different pollen types. In terms of charcoal, this equates to differing particle size and morphology. Three source areas were defined; local, i.e. pollen originating within 20 m of the lake edge, extra-local, i.e. pollen travelling from 20 to several hundred metres from the lake edge and regional pollen, which may have a massive source area (Jacobson & Bradshaw, 1981). The proportion of each component varies depending on the size of the lake basin e.g. small basins receive primarily local

pollen (macroscopic charcoal) whereas in large basins extra-local and regional pollen (microscopic charcoal) "swamps" the local signal (Figure 2.5).
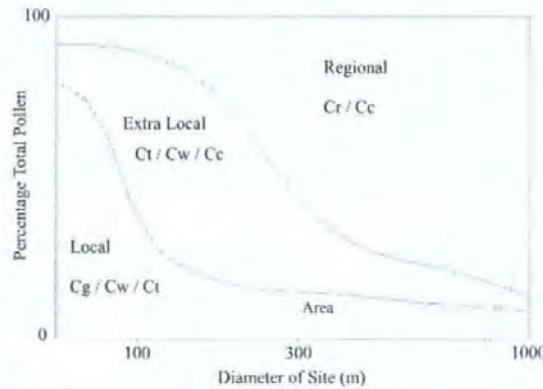
Figure 2.5: The relationship between basin size and pollen source area (Jacobson & Bradshaw, 1981). See Figure 2.4 for explanation of the transport codes.

Prentice (1985): pollen representation, source area and lake size

Prentice discusses the effect of source area and basin size on the spatial representation of pollen cores (Prentice, 1985). Prentice emphasises biases in production and dispersal. Dispersal biases relate to the differential dispersal potential of pollen (and charcoal) determined by grain/particle size, mass and morphology. Prentice assumed the primary mode of airborne transport is above the vegetation canopy and small pollen grains (or microscopic charcoal) are transported further then larger grains (or macroscopic charcoal). Prentice concluded that source area depended on lake size which in turn determined the spatial resolution of a signal. Prentice hypothesised that increasing lake size resulted in the homogenisation of the pollen signal e.g. localised variations in vegetation and therefore the pollen records were not detected in medium to large lake basins due to the level of regional pollen inputs (Prentice, 1985). In terms of charcoal dispersal, as the lake size increases, there will be an increased abundance of microscopic charcoal (extra-local and regional charcoal). Likewise, larger lakes would provide a regional fire signal whereas small lakes will record localised fire events (Clark & Royall, 1996).

Sugita (1993, 1994): Pollen deposition models for the whole lake surface

Sugita's model is an adaptation of the Prentice model and is therefore based on similar assumptions. However, Sugita enhanced the Prentice model by expanding existing source area theory across an entire lake basin rather than predicting pollen load for the central point in a lake basin (Sugita, 1993; 1994). Sugita predicted the pollen source area for entire

lake basins based on their radii e.g. a forest hollow (radius = 2 m^2) is predicted to have a source area of 50-100 m^2, a small lake (r = 50 m^2) has a source area of 300-400 m^2 and a medium-sized lake (r = 250 m^2) has a source area of 600-800 m^2 (Sugita, 1993; Sugita, 1994).

(2.2.8) Are models of pollen transport applicable to charcoal transport?

Charcoal is more variable in size and morphology than pollen. Most pollen grains range in size from 10 to 180 µm whereas charcoal particles range from <10 to >180 µm. Consequently the analogy between charcoal particles and pollen grains relates only to charcoal particles in part of the microscopic size range. However, the processes by which charcoal and pollen are introduced into the environment are different. Pollen is released by plants from their flowers. The height at which pollen is introduced into the atmosphere varies from species to species, and this height is usually fixed at the height of the plant e.g. the tree canopy. Many plant species, particularly those that depend upon wind pollination to transport the pollen away from a plant, have evolved to ensure pollen grains are readily entrained into the atmosphere on their release. During the season at which a plant is pollinating, a plant produces pollen continuously resulting in a constant presence of pollen within the environment. Due to the high abundance of pollen in the atmosphere, it is highly likely that some pollen grains will end up being deposited within a lake basin. In contrast, charcoal is not continually present within the environment. It is introduced as a bi-product of a fire event and therefore can have a fixed aerial source. The height at which charcoal enters the atmosphere, and is subsequently entrained, depends on the nature (e.g. smouldering ground fire vs. a crown fire), heat and intensity of the fire, and this is unique to each fire event. The height in the atmosphere that entrainment of charcoal particles occurs determines the distance to which they are transported from the fire. This in turn can affect the likelihood of a fire event being recorded within a depositional environment. Charcoal and pollen also contrast in their preservation potential. Charcoal, unlike pollen, is resistant to oxidation and biological decay therefore charcoal may persist longer in the environment prior to incorporation into a depositional environment, therefore as shown it may experience greater levels of redeposition within the landscape and the record of a fire event carried further from the fire site.

Despite the contrasts between charcoal and pollen these models do aid in understanding airborne transport and deposition of charcoal, but it must be remembered that models of

pollen and charcoal transport are theoretical. Empirical testing is needed to fully test their applicability. Further research focussing on charcoal dispersal in terms of the links between particle transport potential, basin size and transport mechanisms is necessary to provide a robust understanding of airborne charcoal transport and the effect of these factors on the formation of the palaeofire record. A second, potential analogue for charcoal may be tephra.

(2.2.9) Tephra

Tephra like charcoal does not have a constant presence in the environment. Tephra is also introduced into the environment from a point source when a volcano erupts. The initial transport processes and factors influencing the dispersal of tephra into the environment are similar to those experienced by charcoal. Volcanic factors are equivalent to the nature of the fire event i.e. height of the eruptive column vs. the heat and intensity of the fire which controls the height at which charcoal and tephra enter the atmosphere (Newnham *et al.*, 1999). Likewise meteorological factors, particularly wind, exert a direct control on the dispersal of both tephra and charcoal, as exemplified in Figures 2.2c and 2.6. Rain has also been identified as causing the out-washing of tephra from volcanic plumes (Walker, 1971). It has been hypothesised that rain may have a similar effect on charcoal carried in smoke clouds, however, this has yet to be quantified (Garstang, *et al.*, 1997). Tephra particles are deposited downwind of the volcano, in the direction of the prevailing wind and are sorted based on their density (Carey & Sparks, 1986; Walker, 1971). This has been documented for charcoal in the experiments of Lynch *et al.* (2004) and Clark *et al.* (1998). Based on these similarities, tephra may be comparable to charcoal. In terms of the stratigraphic record, tephra will behave in a similar fashion to charcoal. Peaks in tephra indicate volcanic activity just as pulses of charcoal reflect fire events. Surprisingly, very little empirical research has been conducted into the taphonomy of tephra despite its widespread use in palaeoenvironmental research (Cas & Wright, 1987). As with charcoal, there is still much to be learned concerning its taphonomy and incorporation into lake sediments.
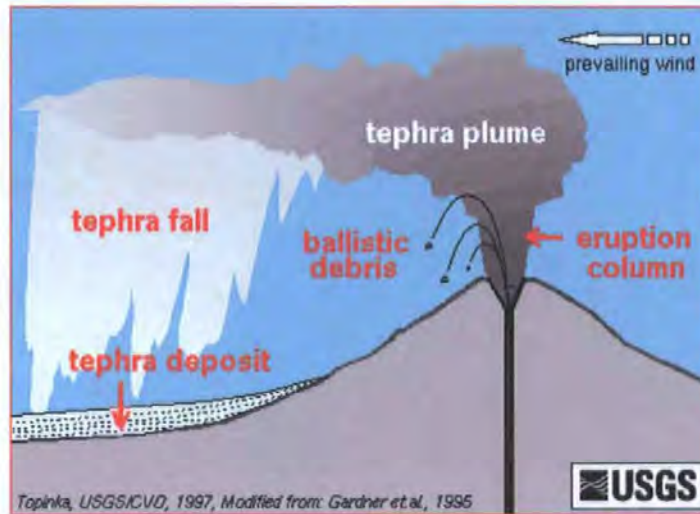
Figure 2.6: The effect of wind on the dispersal of tephra
(http://vulcan.wr.usgs.gov/Imgs/Gif/Hazards/Tephra/tephra_diagram.gif).

(2.2.10) Waterborne transport

The importance of water as a transport mechanism is unknown. Charcoal is susceptible to waterborne transport due to its high buoyancy when particles are dry. High buoyancy is a function of its high porosity (60-80%) which results in a low specific gravity (0.3-0.6) (Odgaard, 1992; Renfrew, 1973). Therefore particles need to be completely waterlogged before deposition occurs in water bodies (Scott *et al.*, 2000). Until particles are waterlogged, they float on the surface of water, which may result in long distance transport. The distance charcoal particles can be transported may be accentuated by the presence of a meniscus around dry, floating particles which protects particles from waterlogging (Nichols *et al.*, 2000).

There are three main mechanism of waterborne transport of charcoal. These are surface or overland flow, rivers and processes that operate within a lake itself, e.g. wave action. Surface flow is a potential mechanism by which charcoal that is stored within the lake catchment after a fire event reaches lakes. However, the occurrence of surface flow will depend strongly on the nature of the vegetation community, local topography and weather conditions within the catchment area of the lake. As with airborne transport, the distance of waterborne transport in rivers is determined by particle size i.e. as particles get smaller the distance they are transported increases (Nichols *et al.*, 2000; Scott *et al.*, 2000).

Experimentation into waterborne transport of charcoal has been limited (Clark *et al.*, 1998). Nichols *et al.* (2000) and Scott *et al.* (2000) conducted research on waterborne

transport of macroscopic particles produced by a heathland fire. They identified sorting of particles based on their size and level of waterlogging. Further research into waterborne transport of charcoal is needed, as identified by experiments into the accumulation rates of contemporary and fossil charcoal sequences e.g. Clark *et al.* (1998) and Lynch *et al.* (2004). Differences in accumulation rates have been identified as a function of waterborne transport i.e. the fossil records were from lakes that received surface flow whereas the contemporary records were derived from sediment traps that measured only airborne transport (Clark *et al.*, 1998). Therefore research into waterborne transport would serve to enhance existing knowledge on charcoal transport and aid in understanding patterns of deposition and remobilisation in lake basins.

(2.2.11) Transport process operating within a lake catchment

As discussed, charcoal can be stored (e.g. in vegetation or soil hollows) in a lake catchment and be delivered to a lake over potentially unknown timescales following a fire event (Gardner & Whitlock, 2001). Numerous factors including the extent and location of the fire from a lake alongside localised catchment conditions (e.g. topography, vegetation type and the time taken for recolonisation to occur) determines the amount of charcoal a lake receives from stores within a catchment (Gardner & Whitlock, 2001; Lynch *et al.*, 2004). Gardner & Whitlock (2001), Whitlock & Millspaugh (1996) and Whitlock & Larsen (2001) have repeatedly identified delayed charcoal inputs catchment to lake through the analysis of contemporary charcoal inputs to lakes. In the analyses of lake sediments from boreal forest in the USA, Gardner & Whitlock (2001) found that charcoal can enter lake basins for a minimum of five years after a fire event. This continued delivery of charcoal to a lake basin following a fire event can potentially "blur" the stratigraphic record of past fire events (Gardner & Whitlock, 2001). This can be exacerbated further by the long distance transport of microscopic charcoal particles. Many lake basins may be receiving continued inputs of charcoal to their sediments. However, it has been hypothesised that when compared to the initial inputs of charcoal into a lake basin following a fire, redeposited or stored charcoal constitutes a relatively minor component of the stratigraphic record of fire events (Blackford, 2000; Whitlock & Millspaugh, 1996)

The study of delayed transport of charcoal to lake basins has been limited (e.g. Earle *et al.*, 1996; Gardner & Whitlock, 2001). Generally these studies have compared charcoal records from burnt and unburnt lake catchments located within closed vegetation communities, e.g. boreal forests, where charcoal can be retained within the undergrowth (Earle *et al.*, 1996;

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Gardner & Whitlock, 2001). The occurrence of these transport processes within open landscape e.g. oak dominated steppe-parkland, such as those reconstructed for the Eastern Mediterranean region over the Last Glacial: Interglacial transition is unknown. However, based on the conclusions of Gardener & Whitlock it is likely in open landscapes the amount of charcoal stored in the vegetation will be less then in boreal forests. Therefore the majority of charcoal entering lake basins via waterborne or surface transport processes will occur soon after a fire event, longer-term delivery of charcoal will only occur as a result of airborne transport processes. Consequently the stratigraphic record of fire events may experience less "blurring".

(2.2.12) Transport processes occurring within lakes

Once charcoal particles and sediments reach a lake basin they are still subject to further taphonomic processes before they are finally deposited. Charcoal particles may experience differential sedimentation as the settling rates of charcoal particles may be highly variable. Settling rates depend on the morphology, density, specific gravity and buoyancy (a function of the saturation levels) of particles. Pollen grains of differing size are recorded as experiencing differential sedimentation (Davis and Brubaker, 1973). Due to the greater variability in size, morphology and density of charcoal it is likely that differential sedimentation will exert an influence upon charcoal deposition.

The taphonomic processes operating within lakes are determined primarily by the morphology of the basin. Basin morphology controls the nature of sediment deposition e.g. whether they are deposited as massive or laminated sediments. Massive sediments are sediments that are deposited as a homogenous unit. They can be subject to post-depositional processes that may result in either the vertical and horizontal mixing of sediments. These mixing processes include; gravitational induced sediment slumping, wave induced sediment mixing, and bioturbation. The effect of each of these processes varies depending on the morphology of the lake and whether or not the lake experiences seasonal stratification.

Waves are periodic movements that are induced by the wind. They have the greatest influence in the littoral zone of lakes where they remobilise sediment which can be carried to the centre of the lake.

Gravitational movement of lake sediments occurs when subaqueous slopes fail and slump (Larsen & MacDonald, 1993). Slumping occurs after gravity-induced failure in the shear forces holding sediments in place. The potential for gravitational movements is determined by the morphology of the lake basin and the shear forces holding sediments in place. Sediment slumping can result in both sediment remobilisation and introduction of variable amounts of sediments from the littoral/sub-littoral zone to deeper waters.

Bioturbation is a mechanism of sediment mixing results from the action of benthic organisms (Davis, 1973; Fisher *et al.,* 1980). The activity of the majority of benthic organisms is restricted to oxygenated waters (Davis, 1973). Therefore, generally, deeper lakes e.g. those that experience seasonal stratification, and therefore anoxia, experience limited biological activity in the lake sediments.

Wave action, gravitational slumping and bioturbation result in the re-suspension of sediments within the lake water. The remobilised sediments can then be moved from the littoral zone to the centre of the lake though process known as sediment focusing (Blias & Kalff, 1995; Likens & Davis, 1975). The centre of the lake is generally the deepest area of the lake and as a result sediment is gradually moved towards it. This is the area of the lake usually sampled when lakes are cored and due to sediment focusing it can have a greater accumulation rate then the periphery of the lake. In terms of fire history studies, which are looking for pulses of charcoal, sediment focusing can mix old and new lake sediments. This can in turn lead to the dilution and homogenisation of charcoal inputs across the lake basin and therefore make reliable identification of past fire events difficult (Whitlock *et al.,* 1997).

Empirical research has been conducted into the effect of these processes on charcoal preserved within lake sediments. Whitlock & Millspaugh (1996) present information collected of charcoal accumulation in eight small lakes from Yellowstone National Park. The samples collected along transects from shallow to deeper waters, from either burned or unburnt in the 1988 wildfires. They identified that there was significant movement and addition of charcoal to the lake sediments after the 1988 fire (Whitlock & Millspaugh, 1996). The majority of the charcoal movement was from shallow to deeper water. However, charcoal accumulation in both the unburnt and burnt catchments was comparable until five years after the burn, reflecting the effect of both airborne and redeposited

charcoal from both within the lake catchment (i.e. surface run-off from store areas) and remobilisation within the lake sediments.

Laminated sediments are sediment layers that are deposited within deep, flat bottomed lakes (O'Sullivan, 1983). The depth and morphology of lakes where laminated sediments occur means that they experience seasonal or permanent stratification (O'Sullivan, 1983). This stratification limits the effect of surface mixing, wave action or currents. Stratification results in anaerobic conditions prevailing in the deepest water which inhibits the activity of the organisms that can cause bioturbation. With the exception of gravitational movements, laminated sediments do not experience the same post depositional disturbance mechanism as massive sediments (O'Sullivan, 1983). Consequently there is no homogenisation or blurring of charcoal pulses. Annually laminated sediments are well suited to fire history reconstructions as they record short-lived changes in lake catchments (O'Sullivan, 1983). Several fire history studies (e.g. Cwynar, 1978; Pitkänen, 2000; Pitkänen & Huttenen, 1999; Swain, 1973; Tolonen, 1983) have successfully used annually laminated sediments to reconstruct forest fires. However, there are relatively few lake basins suited to the development of annually laminated sediments therefore massive sediments are frequently used in palaeofire research (Millspaugh & Whitlock, 1995).

(2.3) Summary

This Chapter has presented the main issues surrounding charcoal production, dispersal and preservation. Air- and waterborne transport mechanisms represent the main processes by which charcoal is carried away from a fire site and transported to depositional environments. As discussed the research into the transport of charcoal particles from the fire site by air and waterborne processes has been limited, therefore existing models of pollen transport were used to understand the potential transport processes by which charcoal particles reach lake basins. Finally transport processes operating within lakes have been reviewed as they exert the final control on the formation of a stratigraphic record of past fire activity. An understanding of these taphonomic processes is important to ensure a robust fire history reconstruction is produced and that appropriate charcoal extraction techniques are applied, as will be demonstrated in Chapter 3.

Microscopic charcoal extraction methods: a critical assessment

Numerous techniques of reconstructing the record of past fire activity preserved within lake sediments have been developed. These techniques utilise both direct (e.g. charcoal) and indirect (e.g. magnetic signals) measures of past fire activity. Charcoal is the most widely used direct measure. It has been successfully used over a range of spatial and temporal timescales to reconstruct palaeo-fire events. Techniques of charcoal extraction can be divided into optical and chemical procedures. This Chapter will present a brief summary of analytical procedures which leads into the thorough investigation that was conducted in to methods of charcoal extraction and quantification. Finally the procedures used to extract and analyse charcoal preserved in the lake sediments of the study sites are discussed. Indirect measures of fire activity, and measures of other aspects of black carbon, aside from charcoal, will not be considered here instead but are summarised in Table 3.1.

(3.1) Microscopic charcoal

Microscopic charcoal (i.e. particles less then 180 μm in size) provides a robust indicator of past fire activity due to its resilience to chemical and biological mechanisms of degradation. Charcoal was originally quantified on pollen slides by palynologists investigating vegetation changes (e.g. Iverson, 1941). It is only in recent years when charcoal has developed as a separate palaeoenvironmental proxy that the need for a universal method of charcoal extraction and quantification has been identified (Clark & Patterson, 1997; Patterson *et al.*, 1987; Rhodes, 1998; Tinner & Hu, 2003). Pollen preparations, sieved residues and petrographic thin sections are the most commonly used methods of microscopic charcoal extraction. Each technique focuses on different size fractions of charcoal that, as discussed, have contrasting transport potential and therefore source areas and can highlight different information about fire events (Carcaillet *et al.*, 2001; Tinner & Hu, 2003). This also means that each technique reflects differing levels of background charcoal e.g. charcoal originating from long distance transport, particle fragmentation or secondary inputs, which also affect the quality of the signal that is obtained. These factors combine to create problems relating to the comparability of the reconstructed fire histories where different methods have been applied (MacDonald, *et al.*, 1991). To illustrate the need for a new approach to the extraction and analysis of charcoal

analysis published methods of charcoal extraction and quantification and the information they convey will be reviewed.

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Technique	Method	Advantages	Disadvantages	Key References
Magnetic measurements	A fire event can produced magnetically enhanced ferromagnetic oxides. Identified by SIRM or magnetic susceptibility.	Provides a catchment specific record of fire events.	Magnetic signal will not form if the reducing environment is not present or the fire temperature is too low. Soil erosion after a fire is necessary for the signal to be preserved in lake sediments.	Rummery, 1983 Gedye *et al.*, 2000.
Sedimentological changes	Investigate sedimentological changes e.g. increased mineral matter, nutrient fluxes or increased in lamination thickness that can be attributed to increased soils erosion after a fire	Can identify areas of interest for further analysis.	Factors aside from fire e.g. windthrow can result in enhanced soil erosion.	Cwynar, 1978

Table 3.1a: Indirect measures of fire activity

Technique	Method	Advantages	Disadvantages	Key References
Thermal treatment	Black carbon is combusted at 375°C. The CO_2 released is measured and calculated as a percentage of the original dry weight of the sample to give the black carbon content. There are numerous variations on this method which can use a chemical pre-treatment to remove organic carbon (plant matter) and carbonates prior to the thermal treatment to give a more precise measure of the black carbon content.	Avoids the need for time consuming counting. Not a labour intensive preparation procedure.	Comparisons of fire history records obtained from charcoal and elemental carbon analyses (e.g. Wang et al., 1999) are not straight forward. Although similar general trends can be identified, the two records are not directly comparable as they are measuring different bi-products of fire events. This method may not be able to detect very low concentrations of black carbon.	Gelinas et al., 2001. Gustafasson et al., 2001. Wand et al., 1999. Noack & Schmidt, 2000. Thevenon et al., 2003; 2004; in press.

Table 3.1b: Measures of black carbon aside from charcoal

(3.2) Optical techniques

(3.2.1) Charcoal extraction

Pollen preparations

The extraction and quantification of microscopic charcoal on pollen slides has become the most frequently used technique of reconstructing fire histories (Whitlock & Millspaugh, 1996). This is because pollen and charcoal counts can be obtained simultaneously with no extra sample preparation. Despite the extent to which this technique is used in fire history reconstructions it does have several limitations. The pollen preparation procedure focuses on particles between 10 µm to 180 µm. Particles larger then 180 µm are usually removed by sieving in the early stages of processing. This creates a size bias toward the smaller size fractions. The pollen preparation procedure is chemically and mechanically rigorous which can result in the fragmentation of charcoal particles (Clark, 1984). This can result in the increased abundance of the smaller size fractions resulting in an overestimation of the number of charcoal particles (Clark, 1984; Saramaja-Korjonen, 1991).

Petrographic Thin Sections

Petrographic thin sections allow the analysis of microscopic charcoal preserved in laminated lake sediments in situ. Following the procedure described in Clark (1988b) water is removed using acetone and then the sample is embedded with resin. This preparation procedure overcomes many of the problems associated with pollen preparations due to the charcoal remaining undisturbed within the sediment block.

Charcoal analysed on petrographic thin sections is larger (from 50 up to 10,000 µm) than those particles analysed on pollen slides and therefore is assumed to represent a local source area (Clark, 1998b). This assumption has been tested and found to hold true in a variety of fire history reconstructions e.g. Clark (1988b), Clark & Patterson (1997) and Clark & Royall, (1995). Analysis of larger charcoal particles may result in more reliable identification of charcoal particles then those made of smaller particles on pollen slides. Likewise the preservation of the charcoal in-situ in laminated sediments means there is limited, if any, post-depositional disturbance (Clark, 1988b).

Oregon Sieving Technique

Millspaugh & Whitlock (1995) developed this technique to extract charcoal from lake sediments. A sample is disaggregated and then washed through a series of nested sieves.

This gentle extraction technique limits potential sources of damage that can fragment charcoal particles. Likewise the emphasis on larger charcoal particles means that the background component has been removed and therefore a reconstruction of localised fire activity is produced.

Bleaching & Filtering

Rhodes (1996; 1998) developed this technique of charcoal extraction based on the bleaching and filtering of lake sediments. It aimed to provide a cheap, quick and gentle method of charcoal extraction minimising physical and chemical stress. This methods has no upper size limit and therefore no size bias, hence it produces a record of fire activity spanning a range of spatial scales. This technique is also gentle and so limits the amount of mechanical damage.

Carcaillet *et al.* (2001b) compared the area of charcoal particles extracted by a standard pollen preparation with a variation on the Oregon Sieving Technique. However, rather then using a series of nested sieves samples were only sieved through a 150 μm mesh (Carcaillet *et al.*, 2001b). They found a weak correlation between the charcoal counts obtained by each method and concluded that each method produced a different signal. This was partly attributed to the removal of the background signal with the sieving technique that was still being counted on the pollen slide (Carcaillet *et al.*, 2001b).

(3.2.2) Quantification of microscopic charcoal

As with charcoal extraction, no standardised method of charcoal quantification has been adopted. Several methods of quantification have been developed, yet due to charcoal commonly been analysed on pollen slides, charcoal is frequented expressed as a proportion of the pollen sum (e.g. Iverson, 1941; Swain, 1973). Three methods have been developed specifically for charcoal quantification, these are: absolute abundance measures, point counts (Clark, 1982) and area measurements.

Absolute abundance measures

Absolute abundance measures involve all charcoal particles, regardless of their size, being quantified (Patterson *et al.*, 1987). This assumes that all particles contribute an equal level of information to the fire history record.

Point Count

Clark (1982) developed the point count method to provide a rapid measure of the charcoal content of samples. Charcoal abundance is recorded based on the number of "hits" of particles scored on a standard number of points (usually 11) on an eyepiece graticule (Clark, 1982). Particles present in the field of view, but which do not "hit" a point are ignored. The area of particles is not measured as Clark thought this contributed no useful information to the fire history reconstruction. However, Backman (1984) (cited in Patterson *et al.,* 1987) found the point count to underestimate the charcoal abundance particularly when the concentration of charcoal in the sample is low.

Area measurements

Area measurements work on the principles of charcoal transport discussed in section 2.2.3. Area measurements place a greater emphasis on the importance of larger vs. smaller particles due to their contrasting transport potential (Batterson & Cawker, 1982). Waddington (1969) first used area measurements in the analysis of charcoal on pollen slides. Waddington measured particles using a gridded eyepiece graticule. Particles were then placed in predetermined size classes. Once all particles have been measured the total area of charcoal in the sample is calculated by multiplying the sum of the number of particles in each size class by the mid-point of each class (Waddington, 1969).

Area measurements techniques are now among the most commonly used method of charcoal quantification; however, they do have limitations. Despite its widespread application, no standardised grid square size or magnification of analysis has been adopted (Patterson *et al.,* 1987). Area measurements are strongly influenced by the extraction procedure used. This is due primarily to the fragility of charcoal. Mechanically and chemically rigorous techniques, e.g. pollen preparations, potentially alter the size distribution of particles (Schmidt & Noack, 2000). This is due to the removal of larger particles and the fragmentation of the remaining particles during processing. This can result in the misrepresentation of the charcoal record particularly if the analysts' primary interest is to reconstruct the spatial scale of past fire events. The extraction procedure does have implications for other quantification techniques, e.g. fragmentation can lead to the overestimation of particle abundance, yet it has the greatest impact on area measurements.

Batterson & Cawker (1982) raised concerns over the emphasis charcoal analysts place upon area measurements and larger particles. They analysed a sedimentary charcoal record following the method of Waddington. The majority of the particles analysed fell in the smallest size fractions (54%) while the larger particles accounted for only 1.2% of all particles quantified (Batterson & Cawker, 1982). Mehringer *et al.*, (1977) also found a similar pattern. However, they did note that when charcoal in the smallest size fractions was more abundant, there was an increase in particle abundance across all size fractions (Mehringer *et al.*, 1977).

The value of area measurements can be further questioned since several analysts (e.g. Batterson & Cawker, 1982; Mehringer *et al.*, 1977; Saramaja-Korjonen, 1991; Swain in Patterson *et al.*, 1987) have found little difference in the trends in fire histories reconstructed using either absolute counts vs. area measurements. Therefore can any extra information be gained by measuring individual particles when the end product is the same? This is compounded further when the limitations of charcoal extraction (e.g. the size biases of the different techniques) and the gaps in existing knowledge concerning charcoal taphonomy are considered. Similar questions were raised by Tinner & Hu (2003) who concluded that area measurements were unnecessary in the analysis of microscopic charcoal.

Image analysis software
This is an alternative method of charcoal analysis suited to use on both pollen slides and petrographic thin sections. The application of image analysis software as a method of rapid charcoal analysis has being proposed and tested by several researchers (e.g. Earle *et al.*, 1996; Horn *et al.*, 1992; Mooney & Black, 2003; Morrison, 1994). Horn *et al.*, (1992) first proposed the technique. Using an automated stage and image analysis software charcoal particles were identified and counted (Horn *et al.*, 1992). Despite the obvious advantages of this technique, due to the speed at which samples can be processed, comparisons between automated and visual counts showed poor correlation e.g. the visual count repeatedly recorded higher counts (Horn *et al.*, 1992; Morrison, 1994). This discrepancy has been attributed to problems concerning the identification of charcoal particles (Morrison, 1994).

Recent applications of image analysis software have taken a semi-automated approach.

Charcoal fragments are identified visually and then a software package is used to measure the particles. Mooney & Black (2003) used image analysis to quantify and measure larger charcoal particles from a digital photograph. The data derived from the image analysis were compared to existing visual count data and the results were comparable (Mooney & Black, 2003). This technique may prove highly useful in fire history reconstruction particularly if size measurements of charcoal particles are to form part of the analysis.

(3.3) Chemical techniques

Winkler (1985) devised the nitric acid digestion and ignition technique as a method of rapid analysis of lake sediments to determine charcoal concentration. Nitric acid is used to digest all the organic matter, carbonates and pyrites persevered in the sediments leaving the charcoal and inorganic material (Winkler, 1985). The samples are then dried for three hours at 450-500°C to burn off the carbon remaining in the sediment (Winkler, 1985). The dry weight of the remaining sediment is then used to calculate the charcoal content as a percentage of the dry weight of the original sample (Winkler, 1985).

Several limitations have been identified that have prevented this technique being widely adopted. Changes in the sediment, e.g. increasing proportions of clay, could influence the recorded charcoal concentration. Clay sediments can absorb nitric acid during the digestion phase of the analysis that can result in an overestimation of the carbon content (Laird & Campbell, 2000; MacDonald et al., 1991). This potential overestimation can be further exacerbated though the evaporation of moisture from clay during the ignition stages.

This technique can also produce erroneous results when there are either low concentrations of charcoal or there are only slight changes in the charcoal concentration (Novakov et al., 1997; Patterson et al., 1987). The inability of this method to detect slight changes in charcoal concentration has been quantified by Rhodes (1996) as a failure to detect variations between 1 to 5% of the overall charcoal concentration of a sample (Rhodes, 1996). While this is a negligible measure in samples with very low charcoal concentrations, this can have an increasing influence on the reliability of the results as the charcoal comprises of a greater proportion of a sample. This is exemplified when the results of chemical analysis are compared to microscopic charcoal counts. The chemical analysis repeatedly underestimated the charcoal content in relation to the results obtained

by the microscopic counts (Patterson *et al.*, 1987).

Based on the literature reviewed into existing methods of microscopic charcoal extraction and analysis, it was decided that prior to an investigation into Eastern Mediterranean fire histories been conducted, issues surrounding charcoal extraction and quantification needed to be resolved. Hence a thorough investigation into microscopic charcoal extraction and quantification was conducted.

(3.4) Investigation into charcoal extraction & analysis

Three commonly used extraction procedures have been selected from the published literature to test the effects of preparation procedures on the fire history that is reconstructed. The methods selected are a standard pollen preparation (Moore *et al.*, 1991), bleaching and filtering (Rhodes, 1998) and the Oregon Sieving Technique (Millspaugh & Whitlock, 1995). Other methods of charcoal analysis are available e.g. thin section analysis, but they are not investigated as they are not directly commensurable and therefore not amenable to comparison under controlled laboratory experimental conditions.

(3.4.1) Charcoal identification

Correct identification of charcoal is a problem associated with the optical analysis of microscopic charcoal. Although charcoal is described by many analysts as being jet black, angular and opaque, (Clark, 1984; Clark, 1988b, Patterson *et al.*, 1987; Swain, 1973; 1978; Tinner & Hu, 2003), the actual identification of charcoal is subjective depending strongly on the experience of the analyst. Accurate identification of charcoal can be difficult for several reasons. There are many particles present in lake sediments that can resemble charcoal e.g. pyrite, dark plant fragments and insect cuticles (Clark, 1984. Partial combustion also hinders identification problems; it results in a spectrum of particles present that span from charcoal to unburnt. Therefore to ensure accuracy in charcoal identification diagnostic criteria were applied to each particles, namely 1) jet black, (Figure 3.1 a, b and c), 2) angular, straight edges (Figures 3.1a and b), 3) straight but fuzzy edges (Figure 3.1c), 4) blue hue (Figure 3.1a and c) and 5) the presence of cellular structure (Figure 3.1b) and represented the most commonly observed characteristics (Figure 3.1). Particles that included a combination of these characteristics were classified as charcoal. All other particles were ignored.
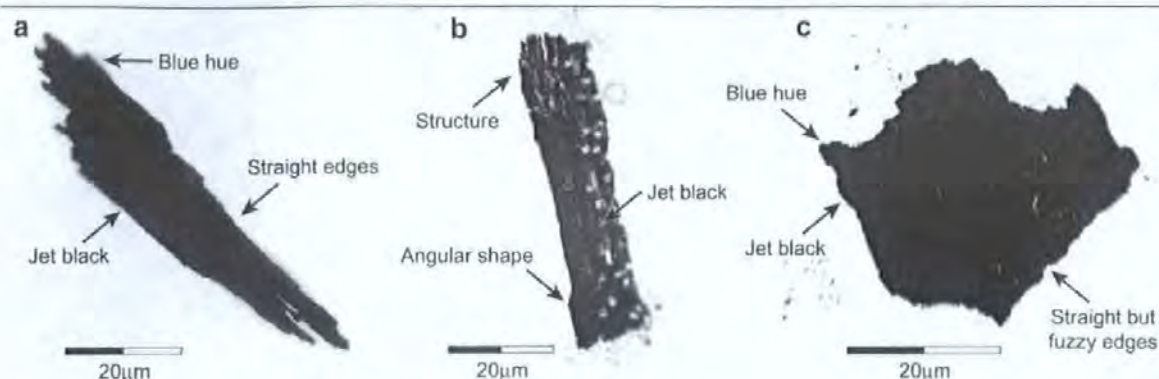
Figure 3.1: Diagnostic characteristics of charcoal

(3.4.2) Sample material

Fossil samples contain an unknown quantity of charcoal, and therefore the record of charcoal produced could reflect either the processing techniques or the abundance of charcoal in the sample. Therefore, for this investigation artificial lake sediments were produced. The control samples were comprised of a known volume of modern charcoal combined with "sterile" lake sediments. The "sterile" lake sediments were Late Pleistocene lake marls from the Konya Basin, Turkey, taken from near the archaeological site of Çatalhöyük. They were examined and demonstrated to contain no charcoal and then bleached to remove all other organic material. The charcoal used in the control samples has been manufactured from a mixture of hardwoods, using traditional methods, by the Forest of Dean Museum Heritage Trust, UK. The charcoal was sieved through a series of nested sieves (mesh sizes: 250 μm, 125 μm, 63 μm, 50, μm and 25 μm) for five minutes using a Wretsch Vibro sieve shaker. These size classes were selected to be representative of the charcoal particles preserved in lake sediments that had extra-local to regional source area. Each sample contained 0.7 g of sterile lake sediment. To each sample 0.1 g of 50 to 63 μm and the 25 to 50 μm size fractions were added along with 0.5 g of the 125 to 250 μm and 63 to 125 μm size fractions. Each preparation technique was thoroughly tested using ten replicate samples.

(3.4.3) Extraction procedures

Pollen Preparation

Pollen extraction followed the standard protocol of Moore *et al.* (1991).

1) 30 ml of 10% Hydrochloric acid was added to 1 cm^3 of sediment to dissolve the carbonates. The sample was then sieved through a 180 μm mesh.

2) Potassium hydroxide digestion to remove humic acids and disaggregate organics

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3) Fine sieving through a 10 μm mesh.

4) Acetylation

5) The sample was stained with safranin and then 2 ml of molten glycerol jelly added. 20 μl of the mixed sample was placed on a slide.

6) The slide was then analysed at 400 x magnification.

Bleaching & Filtering

1) 0.2 g of sediment was placed in 20 ml of distilled water and left for 24 hours to rehydrate.

2) 20 ml of 6% Hydrogen Peroxide was added then the sample was placed in an oven at 50°C for 48 hours.

3) The sample was then filtered through Whatman Number 1 filter paper to remove fine particles.

4) The filtrate was washed into a glass evaporating dish using a minimal amount of distilled water, and then placed in an oven at 50°C to evaporate the excess water.

5) The bleaching stage was repeated.

6) The sample was then washed into 30 ml tubes and 2ml of glycerol added.

7) 100 μl of glycerol was placed on a glass slide to which 10 μl of the processed sample added and mixed. A cover slip was placed on the sample and sealed with clear nail varnish.

8) The sample was then analysed at 200 x magnification.

Oregon Sieving Technique

1) 1 cm^3 of sediment was placed in a 60 ml solution of 10% Sodium Hexametaphophate and left for three days to disaggregate.

2) The samples were then gently washed through a series of nested sieves (mesh size: 63, 125 and 250 μm) with distilled water.

3) Each size fraction was then washed into a 30 ml plastic tube of ml of glycerol added.

4) A 100 μl sub-sample was taken and placed on a glass slide, and a cover slip placed on top. The cover slip was then sealed with clear nail varnish.

5) The samples was then analysed at 100 x magnification.

Density Separation

The use of heavy liquid separation to extract charcoal was first suggested by Clark (1984) but to date this technique remains undeveloped. Therefore heavy liquid separation was tested as an alternative method of charcoal extraction. Heavy liquid separations applied in pollen analysis uses Lithium Hereopolytungstate (LST) with a known specific gravity of 2.2 (Vandergoes & Prior, 2003). Particles e.g. mineral matter, with a specific gravity greater then that of the LST sink and can be discarded. Particles with a lower specific gravity, e.g. pollen and charcoal, float on the surface of the liquid. The actual specific gravity of charcoal varies depending whether the particles are saturated or dry e.g. the specific gravity of dry particles is 0.3 to 0.6 (Renfrew, 1973). It is hypothesised that saturated particles have a similar specific gravity as pollen grains. Therefore using the same specific gravity as used for the pollen preparation would be suitable for charcoal. This was tested by applying a range of specific gravities (from 1.1 to 2.6) on artificial samples. The experiment showed that a specific gravity in excess of 2.2 was suitable. LST with a specific gravity of 2.2 was used in this procedure.

1) 10 ml of 10% Hydrochloric acid was added to 1 cm^3 of sediment to remove the carbonates and disaggregate the sample.

2) The sample was the washed through a 250 μm mesh with distilled water.

3) 10 ml of LST was added to the sample and then it was centrifuged at 2000 rpm for 10 minutes. The samples were then decanted into beakers. 200 ml of distilled water was added and the samples were then left to settle. Once settled the water was removed with a disposable pipette. This stage was repeated twice.

4) The sample was then washed into a 30 ml plastic tube and 2 ml of glycerol added. 100 μl of glycerol was then placed on a slide and 10 μl of sample added. This was then mixed and a glass cover slip placed on top. The cover slip was then sealed with clear nail varnish.

5) The sample was then analysed at 200 x magnification.

Density Separation & Bleaching

This technique was developed based on observations made during the course of this investigation. In the bleaching and filtering the hydrogen peroxide successfully digested organic material. Likewise the density separation removed mineral matter from the samples. Therefore two categories of particles that could potentially misidentified as charcoal could be removed from the sediments if these techniques were combined.

Therefore this technique was tested as a further alternative to the published methods.

1) 10 ml of 6% hydrogen peroxide was added to 1 cm^3 sample and left for 24 hours to react. The sample was then left to settle and the hydrogen peroxide was then removed with a disposable pipette.

2) The sample was then washed using distilled water through a 250 μm mesh. The particles left on the mesh were retained.

3) 10 ml of LST was added to the sample and then it was centrifuged at 2000 rpm for 10 minutes. The sample was then decanted into beakers. 200 ml of distilled water was added and the sample was left to settle. Once settled the water was removed with a disposable pipette. This stage was repeated twice.

4) The sample was then washed onto a 30 ml plastic tube and 2 ml of glycerol added. 100 μl of glycerol was then placed on a slide and 10 μl of sample added. This was then mixed and a glass cover slip placed on top. The cover slip was then sealed with clear nail varnish.

5) The sample was then analysed at 200 x magnification.

(3.4.4) Quantification procedures

Ideally, to ensure confident and directly comparable estimations of the charcoal content of a sample an exotic marker (e.g. *Lycopodium*) should have been added to each sample, however, at the time of this work *Lycopodium* was not available. Therefore to standardise the quantification procedure across the preparation techniques one slide from each preparation was counted. On each slide 66 fields of view across 11 traverses were analysed, and charcoal quantified as number of particles per microlitre original sample. To each field of view the three quantification techniques were applied, namely:

1) Absolute abundance – all particles that could be accurately identified in the field of view as charcoal were counted.

2) Particle area – this was estimated using a grid square graticule. The number of squares each particle covered was counted then the area calculated.

3) Point count – the number of hits particles made on 11 points along a standard eyepiece graticule were recorded (Clark, 1982).

The mean charcoal content quantified per microlitre across the 10 samples was then calculated and is presented in Table 3.2.

(3.4.5) Results

Absolute abundance

Although all the control samples contained the same amount of charcoal there was considerable variability in the number of charcoal particles measured using each extraction procedure (Table 3.2) as reflected by the high standard deviations. This could highlight the potential difficulties in accurately estimating the charcoal content of a sample regardless of the extraction procedure applied. The lowest charcoal counts were produced by the Oregon Sieving Technique. In contrast the density separation and the density separation plus bleaching preparations recorded the greatest number of particles. Differences in the amount of charcoal quantified by each extraction procedure were evident in the results of the one-way ANOVA. This indicated a highly significant difference between the extraction procedures (F-value: 70.62; *P*-value: $<<0.001$). A Fisher's pairwise comparison was conducted to identify which the preparations were significantly different from one another (Table 3.3). The results indicate that the density separation, density separation & bleaching and the bleaching & filtering preparations produced charcoal counts that were significantly different from one another.

Extraction procedure	Mean charcoal particles counted/µl	Standard deviation
Pollen Preparation	55.7	18.4
Oregon Sieving Technique	22.4	6.4
Bleaching & Filtering	186.4	49.5
Density Separation	687.7	185.0
Density Separation & Bleaching	577.9	172.3

Table 3.2: Absolute abundance of charcoal particle counts for the different preparation methods.

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	Bleaching & Filtering	Density Separation	Density Separation & Bleaching	Oregon Sieving Technique
Density Separation	**			
Density Separation & Bleaching	**	*		
Oregon Sieving Technique	NS	**	**	
Pollen Preparation	NS	**	**	NS

NS: non-significant, *significant, **highly significant

Table 3.3: Fisher's pairwise comparison

Point Count

This method was found to be particularly time consuming and produced very low counts. Over the first five samples analysed it was found that very few particles in the sample were counted using this approach (typically 1-5 'hits' per field of view). Given the time which would have been required to process the remaining samples in this way, and in light of the work of Backman (1984) which showed that point counts under-estimate charcoal concentrations at low concentration, the method was abandoned.

Particle size measurements

The pollen, bleaching & filtering, density separation and density separation & bleaching preparations all record the greatest abundance of particles in the smallest size fraction (<625 μm^2) (Figures 3.2a & 3.2b). The particles sizes quantified in the Oregon Sieving Technique contrasts with the other preparation techniques (Figure 3.2b), where the majority of particles were found in the larger size fractions.
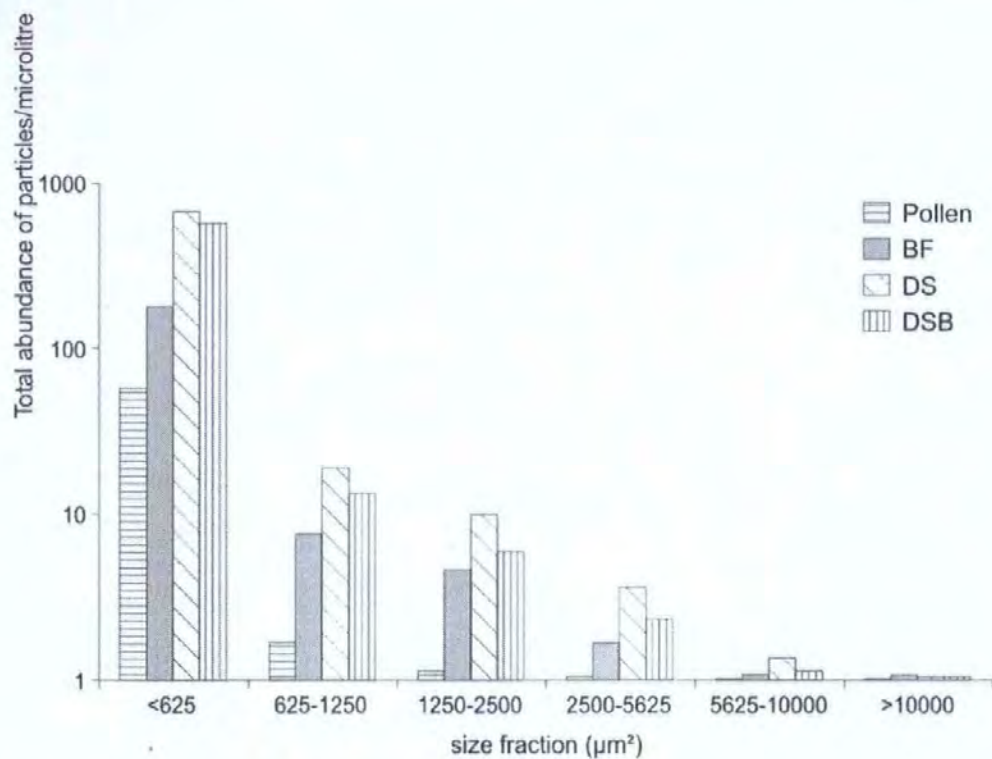
Figure 3.2a: Particles per size fraction (at 100x magnification)
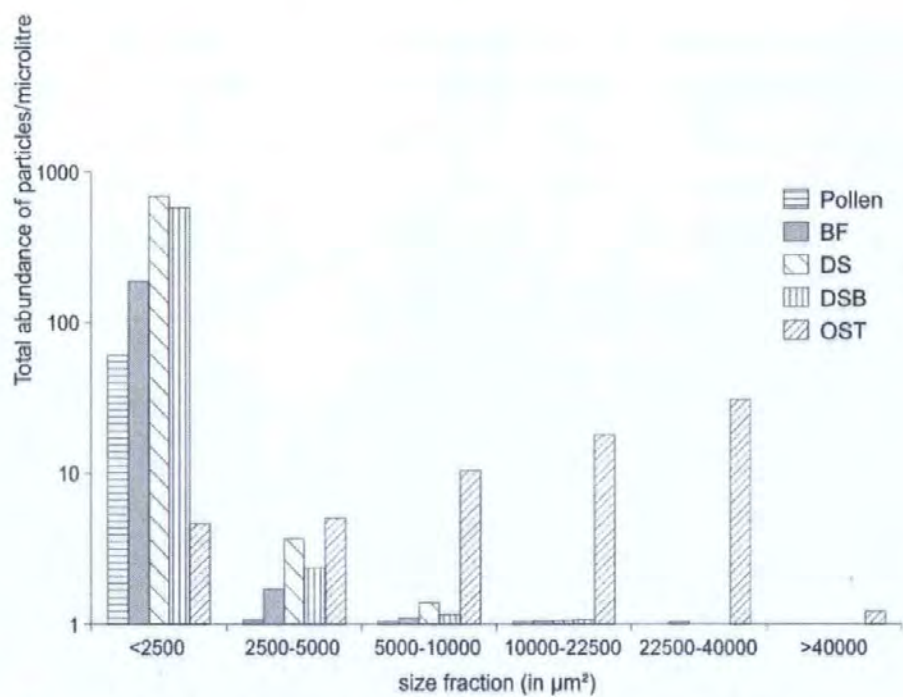
Figure 3.2b: Particles per size fraction (at 200x magnification)

(3.4.6) Discussion

This experiment was devised to assess the potential differences in fire history reconstructions which may result from different fire history reconstructions. This is often

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not considered in the comparison of fire history reconstructions (e.g. Carcaillet *et al.*, 2002) and as this work has demonstrated, despite the variation in the amount of charcoal recorded in the replicate samples (see Table 3.2), the extraction and quantification procedures do have a clear impact on the results of charcoal analysis, and the specific method(s) used will therefore have an influence on the fire history that is reconstructed. This information along with factors including ease of identification and preparation time will be central to the development of the recommendations for further charcoal analysis (see Table 3.4).

Pollen preparation

This preparation involved three different chemical treatments (excluding the HF acid treatment which was not conducted) and mechanical treatments which included micro-sieving, repeated centrifuging (high speed/short time: minimum of 13 times) and mechanical mixing (Table 3.4). Furthermore this preparation was biased toward the smaller size fractions, all particles greater then 180 μm being removed. Therefore there were many potential sources of particle loss with this procedure. As a result, the counts of charcoal made from samples processed with a pollen preparation produced significantly underestimated the actual content of charcoal.

Bleaching & Filtering

This technique was mechanically gentle, therefore minimised the sources of particles fragmentation (Table 3.4). However, it did include two chemical treatments with 6% hydrogen peroxide. This technique is not biased toward any size fraction i.e. there is not a maximum size cut-off and although the samples are washed through an 11 μm filter paper the amount of charcoal lost is thought to be minimal (Rhodes, 1998). Therefore this technique should provide a count of charcoal particles in a similar magnitude to the heavy liquid separations. However, the charcoal counts produced by this preparation were lower then the heavy liquid separation techniques (Figures 3.2a). Hydrogen peroxide has been used previously in the extraction of charcoal from solids (White & Hannus, 1981) and was applied in this method as it has been hypothesised that due to charcoal being chemically and biologically inert; it should not react or be digested by hydrogen peroxide (Rhodes, 1998; White & Hannus, 1981). Yet the lower then expected charcoal counts may indeed reflect the removal of charcoal by hydrogen peroxide, and the effect of hydrogen peroxide on charcoal may need further investigation.

Oregon Sieving Technique

The technique was both chemically and mechanically gentle therefore minimising particle fragmentation (Table 3.4). The size ranges of particles analysed (greater then 63, 125 and 250 μm) were biased toward the larger size fractions. Therefore this method would provide a local rather then a regional record of fire activity. Hence this method is better suited to the analysis of meso and macroscopic charcoal. Consequently, the record produced of fire activity using this technique is not directly comparable to that produced by the procedures that focus on microscopic particles.

Density Separation

Although chemical and mechanical treatments were conducted during this analysis, the severity of these treatments was minimised (Table 3.4). The samples were sieved at 250 μm to remove larger particles that may have a specific gravity higher then 2.2 and therefore not be separated from the denser material. The chemical treatment was limited to 10% hydrochloric acid to remove carbonates and particles could have potentially been fragmented during reaction with the analysis. Initially it was hoped that the samples would separate without the need for centrifuging but even after samples were left over night, the separation was not successful and centrifuging was essential. This lead to a mechanical treatment been applied of one long, slow speed (10 minutes at 2000 rpm) to the samples. Whilst this density separation produced the highest charcoal counts this is more likely to be due to the efficiency of this technique in removing charcoal from the sediments rather then the result of particle fragmentation during centrifugation. The pollen preparation applied a minimum of 13 short, fast centrifugations yet recorded significantly lower charcoal counts then the density separation. Therefore if the centrifugation was resulting in considerable particle fragmentation during either of these preparation procedures similar charcoal counts may have been expected. The significantly lower pollen preparation counts show that this is clearly not the case and indicate that particle recovery is greater with the density separation.

Density Separation & Bleaching

The application of a bleaching stage to the density separation was designed to improve identification accuracy by removing organic matter. However, this procedure, despite being otherwise identical to the density separation, recorded fewer charcoal particles then

the density separation, although recording more charcoal then the other extraction procedures. This again raises concerns over the effect of hydrogen peroxide on charcoal.

Quantification Techniques: absolute abundance vs. area measurements

Selection of the technique to be used to quantify charcoal particles depends on primarily the information required from the study (e.g. is the analyst interested in the local or regional spatial representation of the fire history record?). Related to this are the size range of particles that are being analysed (e.g. micro, meso or macroscopic particles) and the extraction procedure used (a gentle procedure where minimal chemical and mechanical treatments are applied e.g. the OST vs. mechanically and chemically rigorous procedures e.g. the pollen preparation). If, as in the work proposed in this thesis the analyst is interested in regional fire history reconstructions an emphasis will be placed on microscopic particles. When the time taken to measure microscopic charcoal particles is balanced against the amount of information that can be obtained from microscopic particles in relation to transport distances, absolute abundance measures appear to be the most appropriate technique of charcoal quantification. However, if the analyst is interested in reconstructing a local/extra-local record of fire activity, use of a gentle procedure, such as OST, may be most appropriate. In this case, particle area may also be considered, since this can provide valuable information concerning the distance of the charcoal source from the basin (Whitlock & Larsen, 2001). However this is a very time consuming analysis.

Extraction Procedure	Chemical treatment	Mechanical treatment	Size bias?		Preparation time for ca.32 samples /intensity of procedure	Identification ease
			Size range	Spatial scale		
Pollen Preparation	HCl, KOH, Glacial acid, Conc. Sulphuric acid, Acetic anhydride	Centrifuging (x13), mechanical stirring, micro-sieving	>10 to <180 μm	Extra-local to regional	5 to 7 days Labour intensive	Still contains mineral matter & organics
Bleaching & Filtering	H_2O_2	None	>11 μm	Local, extra-local to regional	6 days Not labour intensive	Organic material removed. Still contains mineral matter
Oregon Sieving Technique	None	None	>63 μm	Local	3 to 5 days Not labour intensive	Still contains mineral matter & organics
Density Separation	HCl	Centrifuging (x1)	<250 μm	Extra-local to regional	4 days Not labour intensive	Mineral matter removed. Still contains organic matter.
Density Separation & Bleaching	HCL, H_2O_2	Centrifuging (x1)	<250 μm	Extra-local to regional	5 Not labour intensive	Mineral matter removed. Still contains organic matter.

Table 3.4: Extraction procedure overview

(3.4.7) Implications for further analysis of microscopic charcoal

The techniques investigated here demonstrated varying levels of suitability to the analysis of microscopic charcoal. Ideally, a technique should be selected that minimises the amount of particle fragmentation, since this fragmentation of larger charcoal particles (i.e. meso or macroscopic) into microscopic particles may lead to the overestimation of the total charcoal content of a sample when total microscopic abundance measures are taken. This can be achieved by limiting the number of chemical and mechanical treatments samples experience during preparation (Table 3.4). Likewise the technique applied needs to be suited to the size fractions that are being analysed e.g. Oregon Sieving Technique is best suited to the analysis of particles that have a local source area. Also the extraction procedure selected should represent an attempt to analyse the full range of size fractions present in a sample. Therefore a two-step extraction procedure may be more useful. A sieving stage in the early preparation procedure can remove larger particles which exhibit the greatest vulnerability to particle fragmentation and can, if they are fragmented, lead to overestimation of the charcoal content of a sample. This would leave the smaller size fractions to go through a more rigorous preparation. The suitability of this approach was demonstrated by the density separation repeatedly producing the highest charcoal counts.

This work is clearly a first step into a previously neglected field. Further research is still needed though, with more rigorous testing of each method of charcoal quantification as well as further assessment of the extraction techniques through the use of a standardised volumes of sediment (e.g. 1 cm^2) and an exotic marker, to address the variability in the amount of charcoal quantified (see table 3.2). However, this investigation has also clearly shown charcoal is a separate palaeoenvironmental proxy and as such it is essential to use an extraction and quantification procedure that focuses solely on charcoal extraction if maximum information is to be derived. Applying such a procedure would ensure fire history records are produced that are reliable and comparable between different analysts. It was therefore decided from this experimental pilot study that this approach would be employed for analysis of Late Quaternary sediment cores from the Eastern Mediterranean region.

(3.5) Charcoal extraction

Based on this experimental study the heavy liquid extraction procedure was selected for the extraction of microscopic charcoals from lake sediments (Turner *et al.,* in press). The

heavy liquid separation uses LST (Lithium Hereopolytungstate) Fastfloat (produced by Polytungstates Europe, Wiltshire). The full, two-stage extraction procedure is presented in Figure 3.3.

Sediment block

↓

Disaggregate overnight in 100 ml of distilled water

↓

Material left on the sieve is placed into a 20 ml Sterlyn ← Sieve at 180 μm

↓

Leave to settle, then pipette off the water

↓

Add 30ml of 10% HCl and leave for 30 minutes

↓

Add 2-3 *Lycopodium* tablets. The number of tablets added is determined by the amount of sediment remaining after the HCl treatment.

↓

Add 200 ml of distilled water, leave to settle then pipette off the water

↓

Place the beaker on a hot plate and evaporate the excess water without letting the sample dry out.

↓

Wash the sample from the beaker into a 12 ml tube using 10 ml of LST (specific gravity of 2.5).

↓

Centrifuge the sample: 10 minutes at 2000 rpm.

↓

Pour the top pellet and LST solution into a 250 ml beaker and add 200 ml of distilled water. Leave to settle. Pipette off the water. Repeat twice.

↓

Pipette off the water. Place the sample into a 5 ml plastic tube and add glycerol jelly (1:1 ratio).

↓

Mount the sample on a microscope slide for analysis.

Figure 3.3: Schematic of the microscopic charcoal extraction procedure using heavy liquid

Selecting the optimum specific gravity

The specific gravity of the heavy liquid used determines the amount of charcoal that is recovered from the lake sediments. To establish the optimum specific gravity of the LST, a range of specific gravities (measuring 1.1 to 2.6) were applied to artificial lake sediments. The initial specific gravity of LST fastfloat is 2.8 ± 0.02. The specific gravity of LST was reduced by adding a few millimetres of distilled water, stirring it in, and then weighing 10 ml. The artificial lake sediments the different specific gravities were tested on were made to replicate those in the sequences to be analysed following the procedure described in Section 3.6. Each sample contained the same, known volume of charcoal. The samples were prepared following the method in Chapter 3. The size of the top and bottom pellets after one ten-minute centrifugation was then compared visually (Figures 3.4a and 3.4.b). The top pellet represents the material that is to be analysed and should be comprised mainly of charcoal. The bottom pellet contains the denser, inorganic matter and minerals that are not analysed.

Increasing specific gravity from 1.1 to 2.6

Figure 3.4a: Top Pellets

Increasing specific gravity from 1.1 to 2.6
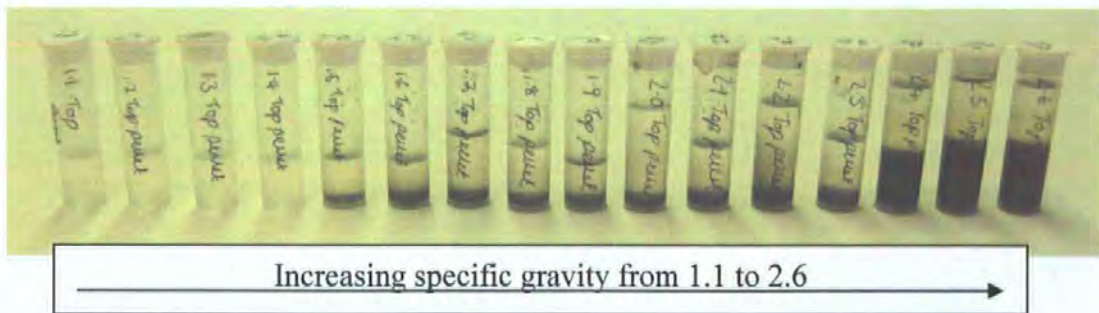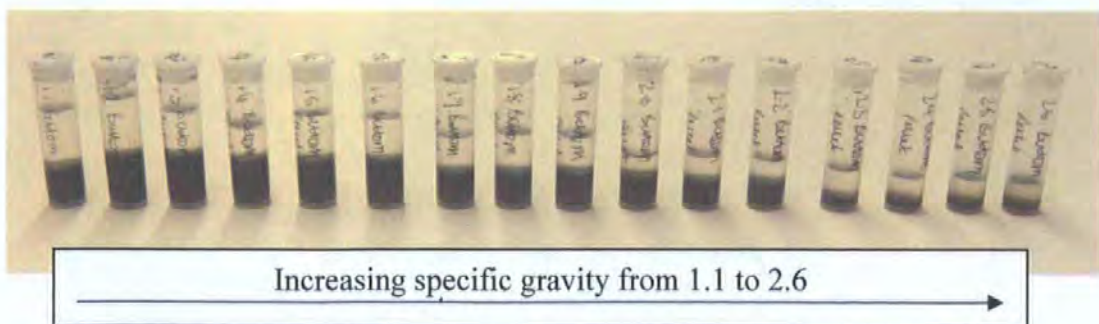
Figure 3.4b: Bottom Pellets

The size of the top and bottom pellets varied with the specific gravity (Figure 3.4a and 3.4b). The lowest specific gravities (1.1 to 1.4) did not produce a top pellet. Specific gravities between 1.5 and 2.3 produced smaller top pellets and larger bottom pellets,

although the size of the bottom pellet did decrease with increasing specific gravity. The smaller top pellets produced using a specific gravity of 1.5 to 2.3 means that the maximum charcoal recovery would not occur. The specific gravities between 2.4 to 2.6 produced the largest top pellets and smallest bottom pellets. This represented maximum charcoal recovery and the optimum specific gravity. To further check the effectiveness of each specific gravity at extracting charcoal, a small drop of each top and bottom pellet was placed on a glass microscope slide and analysed under the microscope. The purpose of this exercise was to see if all the charcoal was extracted from the samples (i.e. there was no charcoal in the bottom pellets). Brief analysis agreed with the comparison of the size of the top and bottom pellets (i.e. the maximum charcoal recovery was achieved by the 2.4 to 2.6 specific gravities). A specific gravity of 2.5 was selected for use on the lake sediment sequences. 2.5 was selected because as LST approaches its maximum specific gravity (2.8) it becomes increasing unstable which results in crystallisation occurring.

Coarse fraction extraction

A 250 μm mesh was used to separate the larger fraction. For application to actual lake sediment samples the mesh size was reduced to 180 μm. This was to ensure a regional record of fire activity was analysed, as particles smaller then 180 μm are hypothesised to have a regional source area (Clark, 1988a). This mesh size also served to reduce further the number of larger charcoal particles that may enter the preparation, be fragmented and potentially have an impact on the reliability of the reconstructed microscopic charcoal content. Furthermore, preservation of the larger charcoal particles, particularly if they are present in significant quantities, offers a potential dating medium (Vandergoes & Prior, 2003).

(3.6) Charcoal quantification

Of the two approaches tested in the methods investigation to quantify charcoal (total abundance counts vs. particle area measurements), total abundance measures were used in this research. Compared with particle area measurements, total abundance counts provide a quick measure of the charcoal content of a sample. The speed at which samples were processed using total abundance counts allowed many more samples to be analysed in the available time. This enabled higher resolution fire history reconstructions to be produced for the sites where adequate sample material was available (Akgöl, Eski Acıgöl and Nar Gölü). These higher resolution fire history reconstructions were perceived to be of greater

value than to this research. In addition this research focused primarily on the reconstruction of regional fire activity which is largely represented by microscopic charcoal particles (Clark & Patterson, 1997; Patterson *et al.*, 1987). In this context particle area measurements would contribute a limited amount of information in relation to the amount of time taken for the measurements.

Total abundance counts do not provide information on the size of charcoal particles analysed and therefore the amount of information that can be obtained relating to the spatial resolution of the fire history reconstruction is limited. However, several charcoal analysts have suggested that sustained peaks in microscopic charcoal which are considerably larger then the background level of charcoal may reflect fires occurring within the vicinity of the core location (e.g. Asselin & Payette, 2005; Innes *et al.*, 2004; Pitkänen, 2000). If peaks in charcoal considerably greater than the background level of charcoal entering the lake can be identified, this may provide data on the spatial resolution of the fire events.

Lycopodium

To calculate the concentration of charcoal per 1 cm^3 of sediment, the exotic marker *Lycopodium* was added to each sample (Stockmarr, 1971). Each *Lycopodium* tablet contains 18,583 *Lycopodium* spores per tablet. Based on the amount of sediment remaining in the first batch of samples from each sequence following the HCl treatment, either two or three *Lycopodium* tablets were added. The Akgöl and Lake Hula sediments contained abundant carbonates. Therefore the volume of the samples was reduced considerably by the HCl treatment, so two *Lycopodium* samples were added to the samples. Three sites (Eski Acıgöl, Nar Gölü and Çatalhöyük) contained either fine sediments or organic rich debris that were not removed in the early stages of the preparation, so three *Lycopodium* tablets were added.

Microscopic analysis

Every sample was analysed at x200 magnification using an Olympus BX50, high power microscope. Charcoal was counted until a predetermined number of *Lycopodium* spores were quantified. For the Akgöl, Çatalhöyük and Hula samples charcoal was quantified until 250 *Lycopodium* spores were recorded. This number of marker spores was selected based on the work of Finsinger & Tinner (2005). In Eski Acıgöl and Nar Gölü the overall

abundance of charcoal was lower, therefore the *Lycopodium* count was reduced to 100 spores. Although this was below that recommended by Finsinger & Tinner (2005), the time taken to reach *Lycopodium* counts of 250 was not justified by the low levels of charcoal quantified. It was felt that reliable counts were still being obtained despite only 100 spores being counted as the heavy liquid separation technique proved more effective then the pollen preparation at extracting charcoal (Turner *et al.,* in press).

(3.7) Data analysis

The initial raw charcoal counts were converted to the concentration of charcoal particles per cm^3 of sediment analysed using Tilia (version 2.02) which uses the following equation (Bennett & Willis, 2001; Grimm, 2004):

Charcoal concentration = (exotic spore added x charcoal counted)/exotic spore counted

Charcoal concentration values can potentially be distorted by high charcoal inputs to a lake or low sediment accumulation rates (Bennett & Willis, 2001). Therefore, the charcoal concentration data for Akgöl, Eski Acıgöl, Lake Hula and Nar Gölü were converted from concentration to charcoal influx values using the following equation (Bennett & Willis, 2001):

Charcoal influx = Charcoal concentration (cm^3)/sediment accumulation rate (cm/year^{-1})

Accurate influx estimations are dependant on good chronological control which is a function of the age model. This is to ensure that influx measures reflect changes in sedimentation or hiatuses in sedimentation that may have occurred. In this thesis the published age models (e.g. Meadows (2005) and Roberts *et al.* (2006)) are based on linear interpolation between dated samples, the ages for the top and base of the sequence were then extrapolated from the age depth line. Whilst this is viewed as a crude approach to age modelling it does, when the analytical errors on the dated material are small, provide a reasonable estimate of the age of a sequence and ultimately a robust reflection of the sedimentation rates (Bennett, 1994). However, as will be discussed in Chapter 4 and Chapters 5 to 8, the dating of several of the study sties is problematic (e.g. Akgöl, Eski Acıgöl & Lake Hula). The lake basins analysed in this thesis are carbonate rich therefore the radiocarbon dates are subject to an age-offset due to the presence of old carbon within

the system. In some cases this problem has been circumvented due to the presence of laminated sediments (e.g. Nar Gölü) or through the application of alternative dating techniques (e.g. uranium series dating). Yet in several sequences (e.g. Akgöl, Eski Acıgöl & Lake Hula) dating remains problematic, which undermines the validity of the influx calculations. As these problems were not resolved within the timescale of this research caution was taken when interpretations of the charcoal influx data were made. Therefore overall trends in charcoal influx were considered when changes in fire activity through time were been discussed.

Charcoal influx measures can also be affected by small-scale variations in sediment accumulation rates that can occur on short timescales (e.g. less the ten years) (Bennett, 1994). Whether or not these variations are detected, and therefore whether they have an impact upon the reconstructions that are produced, depends on that sampling resolution which is applied. In this research the sampling resolution used was course enough (e.g. a sampling resolution and strategy was selected that allowed changes in fire activity to be averaged out over the temporal resolution of the samples; see Chapter 4 for details) for small scale variations in sediment accumulation not to influence the charcoal influx measures obtained.

(3.8) Data presentation

Results were presented using Tilia Graph (version 2.02) (Grimm, 2004) and C2 (version 1.4.2) (Juggins, 1991). Many of the samples that were taken spanned several centimetres/laminations of the sequence, therefore the mid-point of each sample depth/lamination count was used to present, and calculate the age of, the sample.

(3.9) Summary

This Chapter has presented a detailed review of direct (optical and chemical) methods of charcoal analysis. This review resulted in a comprehensive investigation into optical methods of microscopic analysis whereby several published and two new methods of charcoal extraction were thoroughly tested. As a result of this study a new two-step microscopic charcoal procedure using heavy liquid separation was developed further to extract charcoal preserved within lake sediments. Methods of data analysis and presentation were also considered.

Site Descriptions & Sampling Strategies

This Chapter will discuss the criteria used to select the study sites used to reconstruct Eastern Mediterranean fire history. A detailed review of the environmental setting and existing palaeoenvironmental research will then be presented. Finally the sampling protocol applied to each of the study sites will be discussed.

(4.1) Site Selection

Over the past 15 years a large number of lake cores have been collected and analysed from Central Turkey (and beyond) as part of wider research programmes (e.g. KOPAL) to investigate the environmental history of the region (e.g. Baruch & Bottema, 1991; Roberts *et al.*, 1999; Roberts *et al.*, 2001). This has resulted in a wealth of archived lake sediment cores available for this research. From this selection of archived material a range of sites were selected for this microscopic charcoal analysis based on the following key considerations:

- Could a fire history reconstruction be provided that would cover the last 20,000 to 15,000 years and especially the key time interval of the GS-2: Holocene transition (i.e. 20,000 to 8,000 years BP)?

- Was other multi-proxy (e.g. pollen and stable isotopes) data already available for each site that would aid the interpretation of the fire history record?

- What was the recruitment area of each lake basin in relation to its source area of charcoal inputs? Ideally this project was focussed on the reconstruction of regional fire histories; therefore lake basins with large source areas were preferable.

- What was the proximity to archaeological sites that span the transition to Neolithic agriculture? In the Levant there is evidence of a shift toward sedentary hunter-gather settlements, which were the precursors to the adoption of agriculture, from the early stages of GI-1 (ca.14,700 cal. years BP onwards) whereas in Central Turkey this did not happen until ca. 9,300 cal. years BP (Bar-Yosef, 1998; Asouti & Hather, 2001).

Based on the above criteria five sites were selected, namely; Akgöl Adabağ and

Çatalhöyük, both located in Konya, central Anatolia, Turkey, Eski Acıgöl and Nar Gölü, both located in Cappadocia, Central Turkey and Lake Hula (Israel), the latter cored by S. Bottema, State University of Groningen (Figure 4.1). Table 4.1 presents an overview of each site and Table 4.2 a summary of the field techniques used to collect the sequences.

Site	Location	Basin Type & area (in m^2)	Length of record and nature of the lake sediments	Hypothesised source area of charcoal inputs*
Akgöl	Konya, Central Turkey (37°30'N, 33°44'E)	Formerly an open shallow marsh lake. **50,000 m^2	Late Glacial (ca.15,000 cal. years BP) through to 3000 cal years BP, although there is a hiatus in sedimentation between ca.9,700-6,500 cal. years BP. Massive sediments.	Local to regional
Çatalhöyük	Konya, Central Turkey (37°30'N, 33°00'E	Infilled Oxbow lake **<50 m^2	A 1,000 year record hypothesised to be from the time of the occupation of Çatalhöyük West (ca.8,000 cal years BP). Massive sediments.	Local
Eski Acıgöl	Cappadocia, Central Turkey (38°33'N, 34°32'E)	Drained crater lake 660,128 m^2	GS-2 through to the Late Holocene. (ca.18,000 cal. years BP). Annually laminated from ca.6,000 to >17,000 cal. years BP	Regional
Nar Gölü	Cappadocia, Central Turkey (38°22'N, 34°27E)	Extant crater lake 556,500 m^2	Late Holocene (last 2,000 years). Annually laminated for the whole record,	Regional
Lake Hula	Jordan Rift Valley, northern Israel (33°10'N, 35°35'E)	Formerly an open marsh lake. 23,320,000 m^2	GI-1 through to the Late Holocene. Massive sediments.	Local to regional

Table 4.1: Summary of the basin type, length and nature of its record, and hypothesised source area of charcoal inputs to each of the study sites

* See Chapter 2 (Section 2.3.2) for a full explanation of charcoal source area theory.

** The area of these two lakes was estimated during fieldwork based on evidence from within the wide environment, e.g. shoreline deposits etc., as Akgöl had been drained at the time of coring, but the area of the main lake was estimated in 1980 and Çatalhöyük had been in filled making precise estimations of basin area impossible (Leng *et al.*, 1999; Roberts, pers. comm..).

Site	Coring method & year of collection	Core length (in cm)	Core length (in years)	Sediment Type	Full fieldwork description available in:
Akgöl (Konya, Central Anatolia, Turkey)	Two cores in 1995 (AGL95A & AGL95B) Eijkelkamp vibro-corer with a cobra motor, sealed coring tubes and a core catcher	AGL95A: 847 cm AGL95B: 440 cm	AGL95A ca. 25,000 years but 2 hiatuses in sedimentation. AGL95B remains undated	Massive. Pale grey-buff calcareous clay marls	Roberts et al., 1999
Çatalhöyük (Konya, Central Anatolia, Turkey)	1999 Eijkelkamp vibro-corer with exchangeable open gouge and lined sample heads.	566 cm	ca.1,000 years, (Early Holocene)	Massive. Organic rich unit with cultural debris	Roberts et al., 1997
Eski Acıgöl (Cappadocia, Central Turkey)	1996, 1997 and 1999 Above 1350 cm: a modified Livingstone corer (length 100 cm, barrel 5 cm) Below 1350 cm: Eijkelkamp corer with a percussion cobra motor and closed head attachments All cores correlated to form a master sequence	Master sequence length: 1566 cm	ca.18,000 years	Massive 75 to 607 cm. Annually laminated from 607 to 1566 cm.	Roberts et al., 2001
Lake Hula (Israel)	1987 Dachnowsky corer	1625 cm	ca.20,000 years (depending on chronological issues)	Massive Pale grey-buff calcareous clay marls	Baruch & Bottema, 1991; 1999

Nar Gölü (Cappadocia, Central Turkey)	2001 Top ca.65 cm: Glew corer Livingstone coring system 2002 Mackereth coring system All the cores correlated to form a master sequence	Master sequence length 376 cm	ca.1,700 years	Annually laminated	England, 2006 Jones, 2004

Table 4.2: Fieldwork summary – this represents a very brief overview of the field techniques used to collect the material used in this research. See Figure 4.1 for the location of the study sites.

Core storage

Following collection and sampling for the initial multi-proxy analysis to be conducted the Turkish cores were kept in cold storage the University of Plymouth. The Israeli material was kept in dry storage at the Department of Archaeology, Rijksuniverteit Groningen, the Netherlands.
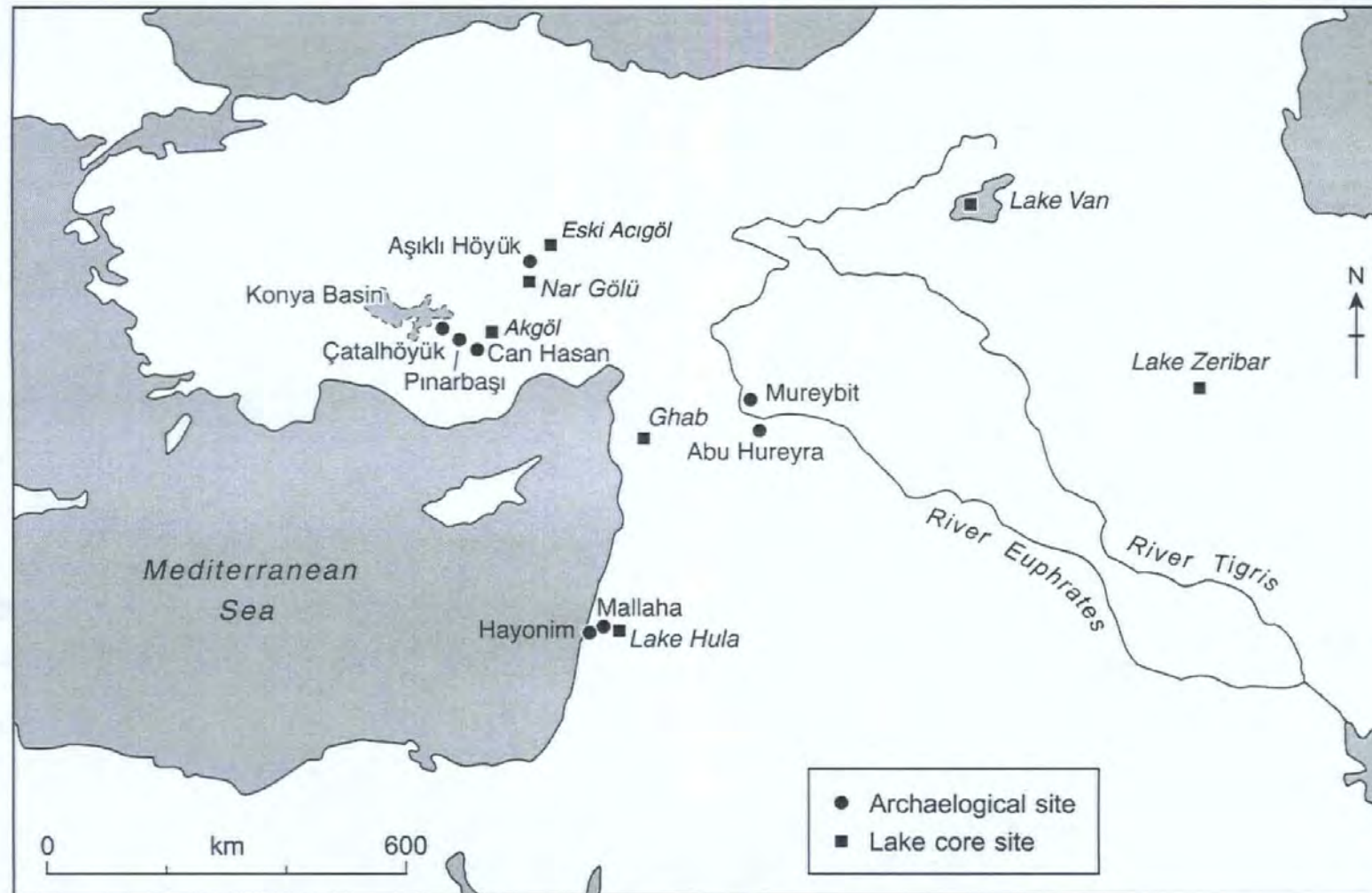
Figure 4.1: Map of the study sites and the sites discussed in the text.

(4.2) Site Descriptions

This section provides a summary of the geology, climate and vegetation at each of the study sites together with a brief overview of the palaeoenvironmental research already conducted and the archaeological significance of each site.

(4.2.1) Central Turkey

The sites located in Central Turkey are classified by Türkeş (2003) as today having a semi-arid climate. Therefore seen as each site experiences similar climatic conditions, similarities would also be expected in the overall characteristics of the vegetation communities. An overall review will be given of the climate and vegetation of Central Turkey. However, the vegetation of each site will be discussed separately as there will be variations due to localised factors such as topography and the history of human occupation.

Climate

The climate of Turkey is diverse. This diversity is a function of both topography and Turkey's location at the transition between atmospheric disturbances and weather conditions that originate in tropical and polar regions (Türkeş *et al.,* 1995). The climate is influenced by the main mid to high latitude westerlies, mid-latitude subtropical high pressure systems and the southern Asian monsoon (Türkeş, 2003; Wigley & Farmer, 1982). The Mediterranean Sea can modify the effects of these factors by acting as either a source or sink for heat and moisture, with increasing distance from the Mediterranean coastline the climate is strongly influenced by elevation and increasing continentality (Wigley & Farmer, 1982).

Due to its elevation (ca.1000 m a.s.l) and distance from the coastline, Central Turkey, as mentioned, has a climate that is classified as semi-arid (Türkeş, 2003; Türkeş *et al.,* 1995). Mean annual precipitation is generally below 400 mm, 30% of which falls in spring. The winter months experience less then 100 mm of precipitation, summer precipitation is even lower (Türkeş, 2003). Average temperatures range from -2°C in January to 24°C in July. Due to the combination of cold, moist winters and hot, dry summers there is a regional moisture deficit in this area (Türkeş, 2003).

Vegetation

The natural vegetation of Central Turkey was classified by Zohary (1973) as Xero-Euxinian which, depending on localised climatic and topographic factors is characterised by either broad leaved steppe forest or grass steppe. These are transitional vegetation communities which contain dwarf shrubs, grasses and scattered trees (Zohary, 1973). The trees are dominated primarily by deciduous oaks (e.g. *Quercus pubescens* (white oak) and *Q. rober* (pedunculate oak)) but also include *Pistacia* sp. (terebinth) and some *Pinus* sp. (pine). Rocky outcrops are characterised by open tree or scrub vegetation including *Celtis turnefortii, Prunus ursine* (bear plum) *and Ulmus campestris* (elm) (Woldring & Bottema, 2001). Due to the longevity of deforestation and grazing in Central Turkey the Xero-Euxinian communities have been replaced by an Irano-Turanian ground flora, which is characterised by *Stipa-Brometum* (Zohary, 1973).

The Konya Basin

Both Akgöl Adabağ and Çatalhöyük are located in the basin of the Pleistocene palaeolake Konya (Figure 4.1); therefore an overall description is given of the geology of this area, followed by a brief overview of the two sites separately.

Geology and Setting

The Konya Basin (37°38'N, 33°35'E) is located on the southern side of the Central Anatolian Plateau at an altitude of ca.1,000 m a.s.l. (Leng *et al.*, 1999) (Figure 4.1). The area is underlain by both volcanic and sedimentary rocks but consists mainly of freshwater limestones of Tertiary age (Leng *et al.*, 1999). The Konya Basin is surrounded to the south and west by the Taurus Mountains.

Today most of the lake basin is dry and only residual lakes (e.g. Akgöl), remain in depressions located throughout the basin. The former palaeolake had an area of ca.4,000 km^2 and a catchment of ca.20,000 km^2 (Fontugne *et al.,* 1999; Roberts, 1983). During GS-2 a lake was present within the Konya Basin (ca.25,000 to 20, 000 cal. years BP) which was a hydrologically closed basin with no surface outlets except for a few karstic sink holes. The lack of surface outflows means that the Konya Basin was a closed basin and therefore it should have being a hydro-climatically sensitive lake (Roberts, 1983). There is widespread evidence of the extent of the Konya Basin including shoreline deposits, fossil beaches, and sediments occupying depressions in the basin (Fontugne *et al.,* 1999; Roberts, 1983). Some of these depressions are now occupied by marshes, playas and small lakes

such as Akgöl (Roberts, 1983). In these depressions, complete lithostratigraphic sequences can be found that cover the time of the former palaeolake and beyond (Fontugne *et al.*, 1999). Through analysis of changes in the shoreline and the lithostratigraphy of the alluvial and sedimentary depressions, the advances and retreats of the palaeolake lake level have been investigated, and the environment of the Konya Basin reconstructed (e.g. Fontugne *et al.*, 1999; Leng *et al.*, 1999; Roberts 1983; Roberts *et al.*, 1999).

As well as providing a record of environmental change in the Late Pleistocene, the Konya Basin also hosts the earliest records of Neolithic settlement. The Neolithic settlements of Çatalhöyük (together ocuupied between 9,500 and 7,900 cal. years BP) and Can Hasan III (occupied between 9,500 and 8,500 cal. years BP) (Figure 4.1) were located on the alluvial fans that extended far into the Konya Basin covering the lacustrine sediments (Asouti & Hather, 2001). These alluvial deposits were laid down by rivers e.g. the Çarşamba River which across the Konya Plain after the lake had dried up. The Çarşamba River has deposited the largest alluvial fan which now measures 474 km^2. This fan supported many settlements as is evident through the number of mounds or höyüks (e.g. Çatalhöyük) present that have since been buried by Holocene alluviation. A third, important Neolithic site in the Konya Basin is the rockshelter site of Pınarbaşı (occupied between 10,300 and 10,000 cal years BP) (Asouti, 2003) (Figure 4.1).

Local vegetation

The natural vegetation of the Konya Basin is herb-rich steppe/dwarf shrubland (van Zeist & Bottema, 1991). Due to the longevity of human impact on this area and intensive grazing, the natural vegetation has possibly been replaced by *Artemisia* sp. steppe (van Zeist & Bottema, 1991).

(4.2.1.1) Akgöl (Plate 4.1)

Akgöl was the largest residual lake of the former Late Pleistocene Lake Konya. It is located in a depression at the eastern edge of the Konya Basin (Figure 4.1). The depression consists of a central, saline playa, the main lake (Akgöl), a beach ridge of Pleistocene origin and marshes (known as Akgöl Adabağ) at the margins (Figure 4.2). The beach ridge separates the main lake and the marshes. Until the lake was drained in the 1980s, it was a large (the estimated area in 1980 was 50 km^2), shallow, open marsh lake. The principal inflow enters Akgol through the Zanopa River which is fed by the largest karstic water spring of the Konya Basin at Ivriz (Leng *et al.*, 1999). Minor freshwater

inputs enter Akgöl from ephemeral streams running off the limestone hills to the south of the lake basin (Leng *et al.,* 1999). The main outflow to Akgöl is a sink hole to the southern margin of the lake basin (see Figure 4.2).

Plate 4.1: Akgöl Adabağ (Source: N. Roberts).
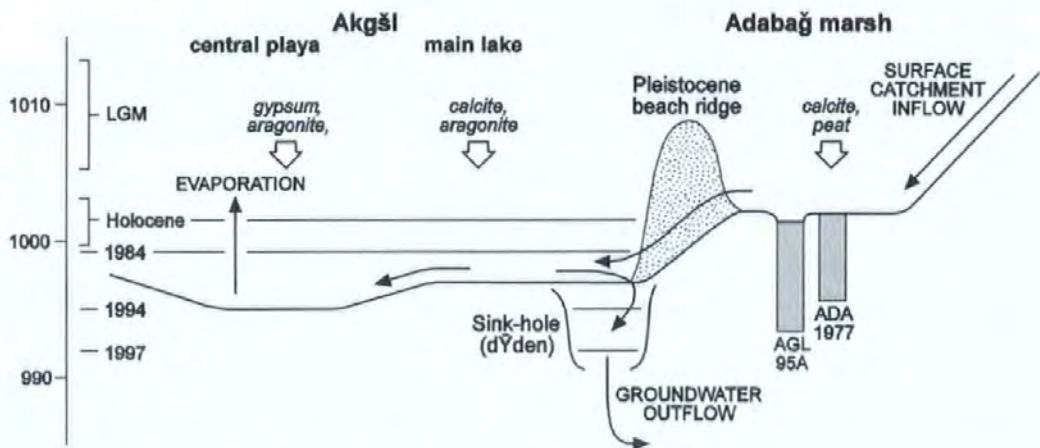
Figure 4.2: Schematic cross section of Akgöl (Roberts *et al.,* 1999).

Previous palaeoenvironmental research

Akgöl Adabağ (37°30'N, 33°44'E) was originally cored in 1977 (by S. Bottema, N. Roberts, W. van Zeist and H. Woldring) and then re-cored as part of the KOPAL Project in 1995, during which two cores were recovered (by Professor Neil Roberts and colleagues) (see Figure 4.2 for the coring locations and outflows). In 1977, a 620 cm core was obtained that spanned the Mid Holocene to Late Glacial. The basal part of the sequence was radiocarbon dated to 15,000 cal. years BP and the pollen record analysed (Bottema & Woldring, 1986). The absence of pollen identified ca. 8,957 cal. years BP was interpreted

to represent a hiatus in sedimentation due to desiccation of the lake (Bottema & Woldring, 1986). However, due to poor sediment recovery and low preservation of pollen in the top 115 cm of the core, the Late Holocene was not recorded in the core (Bottema & Woldring, 1986). The longer 1995 (AGL95A) core measured 847 cm but, the sedimentary sequence was not continuous. Diatom analysis and dating identified hiatuses in sedimentation at 440 cm and ca.600 cm (Roberts *et al.,* 1999). Below 440 cm sediments were dated to 24,600 cal. years BP. The section of the core between 126 and 440 cm spans the Late Glacial though to 9,602 cal. years BP (Leng *et al.,* 1999). A thorough multi-proxy investigation was conducted on the 1995 sequence which included dating (^{14}C and Uranium-Thorium (hereafter U-Th)), stable isotopic, palynological, diatom and lithostratigraphic analyses (see Leng *et al.,* 1999; Roberts *et al.,* 1999 and unpublished data). A second (AGL95B), parallel core was taken next to AGL95A. This core was shorter (only 420 cm long) and most of it to date has not undergone any analyses.

The isotopic analyses identified a large input of freshwater and a sustained change in the evaporation: precipitation ratio of Akgöl between 13,000 and 10,600 cal. years BP related to climatic warming associated with the onset of the Holocene (Leng *et al.,* 1999; Roberts *et al.,* 1999). Over the same interval biological remains (e.g. diatoms) preserved within the core imply the system was fresh to slightly brackish (Roberts *et al.,* 1999). The palynological investigation conducted on the 1977 sequence concurs with the interpretations of Leng *et al.* (1999) and Roberts *et al.* (1999). GS-2 was characterised by an open, treeless landscape dominated by *Artemisia* sp., Chenopodiaceae and *Ephedra* sp. (Bottema & Woldring, 1986). Arboreal pollen values measured between 1 and 9%. During the Early Holocene (based on a constant sedimentation rate) an increase in moisture availability occurred as reflected by the replacement of desert steppe with grass steppe and the appearance of *Betula* sp. (birch) (Bottema & Woldring, 1986). A clear climatic reversal associated with GS-1 is not easily recognised from the pollen record at Akgöl (ADA77). Further climatic improvement resulted in the gradual increase in *Quercus* sp. and *Juniperus* sp. (Juniper) (Bottema & Woldring, 1986).

From the three cores taken from this site AGL95A will be used for a high resolution analysis of the microscopic charcoal from 440 cm upward. Previous core descriptions identified a dark-coloured, charcoal-rich band at ca.284 cm present in the AGL95A and AGL95B cores. The presence of this band in both cores offers the opportunity for an investigation into incorporation of charcoal particle within lake sediments and the effects

of the remobilisation of charcoal within the lake upon the reconstructed fire history.

(4.2.1.2) Çatalhöyük (Plate 4.2)

Çatalhöyük is located on an alluvial fan deposited by the Çarşamba River. The site consists of two mounds; Çatalhöyük East and West which at the time of occupation were divided by the Çarşamba River (Figure 4.3). Çatalhöyük is one of the earliest sites of Neolithic occupation; therefore it has been the subject of extensive archaeological excavations since it was discovered by J. Mellaart in the 1950s (Asouti & Hather, 2001). The East Mound was occupied from ca.9,300 to 8,200 cal. years BP, the West Mound is less well dated but is Early Chalcolithic in age dating to between 7,900 to 7,800 cal. years BP (Cessford, 2001; Roberts pers. comm.). Archaeological evidence has shown that Çatalhöyük was a site of dense human occupation. Excavations have uncovered closely packed mud brick houses, numerous paintings and artefacts such as pottery tools that are thought to represent objects of daily life (Mithian, 2003). Archaeobotanical evidence demonstrates a subsistence economy that relied on both domesticated and wild resources (Asouti & Hather, 2001). Alluvial fans such as this were though to be attractive to Neolithic peoples due to the diversity of the flora and fauna present. This diversity was a direct consequence of periodic flooding, soil fertility and the microhabitats associated with alluvial fans (Brown, 1997).

Plate 4.2: Aerial view of the East Mound of Çatalhöyük (Source: N. Roberts).

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Previous palaeoenvironmental research

Alongside the archaeological investigations, palaeoenvironmental research has been conducted, again as part of the KOPAL Project. The mounds of Çatalhöyük and the Çarşamba alluvial fan were originally cored in 1994/5 and then again in 1999 (Figure 4.3). Palynological (Eastwood *et al.*, 2006) and sedimentological analyses (particle size, magnetic susceptibility and LOI) (Roberts, *et al.*, 1997; 1999) were conducted on the 1994 and 1995 cores. It has been proposed that the 1995/1999 cores (Figure 4.3) cut through a small oxbow lake (which superimposed on a alluvial fan) and was used for refuse disposal by the inhabitants of Çatalhöyük (N. Roberts, pers comm.). This is being tested further though analyses of the 1999 material which has included further palynological analyses and dating.
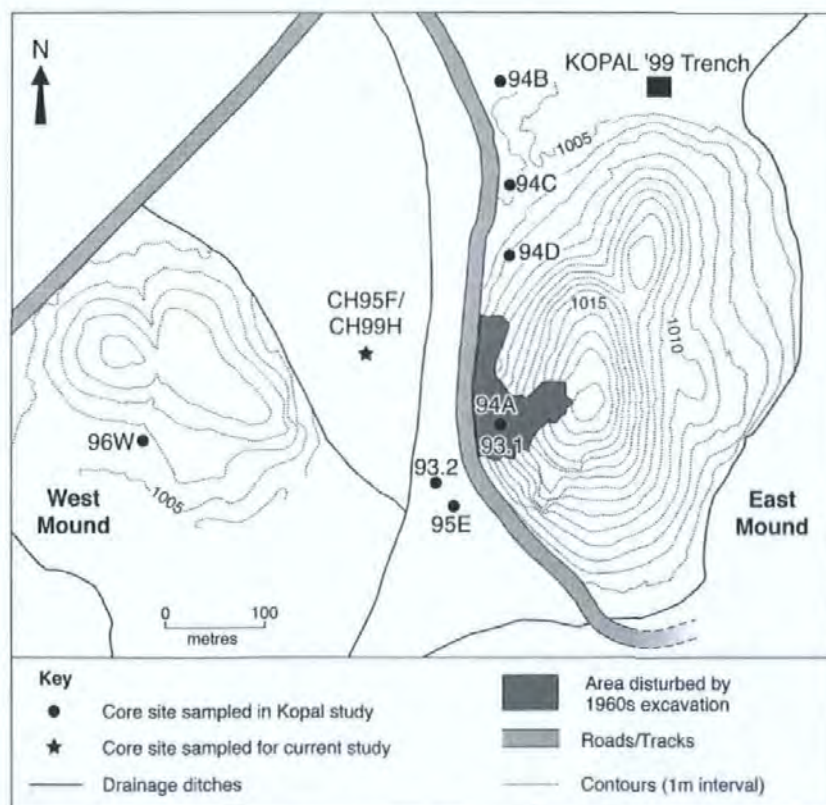
Figure 4.3: Map of Çatalhöyük with the coring locations added (Roberts *et al.*, 1997).

The investigations into the lithostratigraphy of Çatalhöyük and the alluvial fan of the Çarşamba River showed that deposition of the fan began in the Early Holocene. Dark, organic sediments were deposited by a marsh or back-swamp area that developed over the lake marls of the Konya Basin (Roberts *et al.*, 1999). Fine alluvial sediments were deposited from ca.9,500 to 9,000 cal. years BP until sometime in the Mid-Holocene (Roberts *et al.*, 1999). Therefore it is likely that alluviation continued throughout the

occupation of Çatalhöyük. Aside from the small oxbow lake, palaeochannels of the Çarşamba River have also been found that flowed between the two occupation mounds and in the surrounding area (Roberts *et al.*, 1997).

The pollen analysis conducted on the 1995 sequence recorded unusually high percentages (ca.70%) of *Cerealia*-type pollen and numerous clumped pollen grains (Eastwood *et al.*, 2006). Therefore, this sequence records in detail both the on-site use of plants as well as the composition of the regional vegetation. These high levels of *Cerealia*-type pollen were hypothesised to be the product of secondary production i.e. they were introduced to the site attached to herbaceous matter or cereals. This vegetation was then used for either bedding or fodder (Eastwood *et al.*, 2006).

Microscopic charcoal analysis will be conducted on core CH99H taken from a small oxbow lake (shown on Figure 4.3). This core had already been sampled for pollen analyses; hence a complete sequence is not available.

Cappadocia

Geology and Setting

Eski Acıgöl and Nar Gölü are located in the Cappadocian region of Central Anatolia. Cappadocia forms part of the Anatolian Volcanic Province, which has a long history of volcanic activity as exemplified by the presence of evidence of at least nine large eruptions that date to the Neogene (Druitt *et al.*, 1995).

As with the Konya Basin, Cappadocia has a long history of human occupation. To the south west of Eski Acıgöl is the Neolithic site of Aşıklı Höyük (Figure 4.1). Aşıklı Höyük dates to between 10,000 to 9,500 cal. years BP and contains evidence of early proto-agricultural practices and houses (Esin, 1991). The surrounding area has almost a continuous record of human habitation due to the availability of natural resources and raw materials such as obsidian (Roberts *et al.*, 2001).

Local vegetation

The long history of human activity in this area has had a significant impact on the vegetation. The continued clearance of woodlands to provide timber and fuel has depleted the woodland significantly. This has been exacerbated by the presence of and overstocking with grazing animals, which have prevented woodland regeneration (Woldring & Bottema,

2001). As a result tree growth is sparse and spiny, fragrant or toxic species dominate the ground cover (e.g. *Achillea santolina*) (Woldring & Bottema, 2001). The natural vegetation community of the area would be characterised by open oak parkland, today degraded oak-juniper scrub covers the upland parts of Cappadocia.

(4.2.1.3) Eski Acigöl

Eski Acıgöl (Plate 4.3 and Figure 4.1) was formerly a crater lake located within a larger caldera that formed during a period of Mid-Pleistocene volcanic activity (Woldring & Bottema, 2001). The lake is now dry due to drainage in 1972 because of problems associated with the mosquito population of the lake. The site consists of two overlapping explosion craters which are bordered by a rhyolitic intrusion (known as the Güneydağ Dome), in the southern half of the crater (Figure 4.4). The intrusion has been dated (using fission track dating) to 25,000 to 20,000 years BP, which gives a maximum age for the lake sediments (Roberts, *et al.*, 2001).

The former lake is located at ca.1,270 metres a.s.l, it had a diameter of 400 metres and the catchment area has been hypothesised to have not been much larger then the overall size of the lake (Roberts *et al.*, 2001). Eski Acıgöl was hydrologically closed therefore it was sensitive to climatic changes.

Plate 4.3: Eski Acıgöl viewed from Güney Tepe (N. Roberts).
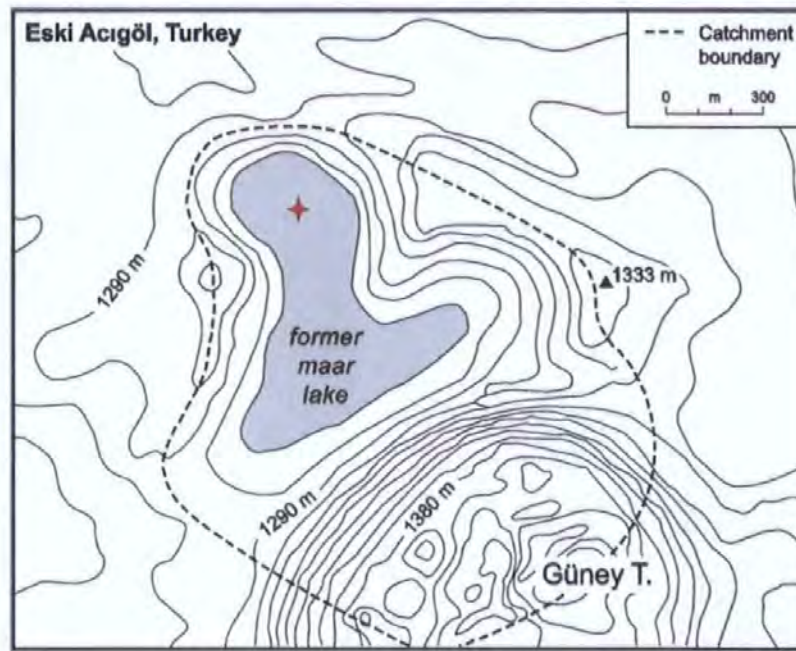
+ Core Site

Figure 4.4: Schematic of the Eski Acıgöl

Previous palaeoenvironmental research

Eski Acıgöl was originally cored in 1992 by Prof. H. Woldring and colleagues. This core measured 1485 cm and extended to the GI-1 (Woldring & Bottema, 2001). They conducted a thorough palynological investigation on this sequence and also ^{14}C dated the sediments (see Woldring & Bottema, 2001). The site was again cored by Prof. Neil Roberts and colleagues in 1996, 1997 and 1999. In total, over 16 metres depth of sediment was recovered. The sequences have been cross-correlated and a master sequence (measuring 1566 cm) formed which spans the whole of the Holocene through to the GS-2. A thorough palaeoenvironmental investigation was conducted on the master sequence, including isotopic, diatom, mineralogical and sedimentological analyses and dating (^{14}C and U-Th) (see Roberts *et al.*, 2001). One of the most interesting features of this site is the presence of thin, annually deposited laminations throughout the whole sequence below a depth of six metres. At six metres an abrupt shift in the depositional environment occurred which led to the halt in lamination deposition and a shift to non-laminated silts and carbonates (Roberts *et al.*, 2001). This is likely to be a consequence of a change in the depth of the lake. The dating of this site is complicated, because ^{14}C dates consistently produced an off-set of ca.3,000 years (Roberts *et al.*, 2001). It was hypothesised that this was a consequence of volcanic degassing and the incorporation of "old carbon" into the organic matter produced in the lake. Further U-Th dating proved successful but have large

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standard errors (Roberts *et al.,* 2001). Therefore a high resolution chronology of this site still needs to be established.

Analyses of the pollen and multi-proxy data have shown broad agreement with the pollen records from Lake Van and Lake Zeribar (Roberts *et al.,* 2001). Eski Acıgöl experienced a series a climatic shifts from cold to warm conditions synonymous with those experienced not only in the Eastern Mediterranean but also the northern hemisphere (e.g. GS-1) (Alley *et al.,* 1993; Rossignol-Strick, 1995). The transition from GS-2 to the Holocene was marked by a rapid change in both the lake ecosystem and the regional environment. The vegetation community switched from Chenopodiaceae and *Artemisia* dominated steppe to Gramineae steppe (Woldring & Bottema, 2001). This change in vegetation was matched by a positive shift in the water balance of the lake, indicating increased precipitation: evaporation balance. The Late Holocene saw a shift in the condition of the Eski Acıgöl. The sediments became massive indicating a considerable change in depth from deep to shallow waters. This is supported by the diatom flora and an increased salinity of the lake waters (Roberts *et al.,* 2001). As the Holocene continued the climate become drier, as indicated by the reduction of drought-intolerant tree species and a slight expansion in Chenopodiaceae and *Artemisia* sp. but this period also shows evidence of increased anthropogenic impacts on the vegetation in the region (Roberts *et al.,* 2001).

Although thorough multi-proxy analyses have already been conducted on this sequence it will still be possible to produce a high resolution charcoal record of past fire activity that extends from GS-2 through to the Late Holocene.

(4.2.1.4) Nar Gölü

Nar Gölü (Plate 4.4; Figure 4.5) is an extant, 26 metre deep closed, crater lake located on the northern edge of the Göllüdağ volcanic complex (Jones, 2004). Volcanic deposits in the area surrounding Nar Gölü date to 1.6 million years ago, however, subsequent dating of ash layers to the south of the lake's crater has given them an age of 1.3 million years. Therefore the Nar Gölü crater dates from sometime after 1.3 million years ago (Jones, 2004).

Plate 4.4: Nar Gölü (A Mather).
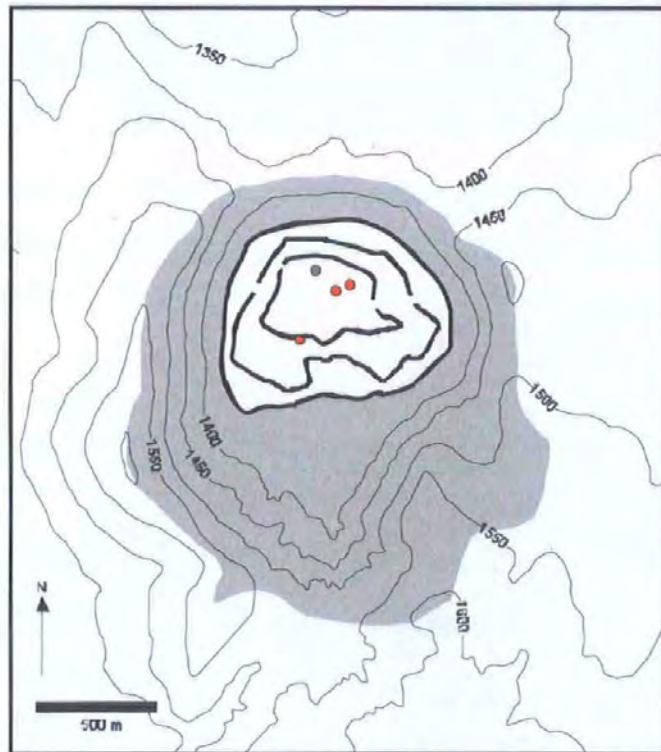
Figure 4.5: Schematic of Nar Gölü (Jones, 2004). The grey area indicates the watershed catchment. The red circles represent the 2001 and grey circles the 2002 coring locations.

Nar Gölü shares similarities to Eski Acıgöl, hence it may provide a useful comparison in terms of the charcoal record reconstructed i.e. particles may have similar source areas and therefore provide a replicate record for the recent part of the Eski Acıgöl sequence. Nar Gölü is also a hydrologically closed lake basin. It is located at an altitude of 1,360 m a.s.l

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(Jones, 2004). The lake has an area of 556,500 m², and as with Eski Acigol it has a relatively small catchment area (ca. 2,408,000 m²).

Previous palaeoenvironmental research

Nar Gölü was originally cored in 1999 which resulted in the identification of laminated sediments. In 2001 the site was again cored and 376 cm of laminated sediments were obtained. Dating of the top 50 cm of the sequence using Lead-210 and Caesium-137 showed that the laminations were annual (Jones *et al.*, 2005; 2006). The rest of the laminations in core were counted to establish the chronology of the sequence which spans the last 1,700 years.

Palynological and diatom analyses are currently in progress on this site, while the stable isotope analyses were completed in 2004 (Jones 2004). The oxygen isotope data were compared to the instrumental climate data for the past 75 years and a good correlation was identified (Jones *et al.*, 2006). Using the oxygen isotope record as a proxy for the regional water balance, major shifts from dry intervals at AD 300 to 500, 1400 to 1960 to wetter intervals in AD 560 to 750, 1000 to 1350 and post 1960 were identified (Jones *et al.*, 2006). These shifts from wetter to drier intervals have been related to changes in the Indian monsoon and North Atlantic winter climate (Jones *et al.*, 2006).

Due to the excellent chronological control (annual laminations spanning the last 1,700 years) it will be possible to produce a high resolution fire history record for the Late Holocene.

(4.2.2) Israel

Climate

Israel's climate is influenced by the same factors (e.g. mid to high latitude westerlies) as Turkey's and therefore experiences similar climatic conditions; long, dry summers and cool winters during which most of the precipitation occurs (Ben-Gai *et al.*, 1999). There is a strong climatic gradient running from the sub-tropical climate of the north of the county to the semi-arid zones of the south of the country (Ben-Gai *et al.*, 1998). The severity of the dry summer months varies along the north-south climatic gradient.

The northern part of the Jordan Rift Valley has a semi-humid climate but there is considerable variation in precipitation and temperature with altitude e.g. mean annual

precipitation in the valley measures 450 to 650 mm whereas in the mountains it measures 500-1000 mm (Baruch & Bottema, 1999).

Vegetation

As with precipitation and temperature, there are variations in vegetation with altitude. The slopes of the Hula Valley are characterised by open *Quercus ithaburensis* (Vallonea oak) parkland (Baruch & Bottema, 1999). In the Golan Heights the *Q. ithaburensis* parkland is replaced by *Quercus ilex* (evergreen oak). The slopes of Upper Galilee are characterised by steppe forest dominated by *Pistacia atlantica* (Mount Atlas Mastic) at the lower elevations to be replaced by Mediterranean maquis at higher elevations (Baruch & Bottema, 1999). Due to the longevity of human occupation of this area, the natural vegetation has been vastly modified though grazing and cultivation, therefore the oak parkland of the Hula Valley occurs sparsely in areas of protected land (Baruch & Bottema, 1999).

(4.2.2.1) Lake Hula

Geology and Setting

Lake Hula is situated 70 metres a.s.l. in the Levantine section of the Syro-African Rift system (Figures 4.1 and 4.6). This part of the Jordan Rift Valley has been occupied by lakes and swamps since early in the Quaternary. This is due to the presence of the basaltic block of Korazim which serves to dam the basin (Baruch & Bottema, 1991). To the west of Lake Hula are the limestone and dolomite mountains of Upper Galilee that extend to 1,200 metres a.s.l.. To the east is the basaltic plateau of the Golan Heights which is at an altitude of 300 to 1,000 m a.s.l. (Baruch & Bottema, 1999).
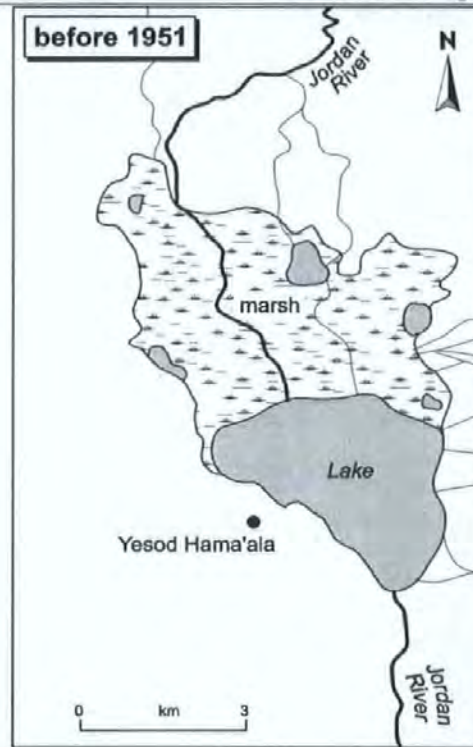
Figure 4.6: Map of the extent of Lake Hula and the surrounding marshes before drainage in 1951.

Today, the lake has largely been replaced by agricultural land due to the drainage of the lake in the 1950s. North of the residual lake are extensive areas of marshland (Baruch & Bottema, 1999). Lake Hula is drained by the Jordan River south into the Sea of Galilee, which in turn drains southward into the Dead Sea (Figure 4.6) (Baruch & Bottema, 1999).

The area surrounding Lake Hula contains numerous important archaeological sites, e.g. Hayonim Cave and Terrace and Mallaha (see Figure 4.1), that span the GI-1 to Early Holocene transition. These sites record the change in human behaviour that saw the shift from the Early Natufian sedentary hunter-gatherer communities to the onset of early cultivation in the Late Natufian (Bar-Yosef & Belfer-Cohen, 1992).

Previous palaeoenvironmental research
Lake Hula has been the subject of considerable palaeoenvironmental research (e.g. Baruch & Bottema, 1991; 1999; Cowgill, 1969; 1973; Stiller & Hutchinson, 1980). This research includes palynological, isotopic and chronological analyses, but these have been far from straight forward. The early palynological work was of a low resolution or poorly published (e.g. Tsukada in van Zeist & Bottema, 1991). Therefore Lake Hula was cored

again in 1987 by U. Baruch and S. Bottema. This core, which measured 1625 cm, came from the centre of the Hula Valley, unfortunately, the precise coring location is unknown (Baruch & Bottema, 1991). This core was radiocarbon dated and a thorough palynological investigation conducted (see Baruch & Bottema, 1991; 1999). However, questions have repeatedly been raised about the dating of this core (e.g. Cappers *et al.*, 1998; 2002 and Meadows, 2005). Cappers *et al.* (1998; 2002) identified a "hard water" effect, therefore the dates were corrected based on $\delta^{13}C$ determinations. The Cappers *et al.* (1998, 2002) chronology has since been reassessed by Meadows (Meadows, 2005). Meadows analysed the contemporary isotopic composition of Lake Hula's water and identified a correction factor of up to 5,500 ^{14} C years (Meadows, 2005). Using this correction factor and the vegetation chronozones of Rossignol-Strick, a pollen record from the Dead Sea and local archaeological information, the chronology of Lake Hula was again revised (Meadows, 2005; Rossignol-Strick, 1995). Consequently, there are two revisions of the original Hula chronology proposed by Baruch & Bottema which need to be considered during the analysis of this sequence.

Isotopic analysis was conducted by Stiller & Hutchinson (1980) to reconstruct the climatic history of Lake Hula. The reliability of this work has since been questioned due to the identification of detrital carbonates in the lake sediments (M. Jones pers. comm.). Detrital carbonates contaminate the authigenic carbonates, therefore an accurate reconstruction of the past hydrology and climate of Lake Hula cannot be produced using stable isotope analysis (M. Jones, pers. comm.). Consequently, climatic conditions have to be inferred from the regional stable isotope reconstructions from stalagmites at Soreq Cave, Israel (Bar-Matthews *et al.*, 1997; 1999).

Based on the Meadows chronology the Hula pollen diagram spans the end of the GI-1 stage, GS-1 and the Holocene. During the GS-1, arboreal pollen values were low ca.20-28% whereas non-arboreal pollen including Gramineae dominated the vegetation community. The higher presence of arboreal pollen at Lake Hula compared to sites in Central Turkey during the GS-1 may reflect a less extreme climate and the presence of trees in sheltered habitats (Jones *et al.*, in review). The onset of the Holocene is marked by an immediate increase in arboreal pollen values, particularly deciduous oak, which by ca.9,000 years BP reached a peak of ca.70%. The gradual expansion of evergreen oak and *Pistacia* also took place. Following the peak in arboreal pollen values there was a sharp decline which coincides with increasing cereal pollen values and has been attributed to

human activity within the local area (Meadows, 2005). Throughout the Holocene there is evidence of a continued human presence in the area (e.g. repeated expansions of olive plantations are evident within the pollen record) (Baruch & Bottema, 1991).

The archived Lake core sequence is not complete. The top two metres, two metres between 10 and 12 metres and last 60 cm are missing, which, in combination with previous sampling for pollen analysis, means that this sequence is incomplete. Therefore it will only be possible to conduct a low resolution fire history reconstruction of this site.

(4.3) Sampling strategy

Fire events produce a pulse in charcoal which is then transported away from the fire site and incorporated into lake sediments (see Chapter 2). Identifying fire events is dependent on finding these peaks in charcoal concentration, yet in the majority of sequences the location of a charcoal peak is unknown. Therefore a contiguous sampling strategy needs to be adopted. The analysis of the whole sequence ensures a thorough record of fire activity is obtained. However, contiguous sampling was not possible for all sequences due to the limited availability of sediment. Therefore two sampling strategies were applied; a) high resolution, contiguous sampling and b) low resolution, spot sampling. The two sampling resolutions were selected to make optimal use of the sediment sequences available to this research and provide robust fire history reconstructions.

To standardise the amount of sediment analysed across all sites, the overall volume of each sample measured 1 cm^3. The volume of each sample was measured using volume by displacement.

a) High resolution, contiguous sampling

Complete archived cores were available for the Akgöl, Eski Acıgöl and Nar Gölü sequences. The Akgöl and Eski Acıgöl sequences were sampled using a depth based strategy. Samples measuring either 2.0 x 1.0 x 0.5 cm or 4.0 x 1.0 x 0.25 cm were extracted contiguously from the core (Figure 4.7). The application of the smaller sample size (2.0 x 1.0 x 0.5 cm) allowed periods of particular interest e.g. the transition from GS-1 to the Holocene to be sampled at a higher resolution and therefore provide a more detailed fire history reconstruction. The dimensions of each sample were selected to provide 1 cm^3 of sediment for analysis.
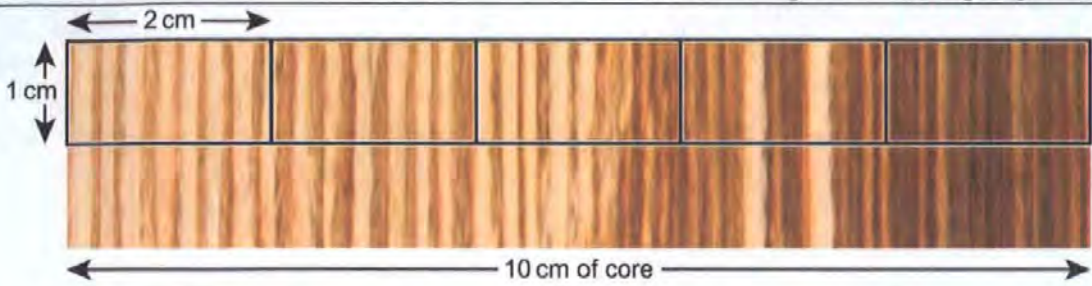
Figure 4.7: Schematic of the contiguous high resolution sampling strategy

The Nar Gölü sequence was laminated for its entirety. This offered the opportunity for a high resolution, temporal based sampling strategy to be applied. The first 100 laminations were sampled contiguously every 10 lamination/varve years. The rest of the sequence was sampled every 20 laminations/varve years. These sampling resolutions were selected to allow correlation with existing stable isotope and palynological research (England, 2006; Jones, 2004).

b) Low resolution, spot sampling

This was applied to the Çatalhöyük and Lake Hula sequences. Both sequences had previously been sampled for multi-proxy analyses therefore the availability of material was limited. In each case, 1 cm^3 of sediment was removed for analysis.

The spot sampling regime applied to the Çatalhöyük sequence was largely determined by material availability. Where possible spot samples were taken at 8 cm resolution.

From the Lake Hula sequence, samples were taken at 8 cm resolution from the part of the sequence hypothesised to span the transition from GI-1 to Holocene (based on the dating revisions of Meadows (2005)). To gain a general overview into the fire history of this site throughout the Holocene, the rest of the sequence was sampled at a 32 cm resolution.

Sample extraction

Due to the cores being in varying states of preservation and desiccation, the removal of samples had to be adapted to the condition of the core. The sediments from Çatalhöyük, Eski Acıgöl, Lake Hula and Nar Gölü were still in relatively good condition and soft, therefore the core surface was cleaned using a scalpel then the sample removed.

Although sediments from Akgöl had dried out whilst in cold storage their stratigraphic

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integrity remained intact. However, the sediments had "set solid" and it was not possible to safely remove the samples using a scalpel. Instead the samples had to be "cut" out of the core using a Dremmel (model 395).

(4.4) Depth correction

Due to the high organic content, previous sampling and age of the cores from Eski Acıgöl, some sections of the master sequence had experienced shrinkage. It was assumed that the core had experienced linear shrinkage. Therefore, a correction factor needed to be applied to ensure the charcoal sample depths correlated with those of the original master sequence. Detailed descriptions had previously been produced by E. Hunt during the original analysis of the master sequence. These descriptions included the establishment of numerous "tie points" which represented notable features, e.g. tephra horizons, and meant the core sections could be correlated. Therefore by using a combination of the original core descriptions, tie points and laminae the sections of the master sequence to be sampled were identified. The current length of each master section was then measured, the percentage difference between the measured section lengths calculated (i.e. the original vs. current length) and the following equation applied to correct the sample depths for shrinkage.

$$\text{Corrected depth} = S_{depth} + (B_{length} \times \text{multiplier})$$

S_{depth} = depth the sample was taken from

B_{length} = sediment block length

multiplier = percentage difference between the original and current length of each section

(4.5) Dating

As discussed, dating has previously been conducted and published on the Akgöl, Eski Acıgöl, Lake Hula and Nar Gölü sequences (Baruch & Bottema, 1999; Cappers et al., 1998; 2002; Jones et al., 2006; Meadows 2005; Roberts et al., 1999; Roberts et al., 2001) therefore the chronologies of these sites will be discussed in Chapters 5, 6, 7 and 8. However, ^{14}C dating was conducted on the 1999 Çatalhöyük sequence as this remained undated.

[14]C dating of the 1999 core from Çatalhöyük was carried out on plant macrofossils extracted and identified from the sequence by A. Fairbairn. In total eight macrofossil samples were dated from six levels throughout the sequence. These samples were dated

using an accelerator-mass-spectrometer at the Oxford Radiocarbon Accelerator Unit. All the radiocarbon ages were then calibrated using CALIB 5.02 (Reimer *et al.*, 2004a; 2004b; Stuiver & Reimer, 1993).

(4.6) Summary

The analysis of the fire history records preserved within each of the five sites presented in this Chapter will result in a comprehensive understanding of the role of fire within the landscape not only during the GS-2: Early Holocene transition but also through the Holocene. The range of archaeological and multi-proxy data available for each of the study sites will enable a full interpretation of the fire history record to be made and the potential driving mechanisms i.e. climate vs. people to be identified. This chapter also described the sampling strategies applied to the different lake sequences and further dating to be conducted on the Çatalhöyük sequence.

This Chapter presents the microscopic charcoal results from Çatalhöyük and Lake Hula. These two sites are presented together as in both sequences from these sites there was limited material, therefore the contiguous sampling regime could not be applied to these sequences (see Chapter 4, Section 4.2.1 for details). Despite this, these sites were still included in this research as Çatalhöyük has provided valuable archaeological evidence of early agro-pastoral practices during two phase of occupation between 9,300 and 7,800 cal. years BP (e.g. Asouti & Hather, 2001; Fairbairn *et al.*, 2002; Fairbairn, 2005; Hodder, 1997; Richards *et al.*, 2003). In the area surrounding Lake Hula there is archaeological evidence for continued occupation since the appearance of advanced hunter-gatherers and early agriculturists ca.15,300 cal. years BP (e.g. Hayonim Cave and Terrace and Ein Mallaha) (Bar-Yosef, 1998). Charcoal results from each site are presented and discussed in relation to the chronology of each site and available multi-proxy data.

(5.1) Çatalhöyük

Çatalhöyük is one of the earliest sites of Holocene occupation in Turkey. It is located on an alluvial fan deposited by the Çarşamba River. The site consists of two mounds; Çatalhöyük East (the oldest mound) (occupied between 9,300 and 8,200 cal. years BP) and West (occupied between 7,900 and 7,800 cal. years BP) which at the time of occupation (were divided by the Çarşamba River. The sequence analysed from Çatalhöyük (CH99H) came from an infilled former palaeochannel of the Çarşamba River that was located between the two occupation mounds (Figure 4.3).

(5.1.1) Lithology

From the 566 cm CH99H sequence the section from 286 to 566 cm was analysed for microscopic charcoal. The section of the core between 0 and 286 cm consisted of sands and silts that were sterile and therefore it was not analysed. The lithology of the core is described in Table 5.1.

Depth (in cm)	Description
0 to 286	Alternating sands, gravels, and silt-clays of alluvial origin. These are sterile culturally and palaeoecologically.
286 to 412	Very dark grey damp organic silt, containing abundant cultural debris, including animal bone, obsidian and charcoal.
412 to 566	Dark grey alluvial silt-clay, locally sandy; cultural debris includes including animal bone, obsidian, pot shards and charcoal.

Table 5.1: Lithology of CH99H

(5.1.2) Microscopic charcoal

In total 27 samples, taken where possible at 8 cm sampling intervals were analysed from between 290 and 566 cm of the CH99H sequence. Results are shown in Figure 5.1 and show an oscillating pattern of change. There are several clear peaks in charcoal e.g. at 479.0, 440.5 and 399.0 to 410 cm (ca.6.3, 6.1 and 8.6 x 10^4 charcoal particles cm^{-3} respectively) (Figure 5.1). Low charcoal values were recorded at 469.0 (7.1 x 10^3 charcoal particles cm^{-3}) and 379.0 cm (8.6 x 10^3 charcoal particles cm^{-3}).
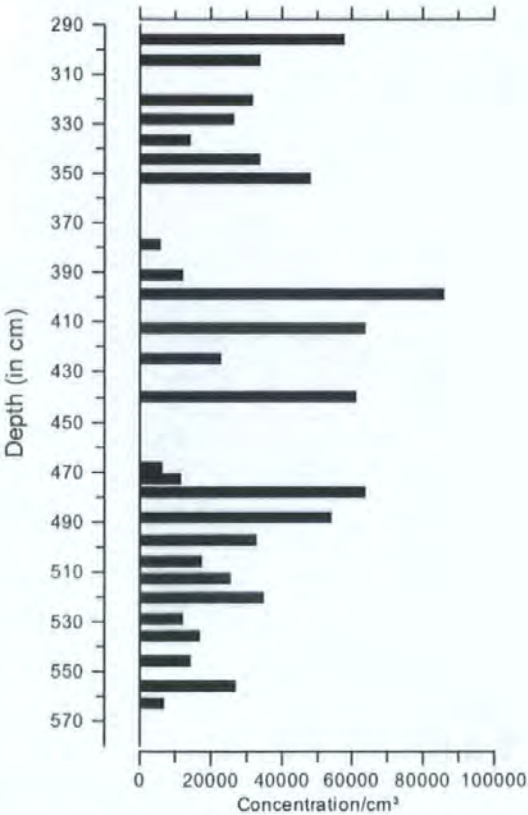
Figure 5.1: Charcoal concentration in CH99H

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(5.1.3) Chronology

The ages of the eight plant macrofossil samples ^{14}C dated from the CH99H sequence are presented in Table 5.2. Sample CH99H 7 produced an anomalous result. A second sample, CH99H4, is older than the remaining six samples. This age difference has been hypothesised to represent the reworking of older material from the East Mound.

Sample number	Core depth cm	Laboratory number	Material dated	Age in uncal. years BP	Age in cal. years BP (in the 1 sigma error range)
CH99H 1	294-304	OxA-14778	Cereal grain (?*Triticum*)	6930 ± 40	7,753 +40/-60
CH99H 2	304-316	OxA-14695	Cereal chaff (?*Triticum*)	6800 ± 38	7,625 +45/-10
CH99H 3	317-325	OxA-14696	Cereal chaff (?*Triticum*)	6826 ± 36	7,670 +10/-50
CH99H 4	357-366	OxA-14779	Single Cerealia grain, *Hordeum*	7215 ± 50	8,100 +50/-35
CH99H 5	475-486	OxA-14780	Cereal chaff (?*Triticum*)	6950 ± 40	7,785 +50/-60
CH99H 6	475-486	OxA-14781	Nutshell, *Prunoides* or *Pistacia*	6995 ± 40	7,840 +30/-50
CH99H 7	535-545	OxA-14784	Cereal chaff and grain (?*Triticum*)	>51,900	n.a.
CH99H 8	558	OxA-14697	Single Cerealia grain	6983 ± 38	7,830 +30/-50

Table 5.2: Results from the ^{14}C dating of material taken from CH99H
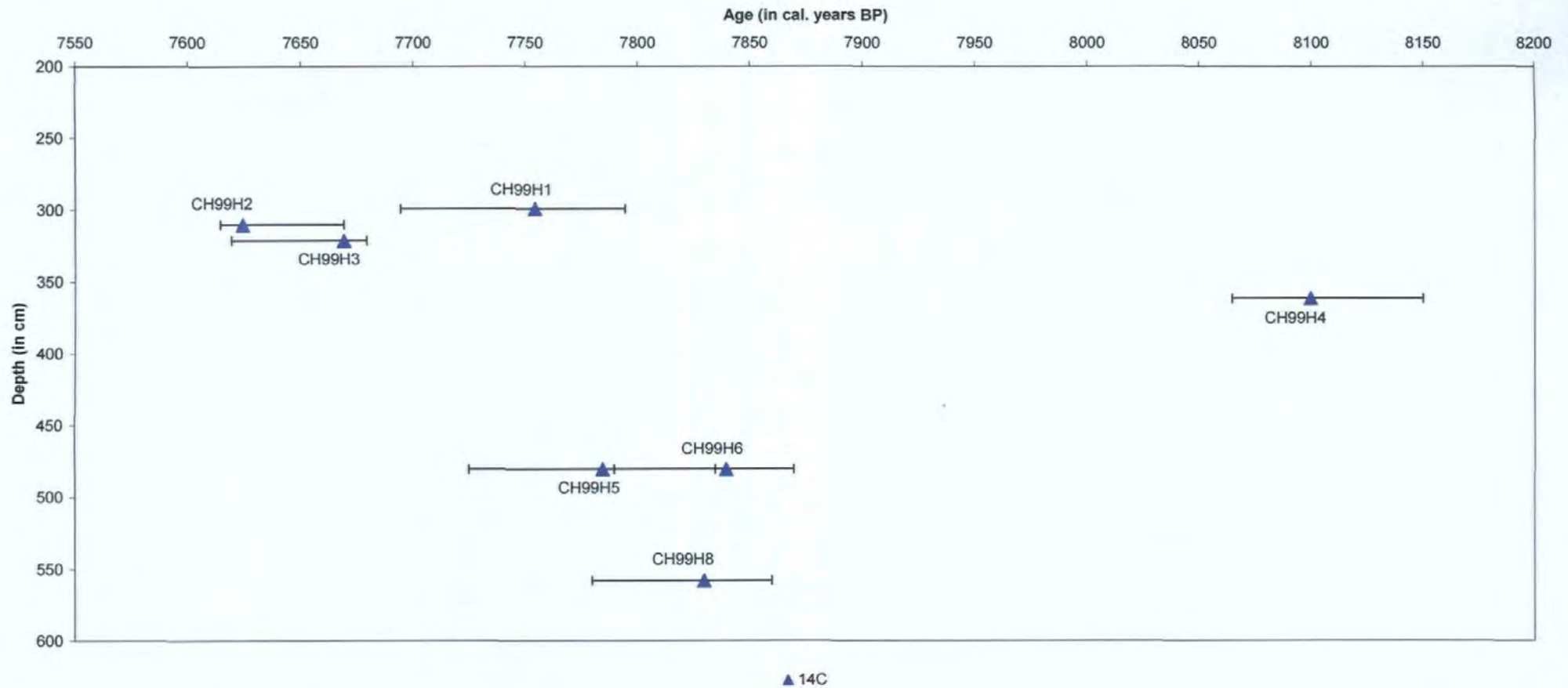
Figure 5.2: Age-depth plot for Çatalhöyük (CH99H)

There is no clear age-depth relationship for CH99H (Figure 5.2). Rather than forming a linear age-depth relationship the samples fall into two clusters (Figure 5.2). One possibility is that this may represent two phases of relatively rapid lake infilling associated with human activity at the site. The lake may have been infilled by waste disposal rather then by gradual sediment accumulation. Archaeological investigations carried out on both the East and West mounds show that on site infilling of houses was widely practised (Bogdan, 2004; Fraid, 1998; Gibson *et al.*, 2002). Evidence also shows that infilling could occur in several phases, with each phase of infilling or waste disposal rapidly buried once it was dumped. Although the CH99H sequence was taken outside the area of immediate habitation, it is likely that similar infilling practices occurred and this therefore may explain the arrangement of the dates on the age-depth model (Figure 5.2). Excavations conducted on a trench (during the KOPAL Project) located in backswamps of the Çarşamba River identified high concentrations of anthropogenic finds e.g. animal and human bones, carbonised plant remains and fired clay objects (Boyer, 1999). These remains may have originated from the disposal of waste within the backswamp area of the Çarşamba River (Boyer, 1999; Frame *et al.*, 1999). It is likely the oxbow which the CH99H sequence was taken from could have formed in a similar fashion.

The ^{14}C dates show the sequence corresponds with the second phase of occupation of Çatalhöyük associated with the Late Neolithic/Early Chalcolithic and the younger West Mound.

(5.1.4) Comparison with pollen data

Analysis conducted by W.J Eastwood (Eastwood *et al.* (2006) & unpublished data) Pollen preservation in the CH99H sequence was poor resulting in low concentration levels (W.J. Eastwood pers.comm; Figure 5.3). Arboreal pollen (*Betula* sp., *Picea* sp., *Pinus* sp. and *Quercus* sp.) was sparse, indicating either the limited abundance of trees near Çatalhöyük or a local pollen signal. The presence of a localised pollen signal is further supported by clumped grains of Chenopodiaceae and Cerealia pollen that were noted during analysis. The occurrence of clumped grains indicates that the taphonomic processes which usually disaggregate the grains following dispersal had not taken place (W.J. Eastwood pers. comm). *Pinus* sp. and *Quercus* sp. were the only tree taxa present (>20%) throughout the sequence (Figure 5.3). As evident in Figure 5.3 there is no apparent relationship between the pollen and charcoal records for this sequence.
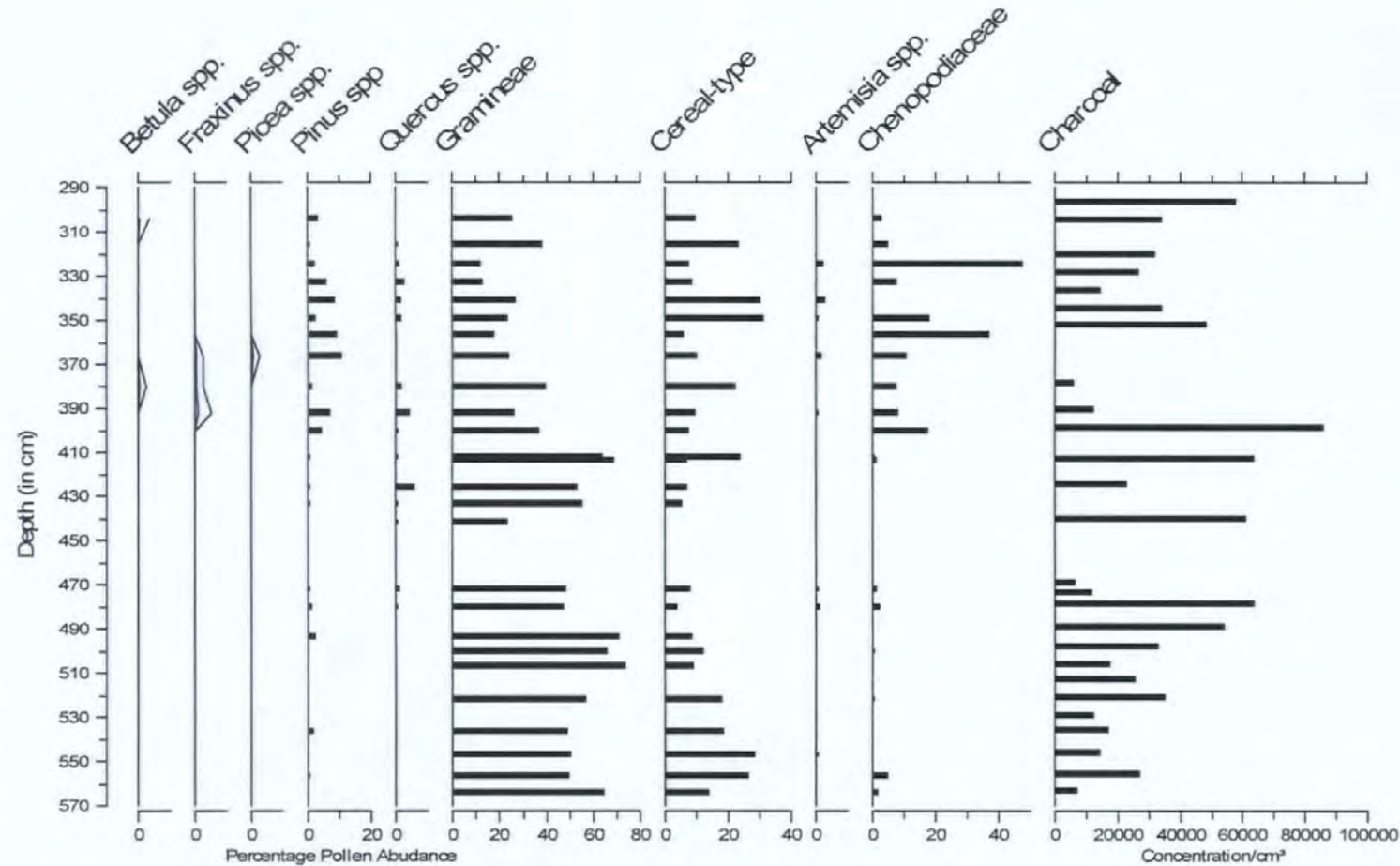
Figure 5.3: Pollen data from CH99H (Eastwood unpublished data). A five fold exaggeration factor has been applied to *Betula* sp., *Picea* sp. and *Fraxinus* sp.

(5.1.6) Climate, biomass, people and fire

As demonstrated by the ^{14}C dates the CH99H sequence may represent a mixed natural and archaeological deposit. The absence of gradual sedimentation prevented a reconstruction of continuous fire history from the sequence for the duration of the occupation. Based on the presence of clumped pollen grains, the low pollen concentrations, and the proximity of the coring location to the occupation site, this sequence is likely to provide a localised record of both fire activity and the vegetation community. Therefore the contribution of this sequence to understanding of regional fire activity will be limited. Furthermore, the absence of a coherent relationship between the fire and vegetation records means that it is likely that different factors are exerting a control on vegetation community and fire activity. It is possible that the pollen record is reflecting the vegetation community within the immediate vicinity of the lake where people were likely to exert the greatest influence. In addition, the presence of tree pollen reflects changes in the wider environment and therefore natural controls on the vegetation community (Asouti & Hather, 2001; Fairbairn *et al.*, 2002). In contrast the fire history record is likely to reflect primarily reworked domestic charcoal associated with cooking and heating.

(5.2) Lake Hula

Lake Hula was, until drainage in 1951, an open lake located within the Jordan Rift Valley. To the north shore of the lake there was a marsh complex through which the Jordan River flowed. Based on the size and shallow shape of Lake Hula it was hypothesised to receive a local to regional input of charcoal to the basin.

(5.2.1) Microscopic charcoal

In total 61 samples were analysed from the Lake Hula sequence. Between 1567.5 and 1210 cm samples were taken, where possible, every 8 cm. From 12 to 10 m there was a two metre gap in the sequence. Following the gap in the core the section between 10 and ca.2 m was sampled at 32 cm resolution. The top two metres of the core were also missing therefore no samples were taken. From 1567.5 to 1210 cm three charcoal peaks were identified at 1543.5, 1511.5 and 1255.5 cm (2.8, 2.5 and 3.2 x 10^4 charcoal particles cm^{-3} respectively) (Figure 5.4). After the peak in charcoal at 1511.5 cm a reduction in the charcoal concentration occurs at 1445.5 cm (1.5 x 10^3 charcoal particles cm^{-3}). After 1445.5cm charcoal concentration values increase, and remain fairly stable until the peak at 1255.5 cm. At 1223.5 there is a small peak in charcoal values (1.3 x 10^3 charcoal particles cm^{-3}) (Figure 5.4).

From 10 to 2 m charcoal values show a number of fluctuations (Figure 5.4). At 966.5 cm there is a peak in charcoal (2.6 x 10^4 charcoal particles cm^{-3}). At 656.5 cm the lowest concentration values of the sequence are recorded (4.4 x 10^2 charcoal particles cm^{-3}). After 656.5 cm charcoal values increase to a similar level as they were previously, until 359.5cm when there is a marked and sustained reduction in charcoal concentrations up to 200 cm (Figure 5.4).
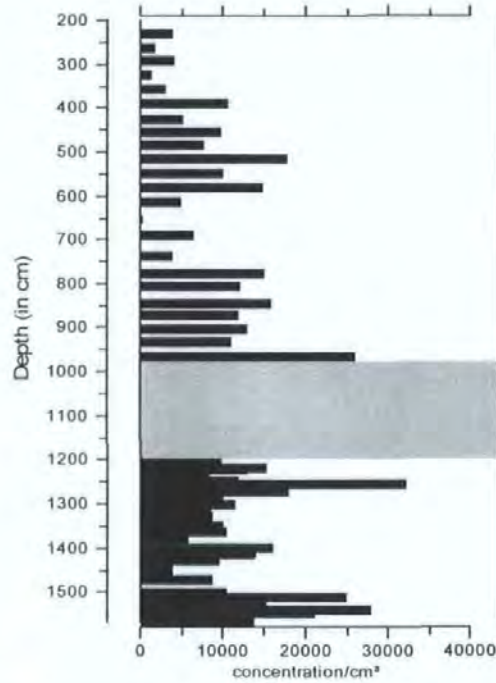
Figure 5.4: Charcoal concentration at Lake Hula. The grey band represents the gap in the sequence between 10 and 12 metres.

(5.2.2) Lithology

In total the Lake Hula sequence measured 1625 cm in length. The sequence consisted of stiff, grey lake sediments with some locally dark patches and mollusc shell remains. There were no major changes in lithostratigraphy downcore.

(5.2.3) Chronology

As discussed in Chapter 4 there are currently two revisions of the original chronology proposed by Baruch & Bottema (1999). Cappers *et al.* (1998; 2002) applied a correction factor (of either 1,200 or 1,600 years) to all of the dates (21 in total, although only ten were presented on the original pollen diagram) obtained by Baruch & Bottema. Meadows (2005) only revised the dates (10 depths, 11 dates) presented by Baruch & Bottema on their pollen diagram. The original chronology and the subsequent revisions are presented in Table 5.3 in calibrated years BP. Each date was calibrated using the original analytical error cited by Baruch & Bottema (1999). All the dates were calibrated using CALIB 5.0.2. (Reimer *et al.*, 2004).

Lab No.	Depth (in metres)	Baruch & Bottema, 1999. Original chronology	Cappers *et al.*, 2002. First revision (a 1,600 year correction applied).	Meadows, 2005. Second revision (up to a 5,500 year correction applied)
GrN-22394	1.59	3,310 +70/-100	1,360 +50/-60	975 +90/50
GrN-22395	2.60	3,520 ± 70	1,560 +80/-40	1,710 +110/-30
GrN-22396	3.20	4,630 +80/-50	2,720 ± 30	2,270 +40/-50
GrN-22397	6.02	7,840 +40/-60	6,210 +80/-40	4,600 +60/-70
GrN-22398	8.26	8,380 +70/-190	6,770 +190/140	6,440 ± 130
GrN-22404	8.28	9,550 +250/-20	7,930 +80/-150	6,460 +110/-70
GrN-17067	10.05	10,430 ±150	8,440 +140/-60	7,685 +150/-70
GrN-17068	11.30	12,325 +90/-180	9,900 +70/-160	8,540 +110/-140
GrN-14986	12.38	13,370 ± 100	11,320 +90/-80	9,500 +100/-50
GrN-22399	14.87a	18,850 ± 160	16,663 ± 350	11,980 +220/-390
GrN-23322	14.87b	18,800 ± 120	16,535 ± 290	11,850 +320/-250

Table 5.3: Proposed chronologies of Lake Hula (dates in cal. years BP within the one σ error range).

There is clearly a localised reservoir age effect exerting an impact on the ^{14}C, in the organic matter, subsequently analysed by Baruch & Bottema. Therefore radiocarbon dating of material from Lake Hula will always be problematic. Through comparisons with the existing pollen record of Baruch & Bottema and marine pollen records, archaeobotanical evidence from Abu Hureyra and the level of the Dead Sea, along with the pollen chronozones of Rossignol-Strick, (1995) Meadows established a new chronology for Lake Hula. Meadows identified the onset of the Holocene as occurring at ca.15 m based on a shift in the vegetation community whereby arboreal pollen values increased and *Artemisia* sp. and Chenopodiaceae began to decline (Figure 5.5). Of the three available chronologies the Meadows chronology is used here to construct the age model for Lake Hula (Figure 5.5). Obviously, given the uncertainties, precise correlations between Hula and other regional or global climato-stratigraphic sequences may be problematic and therefore the chronology of proposed burning events must be treated with caution. Likewise caution must be applied when interpretations are been made of the charcoal data.

The Meadows chronology has had to be extended beyond the interpolated chronology of Meadows (2005) as the sampling for charcoal analysis extended to 1568 cm. An age of 13,000 cal. years BP was given to this depth based on linear extrapolation of the GrN-22399/GrN-23322 sample ages.
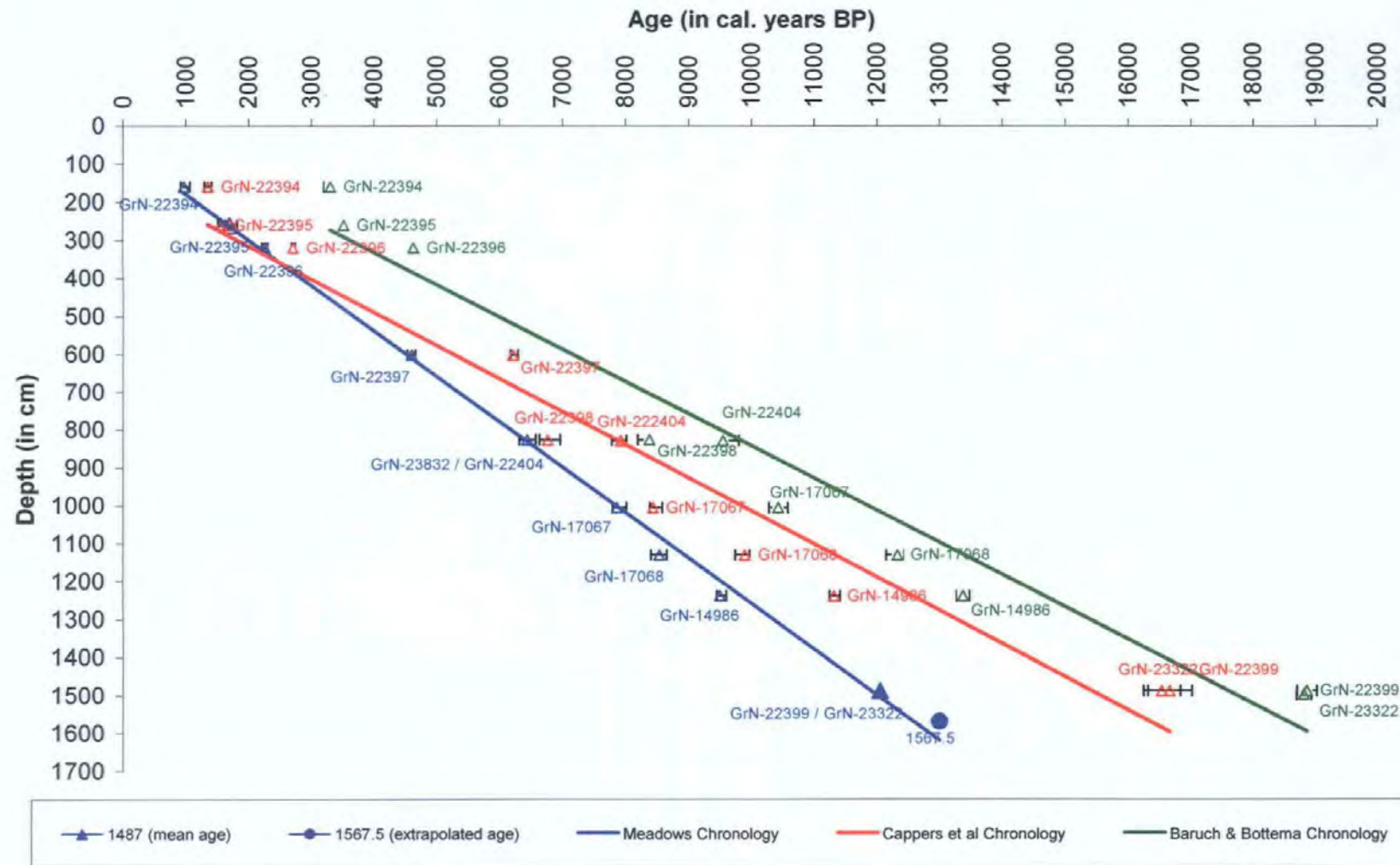
Figure 5.5: Age depth relationships for the proposed chronologies for Lake Hula

(5.2.4) Influx of microscopic charcoal

Due to spot rather then contiguous samples being taken from the sequence, a three-point moving average was applied to smooth the data (Figure 5.6). The overall trends in charcoal influx follow the concentration data. This is explained by the application of a linear age model which assumes linear accumulation of sediment, meaning that influx is directly proportional to concentration (compare Figures 5.4 & 5.6; see Figure 5.5). (compare Figures 5.4 & 5.6; see Figure 5.5). Influx values decline overall from ca.1,500 particles/year/cm^{-2} at ca.12,700 cal. years BP in GI-1, through GS-1 and reach a minimum value of 85.4 particles/year/cm^{-2} at ca.11,400 cal. years BP. Following these low influx values high influx values are recorded in the Early Holocene. From 7,500 cal. years BP (following the gap in the sequence) charcoal influx gradually declined toward the top of the sequence.

Figure 5.6: Charcoal influx into Lake Hula. The grey areas represent gaps in the sequence. The green line is the three-point moving average.

(5.2.5) Comparison with proxy data

(5.2.5.1) Pollen (Baruch & Bottema, 1999)

Unfortunately the raw counts were not available for this sequence, so only the percentage pollen data have been used. Caution has to be applied to the interpretation of these data. The apparent increase or decrease of a particular species may be the product of changing

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Unfortunately the raw counts were not available for this sequence, so only the percentage pollen data have been used. Caution has to be applied to the interpretation of these data. The apparent increase or decrease of a particular species may be the product of changing

ratios in the pollen sum, rather than a reflection of a change in the vegetation community. This may be identified by changes in vegetation that do not correlate with changes in either climate or fire history.

During GI-1 and GS-1 *Quercus* sp. and Gramineae were present indicating the presence of open, oak dominated parkland. Gramineae pollen dominated the non-arboreal constituent of the vegetation community but Chenopodiaceae and *Artemisia* sp. were also important, indicating a steppic component (Figure 5.7). Toward the end of GS-1, minimum influx values were recorded. These low influx values follow the change from the grass dominated to a more steppic herb dominated vegetation community (Figure 5.7). Following the transition from GS-1 to the Holocene there was a progressive increase in *Quercus itaburensis* (Tabor oak) and charcoal influx, and a reduction in Chenopodiaceae and *Artemisia* sp. (Figure 5.7). Coinciding with the increase in *Q. itaburensis* is a reduction in Gramineae. However, this is likely to be partly a product of using percentage pollen data, as discussed above.

After the low charcoal influx values at the GI-1: Holocene transition, charcoal influx increased. This increase follows the increases in *Q. ithaburensis* and maximum *Q. ithaburensis* are reached around the same time as charcoal influx peaks ca.9,300 to 10,000 cal. years BP (Figure 5.7).

Following the gap in the sequence there is an increase in *Olea* sp. and a subsequent decrease in both *Q. ithaburensis* and charcoal influx from 6,775 to 5,050 cal. years BP. From ca.4,200 cal years BP both arboreal pollen and charcoal influx values begin to gradually decline.

(5.2.5.2) Regional stable oxygen isotope data

Due to the presence of detrital carbonates within the sediments of Lake Hula (see Chapter 4, Section 4.2.2) it is not possible to use published stable isotope data (Stiller & Hutchinson, 1980). Therefore a regional $\delta^{18}O$ record obtained from speleothems in Soreq Cave, Israel is used here to provide an overview of the climate in Israel (Table 5.4) (Bar-Matthews *et al.,* 1997; Bar-Matthews & Ayalon, 2004).

Inferring the relationship between the $\delta^{18}O$ and charcoal influx during GI-1 is limited as only two charcoal samples were analysed. However, during GI-1 fires were clearly taking

place. During GS-1 when there is a reversion back to quasi-glacial conditions there appears to be a reduction in charcoal influx (Table 5.4 and Figure 5.6). The climatic optima associated with the Early Holocene correlated with increasing charcoal influx values. The decrease in rainfall from the Mid Holocene coincided with a gradual reduction in charcoal influx to Lake Hula.

	$\delta^{18}O$ range (‰)	General climate summary
GI-1	-6.1 to -5.1‰	Climatic warming. Increasing rainfall (550-750 mm/year) and temperatures (14.5-18.0°C)
GS-1	ca.-5.6‰	Reversal to quasi-glacial conditions i.e. reduced precipitation & temperature and increasing aridity.
Early Holocene	-6.8 to -5.8‰	Climatic optima: higher rainfall (675-950 mm/year) and temperatures (14.5-19.0°C), higher summer precipitation and frost-free winters
Mid Holocene	-6.0 to -5.0‰	Reduced rainfall (450-580 mm/year) and an increase in temperatures (18.0-22.0°C)

Table 5.4: Summary of regional $\delta^{18}O$ data derived from speleothems in Soreq Cave, Israel. (Based on data from Bar-Matthews *et al.,* 1997; Bar-Matthews & Ayalon, 2004)

(5.2.5.3) Phytoliths (E. Jenkins unpublished data)

Phytoliths are silica bodies that form casts of plant epidermal tissues and other shapes during the life span of a plant. When a plant dies and decays these silica bodies remain in the sediment. The high evapotranspiration rates during the growing season in the Eastern Mediterranean give rise to abundant phytoliths, widely recorded in archaeological sites throughout the region. Therefore phytoliths have been used to gain an insight into culturally selected plant resources in the past. Phytolith data may also provide insight into the spatial resolution of fire events. Unlike many palaeoenvironmental proxies, phytoliths are not transported to lakes over large distances (Piperno, 2006). Phytoliths reach a lake primarily through transport by river or stream flow. In arid or sparsely vegetated environments phytoliths can be transported short distances by aeolian processes. However, the overall transport potential of phytoliths is limited and they can give a reliable indication of local vegetation (Piperno, 2006). Due to their limited dispersal capabilities it was hypothesised that phytoliths present in the Lake Hula record would have originated from archaeological sites within the Hula Basin, primarily within the immediate vicinity of the lake. Consequently, phytoliths were used to infer the vegetation in the vicinity of the lake

which may have been burnt. Likewise, clear links between the phytolith and fire history records may reflect local or extra-local fire activity.

Phytoliths were analysed from the same horizons as the charcoal samples were taken. In several of the charcoal samples in the lower part of the sequence (at ca.13,000, ca12,000 and ca.12,200 cal. years BP) *Phragmites* sp., *Cyperaceae* sp. and reed/sedge phytoliths were recorded. In these samples dicot (woody plants) phytolith abundance was low (Figure 5.8). Low levels of dicot phytoliths were also recorded throughout GS-1 into the Early Holocene, until ca.9,600 cal. years BP when maximum dicot phytoliths and charcoal influx values were recorded. Between ca.7,200 and 5,200 cal. years BP dicot, Cyperaceae, *Phragmites* and reed phytoliths were all recorded, however, after 5,200 cal. years BP Cyperaceae, *Phragmites* and reed phytoliths were no longer present in the area (Figure 5.7).

From this it is possible to conclude that only in the basal samples (equivalent to GI-1 to GS-1) is charcoal likely to reflect local burning of reed-sedge marsh vegetation. The high fire frequency inferred from the Early to Mid Holocene must have resulted from regional fire events within the oak-grass parkland biome.
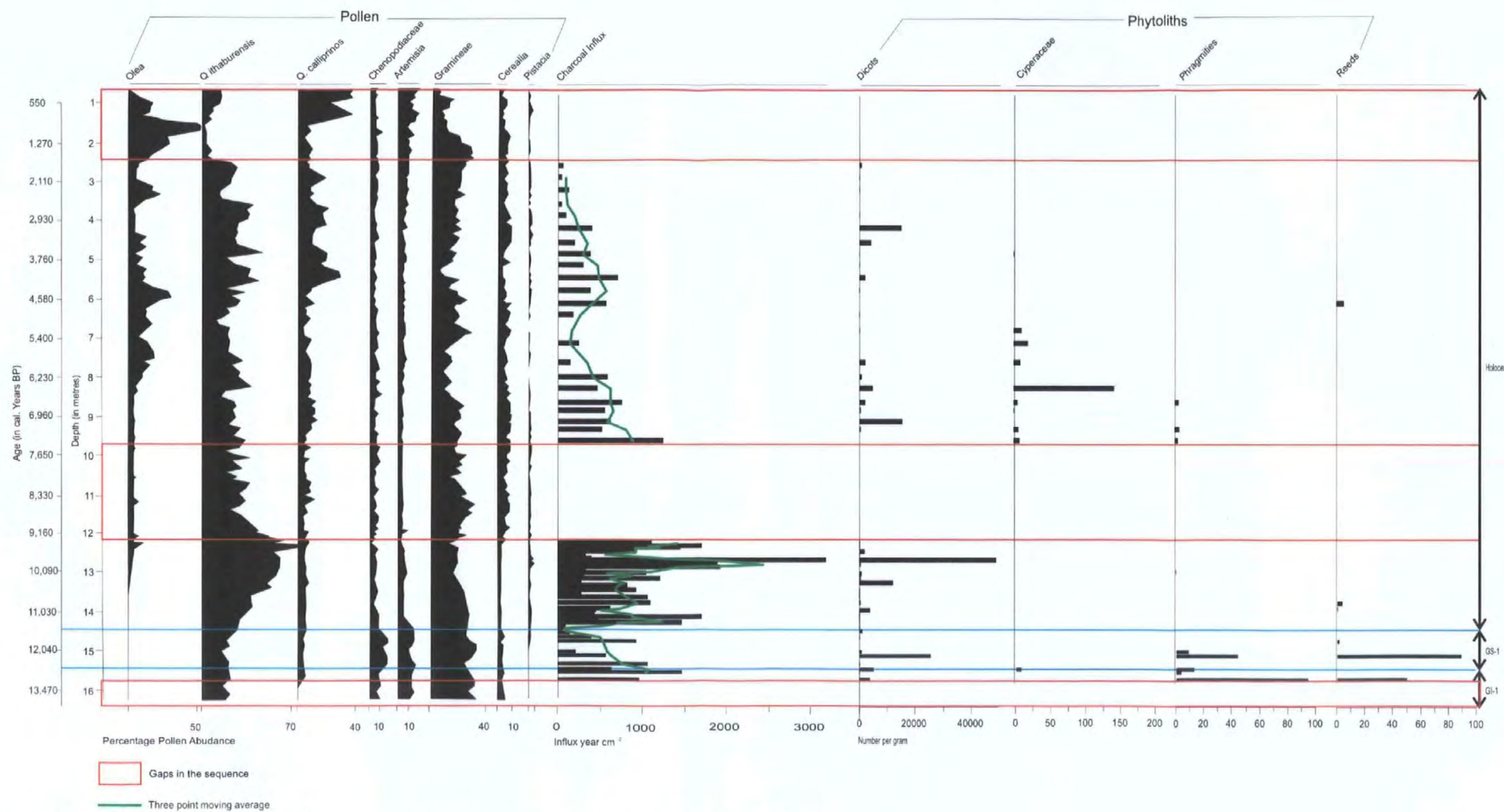
Figure 5.7: Pollen, charcoal & phytolith data (additional sources: Baruch & Bottema, 1999; E. Jenkins, unpublished data)

(5.2.5) Application of the Meadows chronology

Application of the Meadows chronology resulted in minimum offset between timing of the GS-1: Holocene evident in the Hula palaeoenvironmental data and the date given by the Greenland event stratigraphy of Björk *et al.* (1998). They place the transition from GS-1 to the Holocene at 11,500 GRIP years BP. However, the vegetation in the Hula record at 11,500 cal. years BP was still characterised by steppic herbs (*Artemisia* sp. was abundant, although Chenopodiaceae has started to decline). Also, 11,500 cal. years BP was prior to the increase in *Pistacia* sp. and minimum charcoal influx values were recorded. Based on the biostratigraphic pollen zones of Rossignol-Strick (1995), the vegetation community shows greater affinity with GS-1 rather then the Early Holocene. In contrast, by 11,300 cal. years BP charcoal influx has begun to increase, *Pistacia* sp. appeared in the pollen diagram and steppic herbs had declined, presenting a vegetation community associated with the Early Holocene (Rossignol-Strick, 1995). Therefore rather then the transition from GS-1 to the Holocene occurring at 11,500 cal. years BP as is consistent with the Greenland event stratigraphy, it occurs sometime between 11,500 and 11,300 cal. years BP. Precise placement of the GS-1: Holocene transition is not possible as the raw data (sample depths) for the pollen data were not available and spot rather then contiguous charcoal samples were analysed. Based on the available data the transition is placed at ca.11,300 cal. years BP. This discrepancy in the timing of the GS-1: Holocene transition may be due to Meadows applying a date of 10,200 ^{14}C years BP rather then the accepted age of 10,000 ^{14}C years BP. The onset of the Holocene is associated with a plateau in the radiocarbon calibration curve, therefore applying a date of 10,200 ^{14}C years BP for the onset of the Holocene will have an impact upon the calibration of this sample, the placement of the GS-1: Holocene transition and lead to the disagreement between the Hula chronology and Greenland event stratigraphy (Bartlein *et al.*, 1995; Reimer *et al.*, 2004; Telford *et al.*, 2004).

(5.2.6) Climate, biomass and fire

Prior to drainage of the main lake in the 1951 Hula was a large, shallow lake with a marsh toward its north shore (Figure 4.5). The pollen record contains wind pollinated tree taxa (e.g. *Quercus* sp.). These are well represented indicating regional transport, and therefore it can similarly be assumed that the charcoal record at least in part represents a regional signal. The contribution of charcoal originating from the local area is difficult to define. No visible charcoal horizons were identified in the sediments nor were any macroscopic charcoal particles noted during sample preparation that may indicate localised fire events.

However, this may also reflect a limited contribution of locally derived charcoal or low fire occurrence within the lake catchment. The presence of reed and sedge phytoliths in the record during GI-1 and GS-1 represent possible burning of the marsh surface. These phytolith peaks do correlate with an increases in microscopic charcoal, however the absence of any clear evidence of localised fire activity may therefore be a function of the size of the fire events (i.e. they could have been small-scale and produced limited charcoal) or processes occurring after the fire events that affected the formation of a stratigraphic record of fire events (see Chapter 2).

A limitation to the quality of the fire history reconstruction produced from Lake Hula was the availability of material to analyse. The three gaps in the sequence meant that only two samples were taken from GI-1, no data were available between ca.9,100 and ca.7,500 cal. years BP or for the last ca.1,300 years of the sequence. Furthermore, previous sampling for the dating and pollen analyses conducted by Baruch & Bottema (1999) meant that contiguous sampling was not possible. Therefore the "spiky" charcoal influx curve for the Early Holocene could reflect either a variable rate of charcoal influx or be a product of the spot sampling scheme.

Despite this, changes are identified by the charcoal record presented here and these may relate to climatic factors and biomass availability. There is archaeological evidence of human occupation within the vicinity of Lake Hula dating back to ca.14,500 cal. years BP. Therefore it is possible that people have exerted an impact on both the vegetation and fire history throughout the Lake Hula core record. Consequently identifying the driving mechanisms underlying the fire history could potentially be the product of both climatic and anthropogenic factors. These potential impacts will be mentioned briefly, further discussion will be presented when overall fire history of the Eastern Mediterranean region is discussed (Chapter 9).

Greenland Interstadial 1

During GI-1 the southern Levant was characterised by oak-grass parkland in response to climatic warming. This biome type is characterised by regular ground fires, however, the charcoal record for GI-1 is short therefore the inferences that can be made regarding fire activity are limited (Naveh, 1974).

Greenland stadial 1

In the southern Levant, despite the reversion to quasi-glacial conditions during GS-1, the severity of the climatic deterioration was probably not as great as elsewhere in the Eastern Mediterranean (Bar-Matthews *et al.,* 1997; Jones *et al.,* in review). Although arboreal pollen values decreased, trees remained present throughout the record. Likewise, steppic herbs (*Artemisia* sp. and Chenopodiaceae) were present, but, unlike the Anatolian Plateau they did not dominate the vegetation community and instead Gramineae dominated the non-arboreal pollen (Bottema & Woldring, 1986). Charcoal was also present throughout GS-1 indicating adequate fuel availability. As GS-1 progressed so charcoal influx declined, and reached its lowest levels around the start of the Holocene. This could be due to a reduction in fuel availability as toward the end of GS-1 maximum values of *Artemisia* sp. and Chenopodiaceae were recorded.

The Holocene

The Early Holocene is associated with the most favourable climate of the Holocene. Speleothem data from Soreq Cave, Israel have shown that precipitation levels were higher then today and the presence of *Pistacia* sp. indicates frost free winters (Table 5.3; Bar-Matthews, *et al.,* 1997; 1999; Goodfriend, 1999; Rossignol-Strick, 1995; 1999). The increase in precipitation will have increased the net primary productivity of the vegetation community, increasing the fuel load and the potential for an increase fire activity. Clear links between increased humidity, increased vegetation growth and fire activity have been recorded elsewhere e.g. the North American Prairies (e.g. Briggs & Knapp, 1995; Brown *et al.,* 2005; Camill *et al.,* 2003). Indeed there is an increase in charcoal influx to the lake at this time presumably reflecting the effect of changing fuel availability (Figure 5.7). However, this time period also corresponds with the ongoing transition from hunter-gatherer to sedentary communities. Therefore the variable charcoal influx values could also be related to human use of fire.

The Mid to Late Holocene saw the establishment of contemporary climatic conditions in the Levant (Bar-Matthews *et al.,* 1997; 1999). Mean annual precipitation decreased to between 580 and 450 mm/year and mean annual temperatures increased to 18 to 22°C (Table 5.3) (Bar-Matthews *et al.,* 1997; 1999). This climatic shift is likely to have had an impact upon the vegetation community and therefore fuel availability, perhaps explaining the reduced charcoal influx values. Arboreal pollen values do also decrease, however, this is likely to be due to anthropogenic as much as climatic controls on the vegetation

community. The Mid to Late Holocene corresponds to the intensification of human activity within the area as indicated by the continued presence of Cerealia pollen and increased *Olea* sp. pollen, which has been associated with the onset of olive cultivation (Liphschitz *et al.,* 1991). Baruch & Bottema identified three peaks in *Olea* sp. pollen (ca.900, ca.2,300 and ca.5,900 cal. years BP based on the revised chronology) that they attributed to three separate phases of olive cultivation (Baruch & Bottema, 1999). They also noted reductions in *Olea* sp. abundance were followed by increase in arboreal pollen indicating tree populations were controlled (Figure 5.6). Peaks in *Olea* sp. pollen were matched by reductions in *Quercus* sp. indicating the clearance of woodland. Furthermore, prior to the peaks in olive cultivation ca.2,300 and ca.5,900 cal. years BP (no charcoal data are available for the olive peak at ca.900 cal. years BP) charcoal influx values increased. During periods of olive cultivation, charcoal influx was low, indicating that the landscape was no longer burned. The subsequent reduction in *Olea* sp. corresponds with increasing abundance of *Quercus* sp. and has been speculated to represent the abandonment of settlements and re-expansions due to the reduced anthropogenic pressure on the landscape (Schwab *et al.,* 2004). Similar trends in *Olea* sp. and *Quercus* sp. were also identified in Lake Kinneret, Birket Ram crater lake and the Dead Sea (all in Israel) indicating widespread olive cultivation and therefore human activity (Baruch, 1986; 1990; Schwab *et al.,* 2004). As the Holocene progressed and the level of human impact increased, in association with the expansion of cultivation, people rather then climate appear to have exerted a greater control on the environment, and therefore the fire history of the Hula Valley.

(5.3) Summary

This Chapter presented the fire history reconstructions of Çatalhöyük and Lake Hula. The ^{14}C dating conducted on the Çatalhöyük sequence demonstrated that the sequence represented the influence of domestic burning on charcoal preserved in semi-natural deposits.

Lake Hula demonstrates the changing controls on fire occurrence from GS-2 through to the Late Holocene. During the GS-2: Holocene transition climatic factors and fuel availability were the driving mechanisms underlying fire activity, however, as the impact of people on the landscape increased, there are clear correlations between periods of human activity and changes in fire history.

Akgöl

Akgöl was an open, shallow lake located within the former Akgöl Adabağ marsh complex (Figure 4.2; Plate 4.1). Three separate core sequences have previously been collected from the site, one in 1977 and two (AGL95A and AGL95B) in 1995. This chapter will present the results from both the high resolution microscopic charcoal analysis and a replication investigation conducted on the sequences collected in 1995. The top 440 cm of the 847 cm long sequence (AGL95A; Figure 4.2), which covered the GS-2: Early Holocene transition, was sampled and analysed at a high resolution (contiguous samples were taken every 2 to 4 cm) for microscopic charcoal.

(6.1) Microscopic charcoal

Microscopic charcoal was analysed from 104 contiguous samples in AGL95A (Figure 6.1). Variable levels of charcoal were recorded throughout the sequence. There are two short lived peaks in charcoal concentration values at ca.359 cm (1.2×10^4 charcoal particles per cm^3) and at ca.236 cm (6.5×10^3 charcoal particles per cm^3), and one large peak in charcoal at ca.287 cm which measures 1.3×10^6 charcoal particles cm^{-3} (Figure 6.1). Between ca.113 cm and the top of the sequence, charcoal concentration values are consistently higher than elsewhere in the sequence (with the exception of the large charcoal peak) (Figure 6.1).

(6.2) Lithology

In total the AGL95A sequence measured 847 cm, however, as mentioned only the top 440 cm were analysed for microscopic charcoal. Therefore only the lithology for this section of the core is presented in Figure 6.1. A full description of the lithology of this core can be found in Roberts *et al.* (1999). The sediments consist of peaty clay (0 to 120 cm), a buried soil horizon (120 to 128 cm) and pale grey-buff calcareous clay marls below this (Roberts *et al.*, 1999).
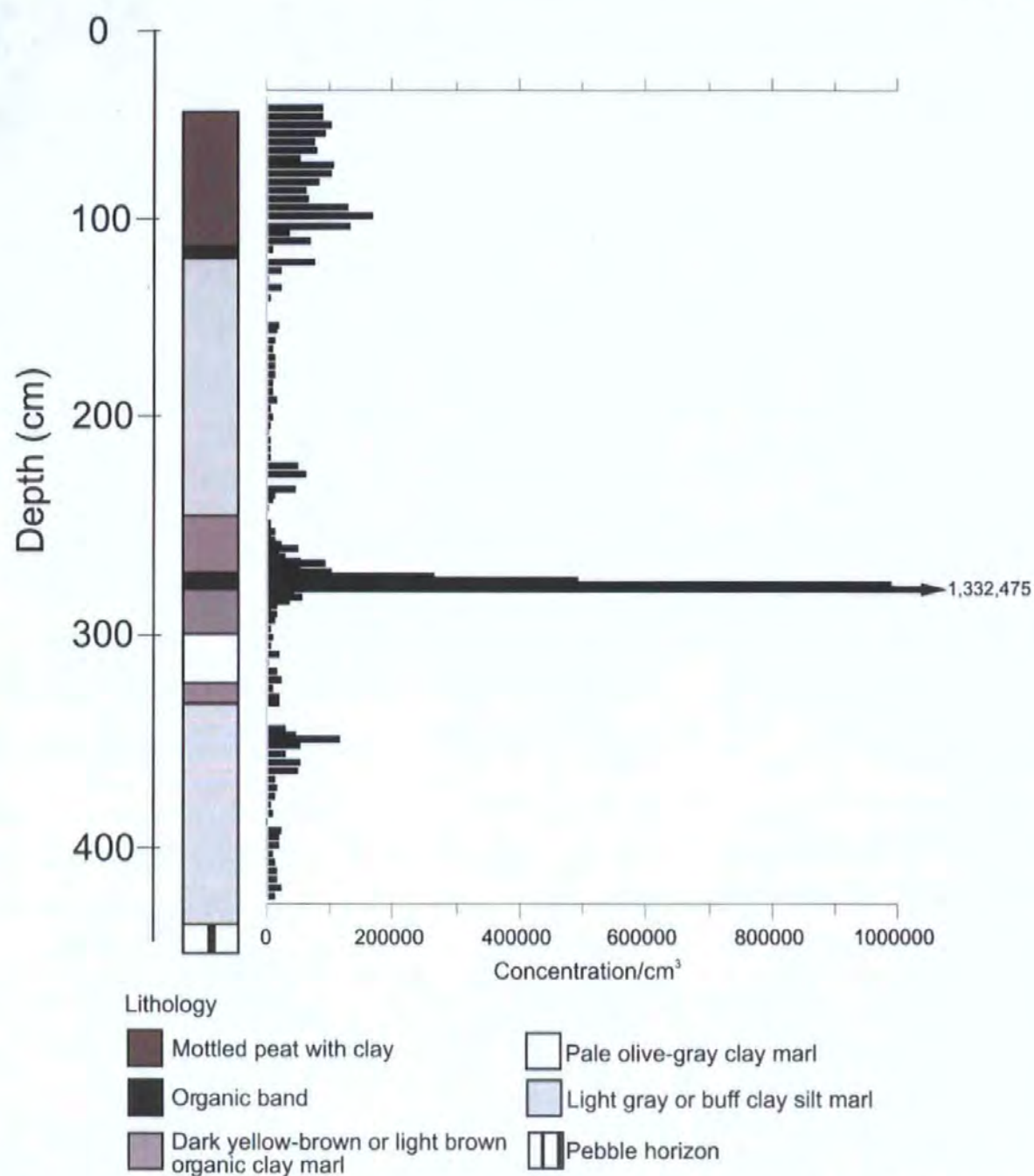
Figure 6.1: Lithostratigraphy and charcoal concentration of AGL95A (a cut-off factor of 100,000 charcoal particles/cm ³ applied to the diagram)

(6.3) Chronology

The age model for the AGL95A sequence above 440 cm was developed through linear extrapolation of ^{14}C and U-Th dates (presented in Table 6.1a, 6.1b; Figure 6.2) and also incorporated changes in the sediment stratigraphy (Roberts *et al.*, 2006). For example, the hiatuses in sedimentation were identified based the presence of a paleosol (Roberts *et al.*, 2006). Mollusc shells, organic material and charcoal were used for [14] C analyses (Roberts *et al.*, 1999). An age-depth model for the depths between 440 and 126 cm was published in Roberts *et al.* (1999). One further date (Beta-136285) has since been obtained and used to constrain the chronology of the Mid Holocene (Roberts *et al.*, 2006). The chronology for the Mid-Holocene (6,500 to 3,000 cal. years BP) was extrapolated by linear interpolation including the Beta-136285 date. Although this may be tenuous, there was no evidence in the sediments above 110 cm (5,900 cal. years BP) of a significant change (e.g. a hiatus) in sedimentation processes within the lake.

A ^{14}C age of 12,183 ca. years BP (sample AA-23926) was recorded on mollusc shells. An old carbon effect had been identified on another sample (AA-23927) therefore it is likely that the application of the same correction factor (620 years) would move this date in line with the U-Th age of 10,600 years BP (AGL95AIII). The AGL95AIII age estimate was used in the placement of the age-depth line as it was thought to provide a good estimate of the true age of the sequence (N. Roberts pers. comm.). A significant shift in the δ^{18}O at ca.250 cm was interpretated as the climatic shift associated with the transition from GS-1 to the Holocene, and therefore was used as an age control in this age model (Leng *et al.*, 1999; N. Roberts pers. comm.).

Three dates were obtained from around 284 cm (Figure 6.2) (AA-23930, AA-23927 and AGL95AVI). These samples gave variable results e.g. the AGL95AVI was considerably older then the ^{14}C ages. AA23930 (13,201 cal. years BP) was measured on the charcoal rich layer (see Figure 6.1) at ca.284 to 286 cm. Because fire is instantaneous event, and the charcoal layer forms a distinct horizon in the core, a higher level of confidence was attributed to this date (N. Roberts pers. comm.). The U-Th date (AGL95AVI) was therefore considered to be an underestimation of the true age. The sample AA-23927 was measured on a mollusc shell and therefore it contained an old carbon effect. Consequently AA-23927 and AGL95AIV excluded and only AA23930 was used in the age-depth model.

The age of the base of the sequence was anchored by stratigraphic cross correlation with the ADA77 sequence which extended further back in time then the AGL95A sequence (Table 6.1b). Therefore the age-depth model was extrapolated to 440 cm based on the GrN-10474 date (Roberts *et al.,* 1999).

Two hiatuses in sedimentation were identified in the age-depth model (Figure 6.2). The first hiatus at ca.240 cm in AGLA95 was identified through discrepancies between the pollen analyses conducted on the ADA1977 and AGL95A sequence (Figures 6.4 & 6.6). In the ADA1977 sequence a peak in *Betula* sp. was identified in the very Early Holocene which was not recorded in the AGL95A sequence. This has been attributed to uneven sedimentation in the lake basin (Roberts *et al.,* 2006). The climatic transition associated with the end of GS-1 and onset of the Holocene would have resulted in considerable changes in both the lake and the surrounding environment which is likely to have affected sediment transport processes to the lake (Roberts *et al.,* 2006). In the part of the lake the AGL95A sequence was taken, this resulted in a minor hiatus in sedimentation (Figure 6.2). This hiatus correlates with the transition from GS-1 to the Holocene. A second hiatus from ca.9,500 to 6,500 cal. years BP was identified based on the presence of a palaeosol at 126 to 128 cm in both cores.

The age depth model demonstrates that the sedimentation rate in Akgöl varied throughout the sequence therefore the temporal resolution of the samples was not constant.

Sample No.	Depth (in cm)	Dating method	Material dated	Pre-treatment	Age (in uncalibarated years BP) + 1 S.D.	Age (in calibrated years BP) + 1 S.D.
Beta-136285	109-112	^{14}C	Bulk organic matter	Acid Wash	5,170 ± 110	5920 ± 84
SRR-5935	126-128.5	^{14}C	Organic matter from a buried soil	Acid Wash	8,690 ± 50	9,602 ± 224 /-73
AA-23926	164-168	^{14}C	Gastropod shells	Acid leaching	10,320 ± 65	12,183 ± 130 /-158
AA-23930	284-286	^{14}C	Charcoal band	Acid Wash	11,110 ± 70	13,201 ± 83
AA-23927	284-286	^{14}C	Gastropod shells	Acid leaching	11,780 ± 70	13,732 ± 136 / -123

Table 6.1a: ^{14}C dates obtained for the AGL95A sequence above 440cm (all dates except Beta-136285 previously published in Roberts *et al.*, 1999).

Sample No.	Depth (in cm)	Dating method	Material dated	Age (in cal. years BP)	Age (in calibrated years BP) + 1 S.D.
GrN-10474	217-221	^{14}C	Organic matter from a buried soil	8,040 ± 140	8,957 ± 230 / -350
GrN-10475	320-330	^{14}C	Organic matter from lake marl	10,920 ± 150	12,841, ± 151
GrN-10476	587-595	^{14}C	Organic matter from lake marl	13,050 ± 950	15,516 ± 1280 / -1407

Table 6.1b: ^{14}C dates obtained for the ADA77 sequence (Bottema & Woldring, 1986)

Sample No.	Depth (in cm)	Dating method	Material dated	Age (in uncalibarated years BP) + 1 S.D.	Age (in calibrated years BP) + 1 S.D.
AGL95AIII	168-170	U-Th	Carbonates	n/a	10,600 ± 1,300
AGL95AIV	286-288	U-Th	Carbonates	n/a	12,000 ± 500
AGL95AVI	362-364	U-Th	Carbonates	n/a	13,400 ± 900

Table 6.1c: U-Th dates obtained for the AGL95A sequence above 440 cm (all dates previously published in Roberts *et al.*, 1999).

Figure 6.2: Age-depth model for AGL95A (Roberts *et al.,* 2006)

(6.4) Influx of Microscopic charcoal

As evident in Figures 6.1 and 6.2, sedimentation rates in Akgöl was not constant throughout time and has been reflected in a comparison between the pollen records obtained from ADA77 and AGL95A (Roberts *et al.,* 2006). However, the changes in sedimentation evident in the sediment stratigraphy were incorporated in the development of the age model for the AGA95A sequence which was then used for the influx calculations to ensure a robust estimation of charcoal influx rates was obtained. Confidence can also be applied to the origin of the charcoal record in that it is more likely to represent changes in fire activity rather then be a function of sedimentation processes (e.g. sediment focusing) occurring within the lake basin. The AGL95A sequence was taken from the centre of the lake; therefore processes that can result in the remobilisation of charcoal from the margins of the lake were unlikely to have occurred. Equally, as evident in Plate 4.1, prior to drainage, Akgöl was a large, shallow open lake basin, meaning that sediment focusing would not have taken place.

The hiatuses in sedimentation mean that a microscopic charcoal record was not obtained for the whole of the Early Holocene (Figure 6.3). However, the overall trends in charcoal influx mirror those highlighted by the concentration data (Figures 6.1 & 6.3). Two peaks, the main peak (ca.13,000 cal. years BP) and a smaller peak (ca.14,000 cal. years BP) occur during GI-1. During GS-1 charcoal influx is lower than in GI-1, and gradually declines toward the end of the stadial. Charcoal values begin to increase in the Early Holocene prior to the hiatus, then following the hiatus there is a peak in charcoal influx at ca.11,000 cal. years BP. Between 11,000 and 10,400 cal. years BP charcoal influx is comparable to that of the latter half of GI-1. After 10,500 cal. years BP charcoal influx is difficult to determine due to a reduced sampling resolution and the subsequent hiatus in sedimentation (Figure 6.3). Charcoal influx in the Mid Holocene is similar to the Early Holocene, and the levels of charcoal entering the lake appear fairly constant with no major fluctuations being recorded.
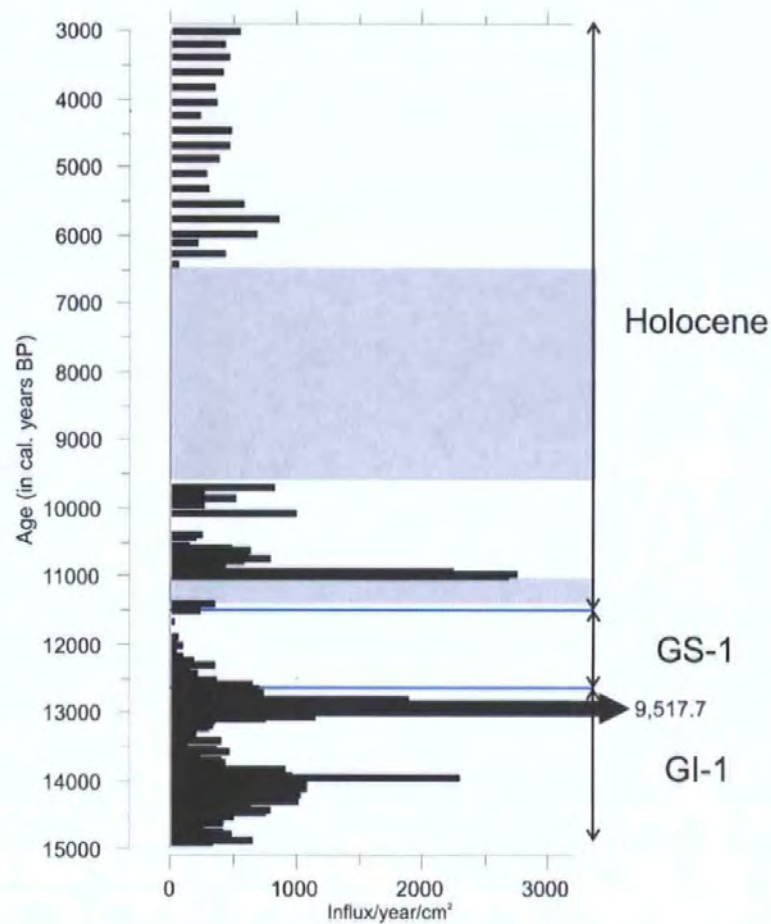
Figure 6.3: Charcoal influx into AGL95A

(6.5) Comparison with proxy data

(6.5.1) Pollen (analysis carried out by W. Eastwood (unpublished))

(6.5.1.1) Percentage pollen data

The available pollen data are at a much coarser resolution then the charcoal data (only 20 pollen samples were analysed compared to 104 charcoal samples). Consequently, major changes evident in the charcoal record which may have had an impact upon the vegetation community at Akgöl, may not be recorded in the pollen record (e.g. the major fire event at ca.13,000 cal. years BP) (Figure 6.4). During GS-1 only two pollen samples were analysed, therefore only a generalised overview of the vegetation community is available over this time period. However, corresponding changes in the charcoal and pollen are identifiable. Between ca.14,800 and 13,000 cal. years BP (GI-1) *Quercus* sp., Gramineae and steppic herbs (*Artemisia* sp. and Chenopodiaceae) predominate and include an abrupt increase in charcoal influx at ca.14,000 cal. years BP (Figure 6.4). During GS-1 low charcoal influx values are matched by a fall in Gramineae and an increase in steppic herbs. In the Holocene, peaks in Gramineae are followed by a slight increase in charcoal influx (e.g. ca.10,400 and ca.10,800 cal. years BP). In the Mid to Late Holocene higher charcoal influx values are recorded, but *Quercus* sp., Gramineae and steppic herb abundances are very low, whereas *Pinus* sp. dominates the pollen diagram, although this is likely to be due to long distance transport (Figure 6.4).

(6.5.1.2) Pollen influx data

Due to the potential misinterpretations of percentage pollen data highlighted in Chapter 5 (Section 6.2.4) pollen influx as well as percentage data are presented for the Akgöl (AGL95A) sequence as the raw data were also available (courtesy of W. Eastwood) (Figure 6.5). The pollen percentage and influx are complementary and show similar tends, however, the influx data do highlight changes in the pollen data not identified using the percentage data. During GI-1 the percentage data shows the replacement of steppic herbs by Gramineae (Figure 6.4), however, the influx data demonstrates that whilst Gramineae do increase, steppic herbs abundance remains high indicating an overall increase in biomass availability. In addition, prior to the large peak in charcoal influx at ca.13,000 cal. years BP, maximum values of Gramineae were recorded (Figure 6.5) indicating there was adequate fuel available in the immediate vicinity of Akgöl. The pollen influx data also support Bottema & Woldring's (1986) hypothesis that during the GI-1: Holocene transition, *Pinus* sp. pollen entering the lake represents long distance transport as if *Pinus*

sp. was growing nearby Akgöl, higher influx values may have been expected. The differences in the information obtained from the influx measures compared to percentage pollen data demonstrate the changes in overall biomass that can sometimes be masked in percentage data. However, at this site, the value of the influx data is clearly constrained by the changes in sedimentation and uncertainties in the age model (see Figures 6.1 and 6.2).

(6.5.1.3) Comparisons of the charcoal influx records reconstruction using the density separation and pollen procedures

Charcoal was previously quantified by W.J. Eastwood during analysis of pollen samples taken from the AGL95A sequence. This provides the opportunity for further comparison of the micro-charcoal records obtained from the pollen and the heavy liquid separation procedures. The pollen analysis was conducted on AGL95A at a lower sampling resolution then the microscopic charcoal analysis. This was due to a detailed pollen record already being available for Akgöl (ADA77 published in Bottema & Woldring, 1986). Therefore the pollen fire history reconstruction lacks the detail evident in the density separation charcoal record. Despite this, the two charcoal records follow similar trends e.g. they both record the increase in charcoal influx to the lake in the Early Holocene (Figure 6.6). However, in concordance with the findings of the methods investigation presented in Chapter 3, the pollen preparation considerably underestimates the amount of charcoal present in a sample (Figure 6.6) e.g. the peak in Early Holocene charcoal influx recorded by the pollen preparation measured 592.2 particles/year/cm^2 whereas in the density separation it measured 2260.9 particles/year/cm^2. This is further evident through comparison of the mean charcoal influx values (see Table 6.2). Again, the mean influx values were greater for the density separation samples than the pollen preparation. As highlighted in Chapter 3, this contrast is likely to be due to the contrasting mechanical and chemical severity of the two preparation techniques.

Climatic episode	Pollen Preparation (particles/year/cm^2)	Density Separation (particles/year/cm^2)
Mid Holocene	25.1	443.1
Early Holocene	239.2	727.6
GS-1	22.7	60.5
GI-1	103.6	529.4

* To make the results comparable the mean values were calculated only for the depths where both pollen and density separation samples were taken.

Table 6.2: Mean charcoal influx recorded by the pollen and density separation preparations *

(6.5.2) Stable oxygen isotopes (Leng *et al,.* 1999)

Stable isotopes were determined on authigenic carbonates (Leng *et al.*, 1999). The $\delta^{18}O$ values respond to changes in both the precipitation: evaporation balance of the lake as well as the changing level of freshwater inputs from the Zanopa River (the main source of inflowing water to Akgöl) (Leng *et al.*, 1999). Two clear negative shifts in the $\delta^{18}O$ record occurred during GI-1 at ca.13,300 cal. years BP and ca.12,650 cal. years BP (Figure 6.4). The negative shift in $\delta^{18}O$ values indicating a shift toward wetter conditions occurred prior to the large peak in charcoal at ca.13,100 cal. years BP. During GS-1 there was a positive shift in isotope values indicating a fall in the precipitation: evaporation ratio and therefore the drying of the lake. This is associated with a fall in charcoal influx to the lake (Figure 6.4).

Following the hiatus in sedimentation during GS-1 increasingly negative $\delta^{18}O$ values were recorded throughout the Early Holocene which was also associated with an increase in charcoal influx to the lake (Figure 6.4). These negative $\delta^{18}O$ have been attributed to an increase in snow and glacier melt water entering the Zanopa River as a consequence of Early Holocene climatic warming (Leng *et al.*, 1999). Negative $\delta^{18}O$ values persisted due to an increase in the precipitation: evaporation ratio indicating higher rainfall more then compensating for the increase in temperature (Leng *et al.*, 1999)

(6.5.3) Phytoliths (analysis carried out by E. Jenkins (unpublished))

Phytoliths were analysed at ca.20 cm resolution from the AGL95A sequence. The first peak in charcoal, ca.14,000 cal. years BP correlates with a peak in total dicots which are associated with woody vegetation. In contrast the large charcoal peak at ca.13,000 cal. years BP, no dicots were recorded whereas there was a peak in *Phragmites* sp. and Cyperaceae phytoliths (Figure 6.4). The peak in charcoal on the Early Holocene also coincides with an increase in dicot phytoliths (Figure 6.4).
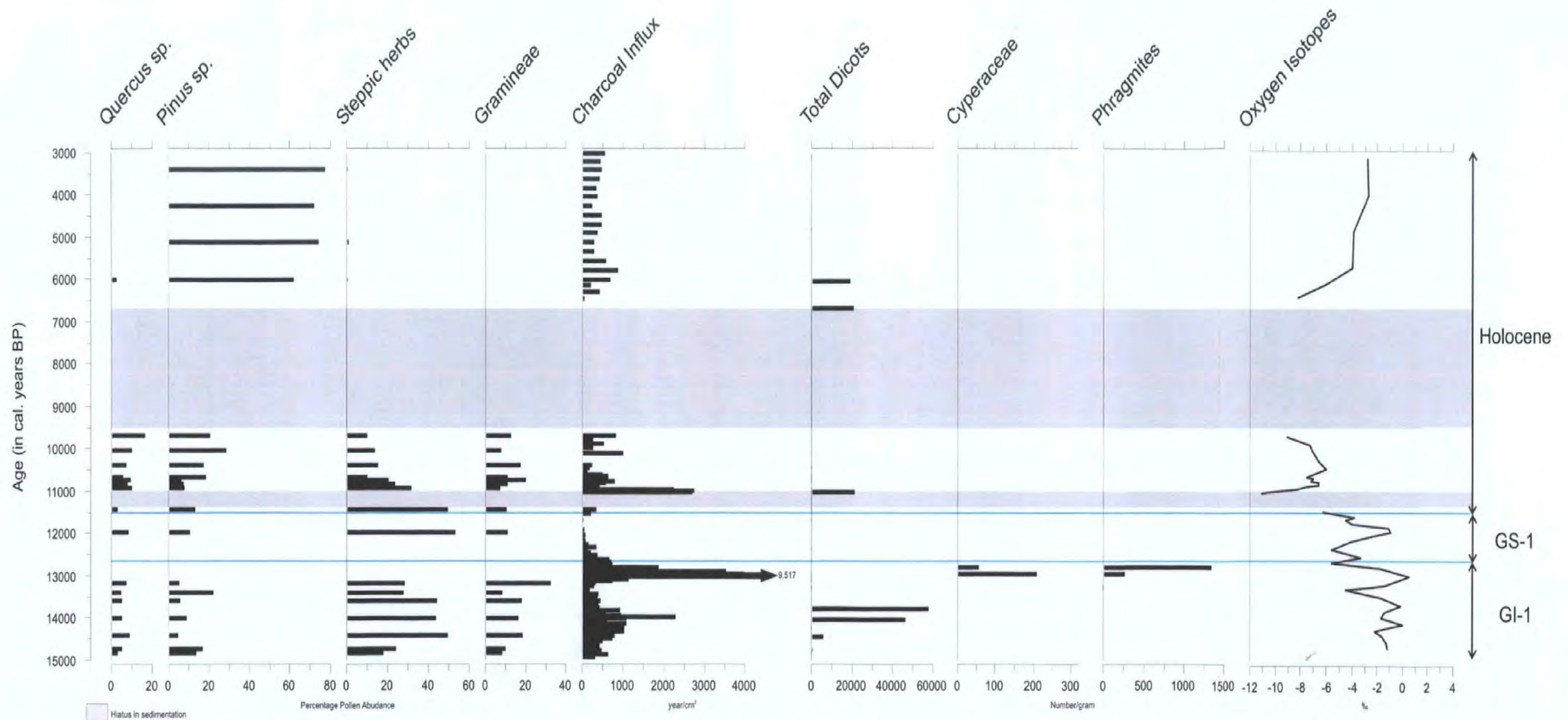
Figure 6.4: Pollen, δ^{18}O, phytolith and charcoal influx data (additional sources: W. Eastwood unpublished, Jenkins unpublished and Leng *et al.*, 1999). Steppic herbs include *Artemisia* and Chenopodiaceae. A cut-off factors of 4,000 charcoal particles per year cm^{-2} was applied to the charcoal influx data to ensure a true representation of the rest of the data, as the peak at ca13,000 cal. years BP dominates the record.
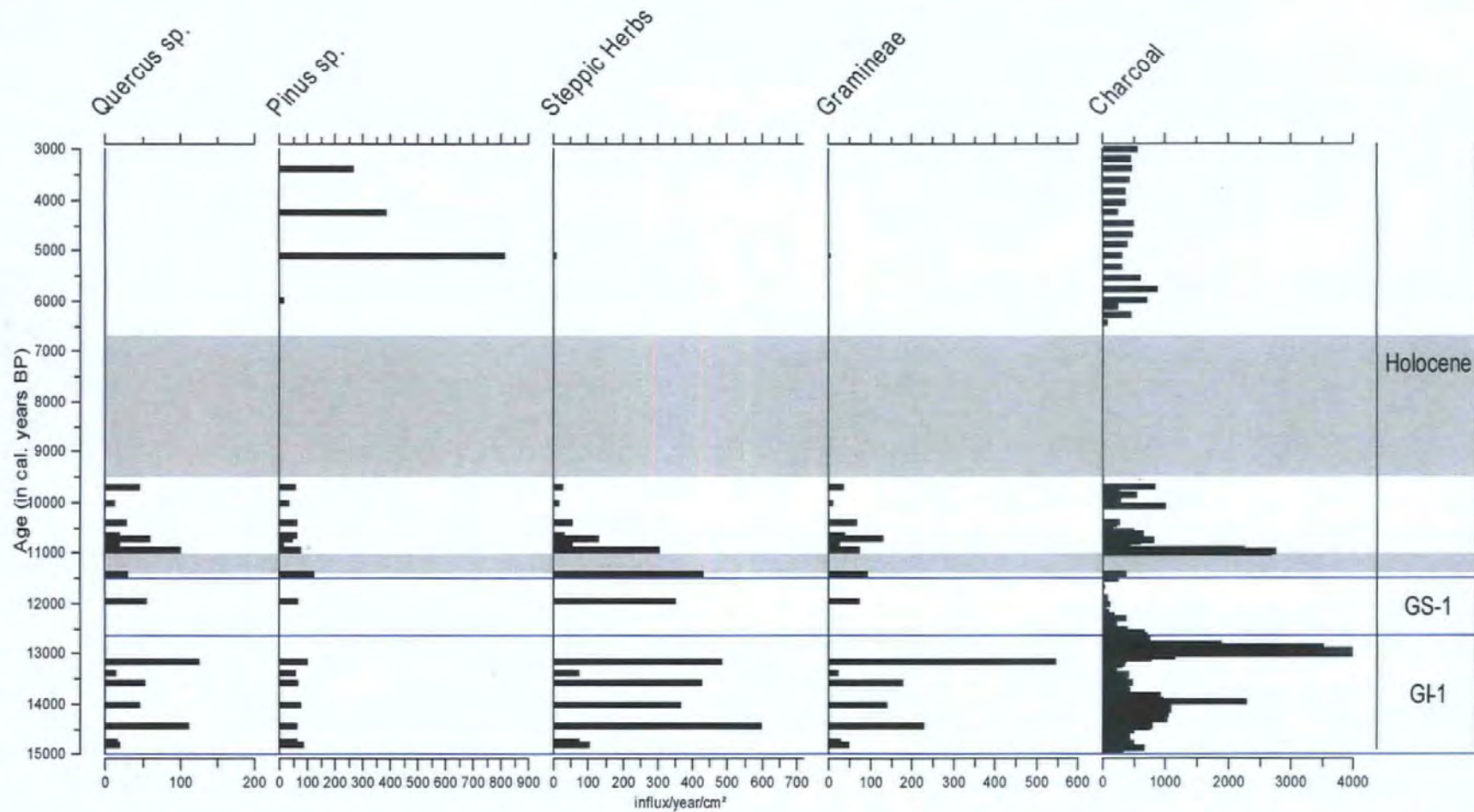
Figure 6.5: Pollen & charcoal influx data (pollen data courtesy of W.J. Eastwood, unpublished data) (grey areas represent hiatuses in sedimentation)
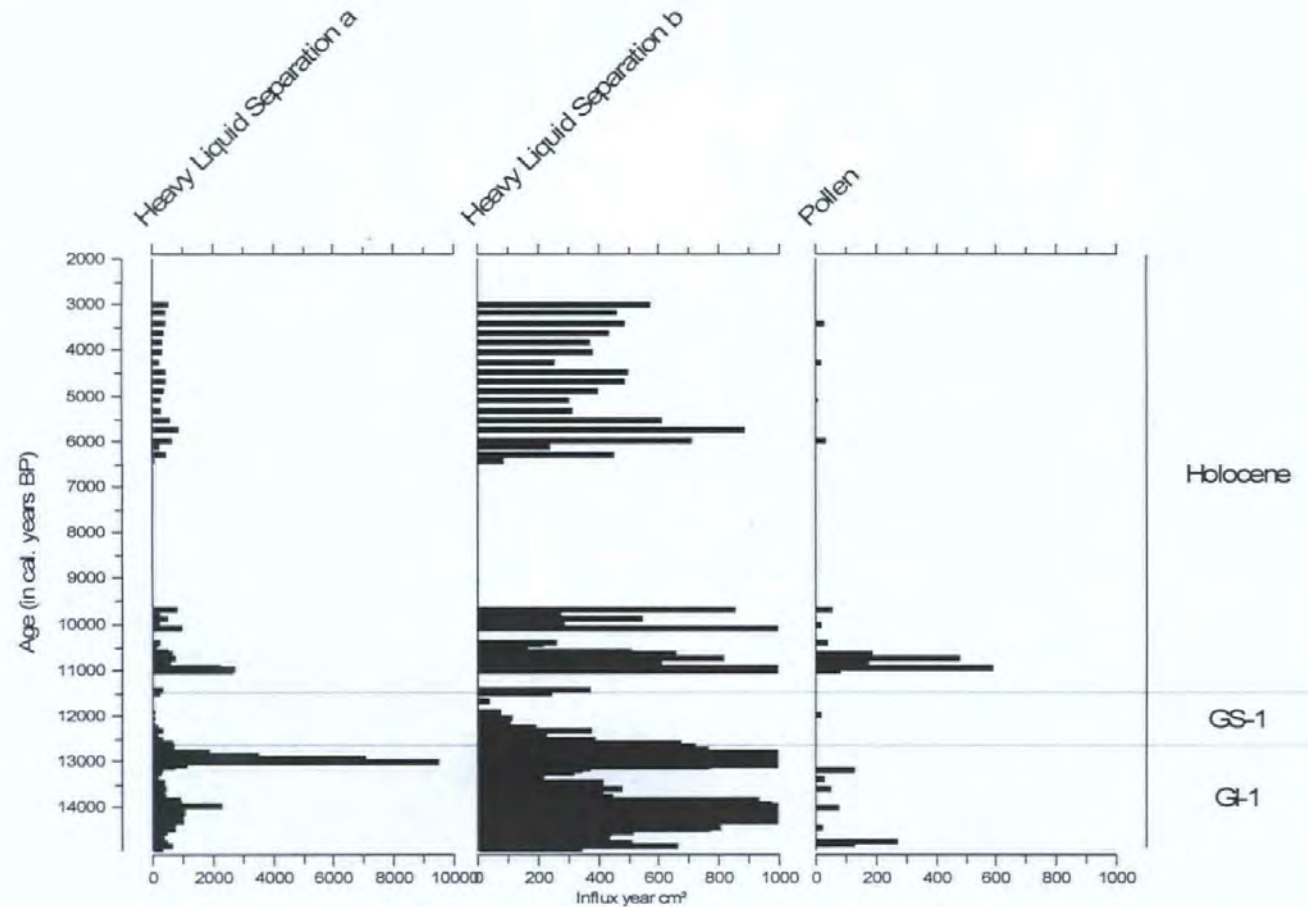
Figure 6.6: Charcoal influx reconstructed using the heavy liquid separation and pollen preparations. To make the data comparable between the heavy liquid separation and pollen preparations charcoal counts are plotted twice; a) without a cut-off factor and b) with a cut-off factor of 1,000.

(6.6) Climate, biomass and fire

Comparisons between other proxy and charcoal influx data do not highlight a clear cause and effect relationship between fire, climate and biomass at Akgöl e.g. a shift to a more favourable climate, resulting in increased biomass and therefore fuel, and increased burning. This may partly be a product of the low sampling resolution of the pollen analysis, particularly over the time of the GS-1: Holocene transition, but it may also relate to the role of local as opposed to regional charcoal. As is evident in Figure 6.4 the potential impacts on the vegetation community of the large fire event at 13,000 cal. years BP are not recorded within the pollen record. However, general changes in the abundance of certain taxa (e.g. Gramineae vs. steppic herbs) may correlate with changing fire occurrence. Higher levels of charcoal influx were recorded when Gramineae rather then steppic herbs dominated the vegetation community. Therefore biomass, climate and fire are likely to be linked, as changes in the vegetation community do follow changes in climate, but the extent to which they are dependent upon one another cannot be identified in this record.

Factors including the morphology of the lake basin and the surrounding landscape may have exerted an important impact upon the fire history record preserved within Akgöl. Lake and catchment morphology have previously been cited as controlling the source area of both pollen and charcoal inputs (e.g. Clark, 1988a; Prentice, 1985; Sugita 1993; 1994; Whitlock & Larsen, 2001, see also Sections 2.3.2 onwards). Akgöl was a shallow, open marsh lake which prior to drainage after 1977 covered an area of 50 km^2. Based on pollen source area theory, the area of Akgöl means that it should receive regional pollen inputs (Prentice, 1985). As discussed in Chapter 4, Akgöl is located at the eastern end of the Konya Plain in the former Adabag marsh complex (Figure 4.2). The Konya Plain is the lake bed of the former palaeolake and is therefore a flat and open landscape. The shape of the lake basin means that Akgöl may receive a local fire history and pollen signal from the marsh along with the area of the Konya Plain in the immediate vicinity of the lake, especially if the fire event occurred at a time of low water level. Regional inputs will originate from more distant parts of the Konya Plain and the surrounding volcanoes and mountain foothills. This will result in a spatially heterogeneous fire history signal being preserved within the lake sediments. Consequently, identifying the contribution of local vs. regional charcoal to a lake the size of Akgöl is not easy; however, through comparisons with existing pollen data (ADA77 & AGL95A) (Bottema & Woldring, 1986), phytolith

data (AGL95A; see Chapter 5, section 5.2.5.3 for an overview behind the rationale of using phytoliths to assist in the interpretation of the fire history record) and taking into consideration the existing pollen and charcoal transport theory presented in Chapter 2, it may be possible. Bottema & Woldring conducted a higher resolution pollen investigation on the core they collected from Akgöl in 1977 (ADA77) (Figure 6.7). Despite the discrepancies between the ADA77 and AGL95A sequence comparisons between the pollen and charcoal data may aid the interpretation of the fire history record.

Large, open shallow lakes such as Akgöl are vulnerable to variations in sedimentation due to changes in lake level, wind driven sediment erosion and redeposition, and non-uniform sediment deposition across the basin (Verschuren, 1999, see also Figure 2.1 and Section 2.2.12). All these factors can affect the integrity of the palaeoenvironmental record and may have occurred throughout the history of Akgöl. Four hiatuses in sedimentation were identified in the AGL95A sequence (at ca.126 cm, ca.240 cm, ca.440 cm and ca.600 cm) as a consequence of significant falls in lake level, which resulted in the cessation in sedimentation and left the lake vulnerable to wind driven and aeolian erosion processes. Not only do these hiatuses in sedimentation represent gaps in the palaeoenvironmental record, it is unknown how much sediment was lost or eroded during the time period over which the lake basin was dry (Verschuren, 1999). Furthermore sedimentation processes have not been uniform across the lake basin. This was identified by comparison of the pollen records obtained from ADA77 and AGL95A. The ADA77 and AGL95A cores were taken ca.200 m apart and there is an estimated 90 cm depth offset between the two sequences (Roberts et al., 2006). This offset has been attributed to the shrinking of the overlying peat after the drainage of the marsh (Roberts et al., 1999). Although similar isotopic signals were recorded in both cores, differences were identified in the pollen record of each sequence. For example the rise in Betula sp. identified in zone 2a in the ADA77 sequence (Figure 6.7) was not recorded in AGL95A (Leng et al., 1999; Roberts et al., 2006). These non-uniform changes in sedimentation have been attributed to periods when the lake level may have varied as a result of climatic changes, e.g. at the end of GS-1 (Roberts et al., 2006). As mentioned, the shallow water and flat morphology of the lake bed may have resulted in the sediments being vulnerable to processes of sediment focusing or redeposition (Figure 2.1, Section 2.2.12). It is unknown whether these processes occurred within Akgöl, but they could have affected the validity of the charcoal record.

For example, it is not certain beyond doubt that charcoal peaks represent actual fire events rather than sediment focusing.

Despite these potential limitations of the palaeoenvironmental record obtained from Akgöl, these factors are likely to have affected the pollen record and do not apply only to charcoal. Although the effects of these processes are unknown, inferences can still be made concerning the fire history of this site. Ultimately, these hypothesised changes in fire history can be tested at a later date if further material becomes available.
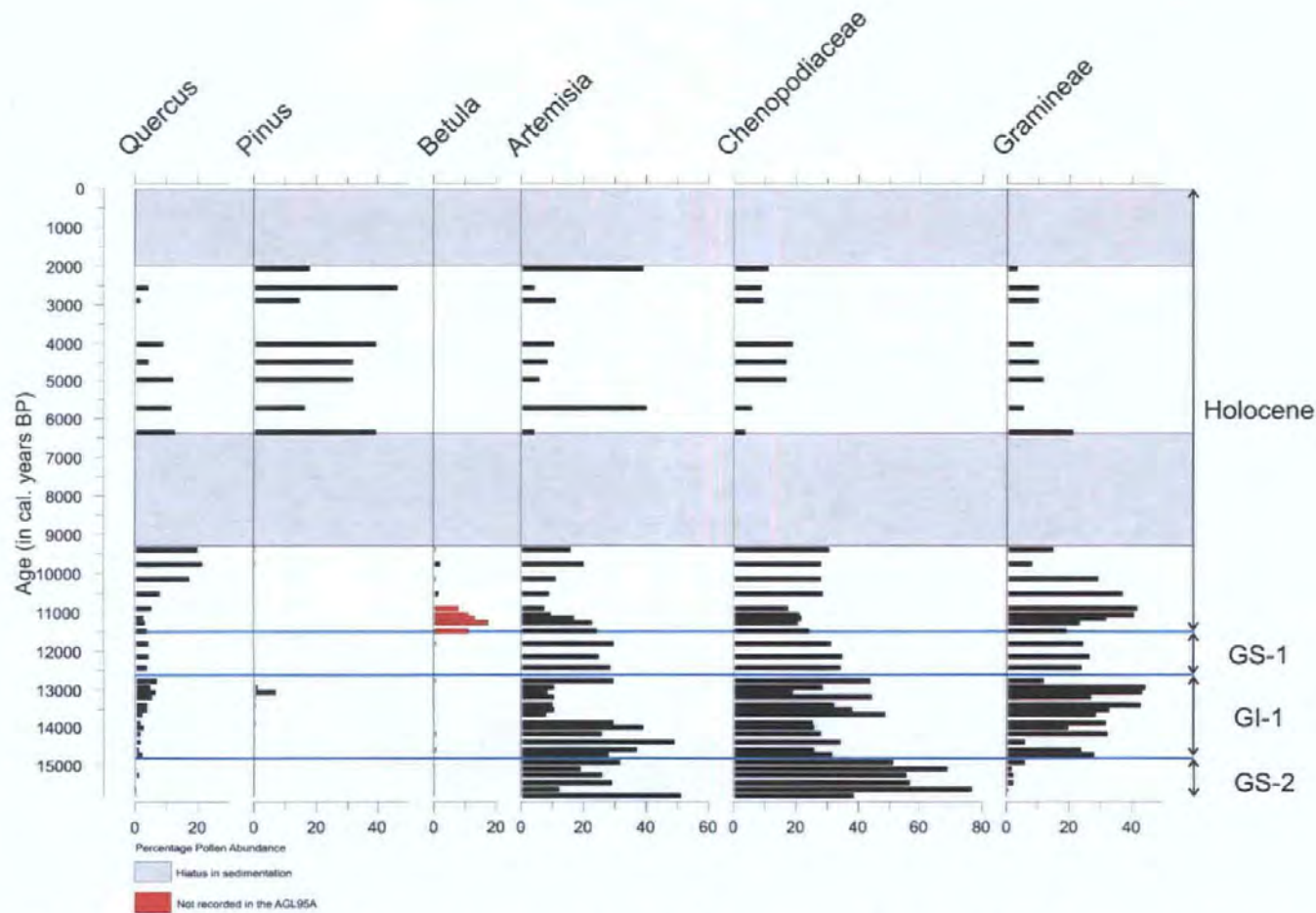
Figure 6.7: The Bottema & Woldring (1986) pollen diagram based on the ADA77 sequence (Bottema, 1987; Bottema & Woldring, 1986; European Pollen Database).

Greenland Interstadial 1

The charcoal peaks that occur during GI-1, particularly the peak at ca.13,000 cal. years BP, are likely to represent a local signal. This is supported by the thickness of this charcoal horizon (Figure 6.8) and form of this charcoal peak (Figure 6.4) at ca.13,000 cal. years BP, and the phytolith data (see Chapter 5, Section 5.2.4 for a brief explanation of the spatial representation of phytolith data). Microscopic charcoal analyses in Europe have demonstrated that peaks in charcoal above background levels can represent local fire events (Pikänen *et al.*, 1999). The pollen record contains a regional as well as a local signal. Bottema & Woldring (1986) speculated that during GI-1 tree pollen (e.g. *Quercus* sp.) was likely to have originated form the foothills of the Taurus Mountains and the slopes of the volcanoes as this is where favourable growing conditions occurred, whereas, the Konya Plain was characterised by open, Gramineae steppe. Based on pollen transport mechanisms (e.g. Tauber, 1965; 1977) the open vegetation of the Konya Plain favours the long distance transport of pollen as there would have been limited barriers to pollen, and therefore charcoal transport. Therefore the pollen and charcoal data will contain a regional element, whereas the phytolith data represent mainly a local signal. Prior to the fire event at ca.14,000 cal. years BP, Gramineae were increasing in abundance, although steppic herbs still dominated the vegetation community. The peak in woody phytoliths in association with the peak in charcoal influx may indicate a local fire event, possibly the burning of steppic herbs which can include woody taxa. The major peak in charcoal at 13,000 cal. years BP coincides with an increase in Gramineae pollen, *Phragmites* and *Cyperaceae* phytoliths which again indicates a localised fire event, most likely the burning of the marsh surface (Figure 6.4). The much greater size of the charcoal peak of the ca.13,000 cal. years BP vs. the 14,000 cal. years BP peak may represent a change in biomass and fuel availability. The warming of the climate in GI-1 would have led to an increase biomass and therefore fuel may have resulted in larger fire events occurring. Based on the hypothesised vegetation at the time of these events, the phytolith data and the shape and size of the charcoal peaks, these fires appear to represent localised fire events superimposed on a regional fire history signal.

Greenland Stadial 1

The onset of GS-1 saw a shift to a cold, arid climate in the area that led to a reduction in tree populations and the replacement of the Gramineae dominated steppe with steppic herbs in AGL95A/ADA77 (Chenopodiaceae and *Artemisia* sp.) (Bottema & Woldring,

1986; Figures 6.5 & 6.7). The subsequent fall but continued presence of charcoal in the sequence indicates long distance transport of charcoal from the wider environment, therefore a regional signal. The climatic deterioration is likely to have resulted in a reduction in biomass in the immediate vicinity of the lake, therefore the incidence of fires would have fallen as fuel availability declined. This shift from a Gramineae, to a steppic herb dominated vegetation community coincides with a fall in charcoal influx values. This supports the hypothesis that Gramineae was an important fuel. However, the source area of charcoal inputs to Akgöl is clearly variable. Likewise, due to the non-uniform changes in sedimentation occurring in Akgöl, fire events may not be represented equally across the whole basin. Identification of fuel sources without the presence of localised supporting evidence must therefore be done with caution.

The Holocene

The climatic improvements associated with the onset of the Holocene (e.g. increased precipitation and temperatures) resulted in a shift in the sedimentation regime of the lake which resulted in changed sedimentation patterns (including short hiatuses in the AGL95A sequence) during the very Early Holocene (Figure 6.5). Following the hiatus, a peak in charcoal is recorded which correlates with a peak in dicot phytoliths. This may indicate a localised fire event, but due to the previous hiatus in sedimentation, and the gap in the vegetation data from this sequence, this is difficult to determine with confidence. The climatic warming saw the return of Gramineae steppe and the expansions of tree populations (particularly *Betula* sp.) on the slopes of the foothills and volcanoes (Bottema & Woldring, 1986; Leng *et al.*, 1999). However, the return of *Quercus* sp. was not immediate and there was a delay of at least several centuries (Bottema & Woldring, 1986; Roberts, 2002). Following a peak in charcoal influx in the Early Holocene, charcoal values stabilised ca.11,000 to 10,400 cal. years BP at a level comparable to that recorded during the GI-1 (Figure 6.5). The landscape of the Konya Plain was still predominately treeless yet charcoal is still recorded appearing to support the hypothesis of Gramineae contributing to biomass availability and therefore fuel.

Following the hiatus in sedimentation (ca.9,500 to 6,600 cal. years BP) charcoal influx values increase and, in contrast with the earlier part of the sequence, are fairly stable (i.e. no major peaks) (Figure 6.5). This may be due to several factors. It could reflect the reduced sedimentation rate, at this time (Figure 6.2) or the lower sampling resolution. This

slow sedimentation rate may result in major changes in the fire history record having been averaged out over time. Alternately, it could reflect the changing source areas (i.e. a shift from heterogeneous to a predominantly regional signal) of charcoal inputs. If fires were occurring within the immediate vicinity of Akgöl, it is likely the peaks of charcoal influx would be recorded, yet no clear peaks were recorded. Likewise from ca.6,000 cal. years BP low levels of phytoliths were recorded within the sequence, supporting the hypothesis of a shift from a local to regional source area. Also, in the Eastwood (unpublished) and Bottema & Woldring (1986) pollen analyses, increased levels of *Pinus* sp. were recorded (Figures 6.4, 6.5 and 6.7). Bottema & Woldring (1986) hypothesised that the increase in *Pinus* sp. abundance represented long distance transport to the lake, supporting the idea that during the later Holocene, the charcoal record represented regional fire activity.

The later Holocene part of the record does coincide with the time at which people were exerting a greater impact on the environment. Unfortunately, the hiatus in sedimentation coincides with some of the earliest settlements e.g. Çatalhöyük, on the Konya Plain. Therefore the effect of these settlements on the fire history record is difficult to assess.

(6.7) Replication Experiment

A visible charcoal horizon is present in the AGL95A sequence at ca.288 to 285 cm dating to ca.13,000 cal. years BP. The levels of charcoal were high not only throughout this horizon but for several centimetres after it. A parallel core, AGL95B was taken one metre away from AGL95A. This charcoal horizon was also visible within the AGL95B sequence (Figure 6.8). The presence of this charcoal horizon within the AGL95B sequence provided the opportunity to investigate the effect of sampling resolution on the fire history reconstruction and also the incorporation of charcoal into lake sediments.

Sampling procedure

Samples were taken at two different resolutions. In the AGL95A sequence contiguous samples had been taken every 2 cm. In the AGL95B sequence samples were taken every 0.5 cm over the 4.5 cm proceeding, through and following the charcoal horizon (from 292.5 to 280.0 cm). The rest of the sequence was sampled at 2 cm resolution (from 280.0 to 232.5 cm).

Sample preparation and analysis followed the procedure described in Section 5.3.3. Again results were presented using TG View (version 2.02) (Grimm, 2004).

(6.7.1) Results

The magnitude and shape of each charcoal peak varied between the two sampling resolutions (Figure 6.8). The AGL95A sequence shows a rapid increase in charcoal from ca.4.5 $\times 10^4$ charcoal particles cm^{-3} at 289 cm to 1.3×10^6 charcoal particles cm^{-3} at 287 cm. There was only one peak in charcoal, after which values gradually declined. It took until 271 cm for charcoal values to return to background levels (i.e. the concentration of charcoal recorded prior to the fire event) (Figure 6.8). In the AGL95B sequence, the charcoal peak concentration was twice that of the peak in AGL95A (2.7×10^6 charcoal particles cm^{-3} in 95B vs. 1.3×10^6 charcoal particles cm^{-3} in AGL95A). The shape of the charcoal peak also mirrored the appearance of the charcoal horizon in the core (Figure 6.8). In the AGL95B sequence two charcoal peaks were recorded, the first, which was the largest peak correlated with the first charcoal band in the horizon which spread the full width of the core (Figure 6.8). This peak was followed by a significant reduction in charcoal concentration values (from 2.7×10^6 to 9.3×10^5 charcoal particles cm^{-3}) which coincides with the lighter band between the two clear charcoal layers. The second,

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charcoal peak (measuring $1.8x10^6$ charcoal particles cm^{-3}) corresponds with the second charcoal peak that does not spread the full width of the core (Figure 6.8). Following the second charcoal peak, concentration values do decline but not as rapidly as in AGL95A. In the AGL95A sequence by 271 cm concentration values decreased to, and remained below $c.1.0x10^5$ particles cm^{-3}, similar levels were not recorded in the AGL95B sequence until 258.5 cm.
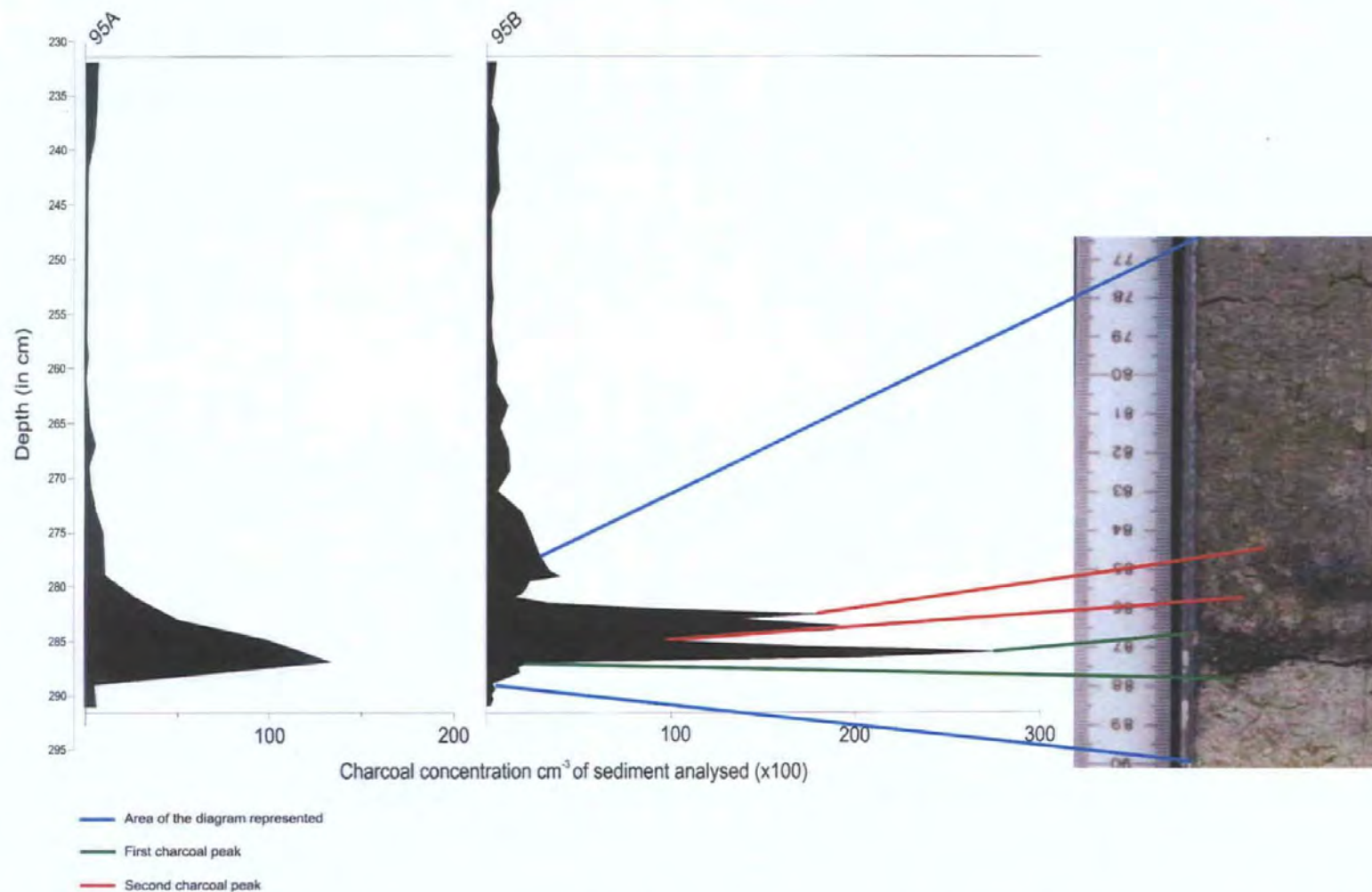
Figure 6.8: Replication experiment comparing adjacent cores AGL95A (2 cm sampling resolution) & AGL95B (0.5 cm sampling resolution)

(6.7.2) Discussion

The higher resolution analysis of the charcoal horizon demonstrates that the sampling interval can influence the fire history reconstruction. The shape of the charcoal peak varied with the two different sampling resolutions (Figure 6.8). Many fire history reconstructions, particularly those conducted alongside pollen investigations are of significantly lower resolution (e.g. Cwynar, 1978; MacDonald *et al.,* 1991; Swain, 1973). Frequently spot, rather then contiguous, samples are taken at fixed intervals. This can result in fire events being missed and therefore an incomplete reconstruction being produced. It is clear that to gain a detailed insight into changing fire histories a high resolution sampling scheme is essential. Whilst the 2 cm contiguous sampling gave a general overview of the fire history of the sequence it did not provide the detail identified by the 0.5 cm sampling interval. This indicates that future fire history studies may benefit from the application of initially coarse resolution sampling strategy (as in the AGL95A sequence) to identify charcoal peaks then a second, higher resolution analysis (as applied to the AGL95B sequence) to gain an insight into the nature of the charcoal peak. This approach has developed and is now widely applied in the analysis of microscopic tephra particles preserved within lake sediments and peat deposits (Hall & Pilcher, 2002; Pilcher & Hall, 1992).

At each sampling resolution charcoal concentrations did not return to background levels immediately after the peak. The charcoal horizon spans only 288 to 285 cm, yet in both sequences charcoal values remain above background levels (i.e. higher then they were before the peak in charcoal occurred) to 271 cm in AGL95A and 258.5 in AGL95B (Figure 6.6). A second peak, identified only in the AGL95B sequence was recorded at ca.286 cm. The time taken for charcoal values to return to background levels and the presence of a second charcoal peak in AGL95B could be due to one of, or the interaction of, the following:

i) *Secondary deposition* - research within forested communities has demonstrated that charcoal stored within a lake catchment in riparian vegetation and surface hollows can be released and transported to a lake for an unknown time after a fire event (Gardner & Whitlock, 2001; Whitlock & Millspaugh, 1996). The duration over which secondary charcoal may enter a lake depends on the time taken for vegetation recolonisation to occur (Gardener & Whitlock, 2001). At the time of this fire event the vegetation at Akgöl was characterised by Gramineae steppe. The open nature of this community

means that charcoal would not be stored or surface flow inhibited as effectively as in closed forested vegetation communities. Therefore if secondary deposition did occur it is likely to have only occurred over a short time period.

ii) *Processes of sediment mixing and remobilisation* –Akgöl was an open, shallow marsh lake (Plate 4.1). Although it is unlikely that sediment focusing exerted an impact upon the fire history record, sediments may have been vulnerable to mixing via wave action and bioturbation described by Larsen & MacDonald (1993) (see section 2.2.12 for a full explanation of the processes). Wave action especially would serve to remobilise charcoal deposited in the initial charcoal pulse following the fire event and carry secondary charcoal into the lake for incorporation into the lake sediments.

iii) *The occurrence of two separate fire events* – the overall charcoal horizon is actually comprised of two separate charcoal layers (Figure 6.8) which are separated by lighter horizon of reduced charcoal concentration. For a reduction in charcoal concentration to occur, the amount of secondary charcoal entering the lake is likely to have been low and the lake environment stable. As indicated by the phytolith and pollen data, the local vegetation at this time was comprised of grasses, reeds and sedges. In post fire environment grasses can rapidly develop and play an important part in vegetation regeneration (Dallman, 1998; Trabaud *et al.*, 1993). Furthermore, at the time of this fire event the sedimentation rate had declined. Based on the hypothesised time taken for post-fire vegetation recolonisation in Mediterranean-type ecosystems to occur, i.e. within 10 years of the fire event dense shrub cover can develop, and the reduced sedimentation rate of the lake at this time, it is likely that there would have been sufficient fuel to support another fire event (Dallman, 1988; Hanes, 1981; Keely, 1977).

Although there is a clear difference in the amount of charcoal quantified with each sampling resolution, and despite the potential occurrence of processes operating within Akgöl that may affect the formation of a stratigraphic record of fire activity, this investigation has shown that overall patterns in fire history can be replicated. This is an important finding as it can add weight to the overall fire history reconstructions made in this thesis.

(6.8) Summary

Analysis of the fire history record preserved within the sediments of the Akgöl basin demonstrates changes in fire activity during the GS-2: Early Holocene transition that followed climatic shifts e.g. limited fire activity during GS-1 which increased with the onset of the Holocene. The source area of charcoal inputs to the lake appears to have varied through time based on evidence from the charcoal and phytolith data which has resulted in a local as well as regional signal of fire activity being recorded.

The investigation into the charcoal horizon preserved in AGL95A and AGL95B demonstrated that the amount of information obtained regarding the nature of fire events preserved within lake sediments is strongly influenced by the temporal resolution of the sampling strategy applied. Therefore, to obtain a detailed and robust fire history reconstruction a high resolution sampling strategy should be applied to sedimentary sequences.

Eski Acıgöl

Eski Acıgöl was a crater lake located within the Anatolian Volcanic Province, Cappadocia. Three core sequences collected in 1996, 1997 and 1999 were correlated together to form a master sequence measuring 1566 cm upon which a high resolution microscopic charcoal analysis was conducted. Contiguous sampling was possible for almost the whole sequence apart from 1264.2 to 1292.2 cm. This was due to the presence of lithified sediments where core recovery was poor. This Chapter will present the results of the microscopic charcoal analysis alongside existing proxy data.

(7.1) Microscopic charcoal

The results are shown in Figure 7.1. They show that charcoal concentrations from Eski Acıgöl are highly variable down core, particularly the section of the record above 1100 cm. There are 10 clear peaks in charcoal concentration at 1397.4, 1311.6, 1055.7, 878.5, 774.1, 613.0, 510.7, 347.5, 231.0 and 82.5 cm (Figure 7.1). Low charcoal values were recorded between 1551.9 and 1436.1 cm, 1266.8 and 1093.8 cm, ca.850cm and ca.650 cm.

(7.2) Lithology

The sediment stratigraphy for ESK96/99 is presented in Figure 7.1. There is a major change in sediment stratigraphy at ca.600 cm whereby laminated lake sediments cease to form and are overlain by non-laminated silts and carbonates (Roberts *et al.,* 2001). The laminated sediments are annual in character and consist of authigenic carbonates, diatom silica and organic matter. Tephra horizons, soft nodular layers and one massive calcitic traventine layer are present in the laminated section of the core (Roberts *et al.,* 2001). Invertebrate remains (e.g. ostracods and chironomid head capsules) are also preserved in the sediments.
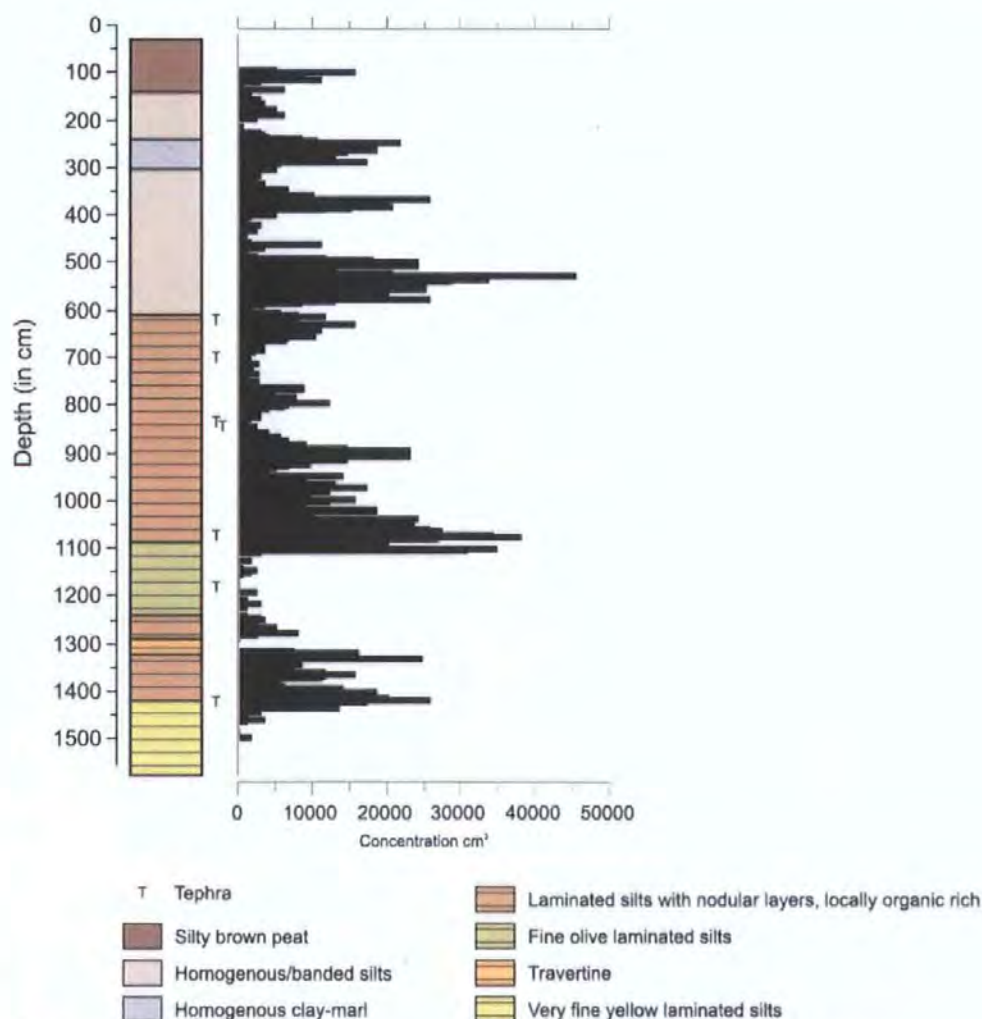
Figure 7.1: Lithostratigraphy and charcoal concentration in ESK96/99.

(7.3) Chronology

As discussed in Chapter 4 (Section 4.2.1.3) dating of this sequence is problematic. The ^{14}C dates exhibit a constant age off-set due to the presence of "old carbon" within the system (Roberts *et al.*, 2001). U-series dates have therefore been used to establish an age-depth model (Figure 7.2). Although the U-Th dates contain large standard errors (Table 7.1) they do, when anchored by a biostratigraphic marker at 1088 cm, provide a reasonable chronology. The biostratigraphic marker at 1088 cm represents the transitions from GS-1 to the Holocene therefore an age of 11,500 years BP was applied to this boundary. This transition is recorded in the lithostratigraphy of the sequence as the switch from laminated olive yellow-green silts to laminated brown-beige marly silt, and is also present at the same depth in the stable oxygen isotopes, pollen and charcoal records (Roberts *et al.*, 2001).

Depth	U-Th age	Ra-Th age
174-176	0	**1,600 ± 250**
685-687	**7,100 ± 3,200**	**6,900 ± 800**
997-999	**11,100 ± 1,900**	>8,000
1248-1250	**14,400 ± 2,600**	>8,000
1408-1410	**16,200 ± 2,700**	>8,000
1557-1565	23,200 ± 2,000	>8,000

Table 7.1: Dates obtained from ESK96/99 using U-series dating. The ages used to construct the age-depth model for this site are highlighted in bold.

Roberts *et al.,* (2001) hypothesised that the final U-Th age was an over prediction as previous fission track dating on volcanic glass from the rhyolitic dome had given ages of 19,000 ± 7,000 and 20,000 ± 6,000 years BP (Bigazzi *et al.,* 1993), giving a maximum age of lake sedimentation of ca.20,000 years BP. Therefore this date was excluded from the age model. The age model was constructed using a linear trend line.
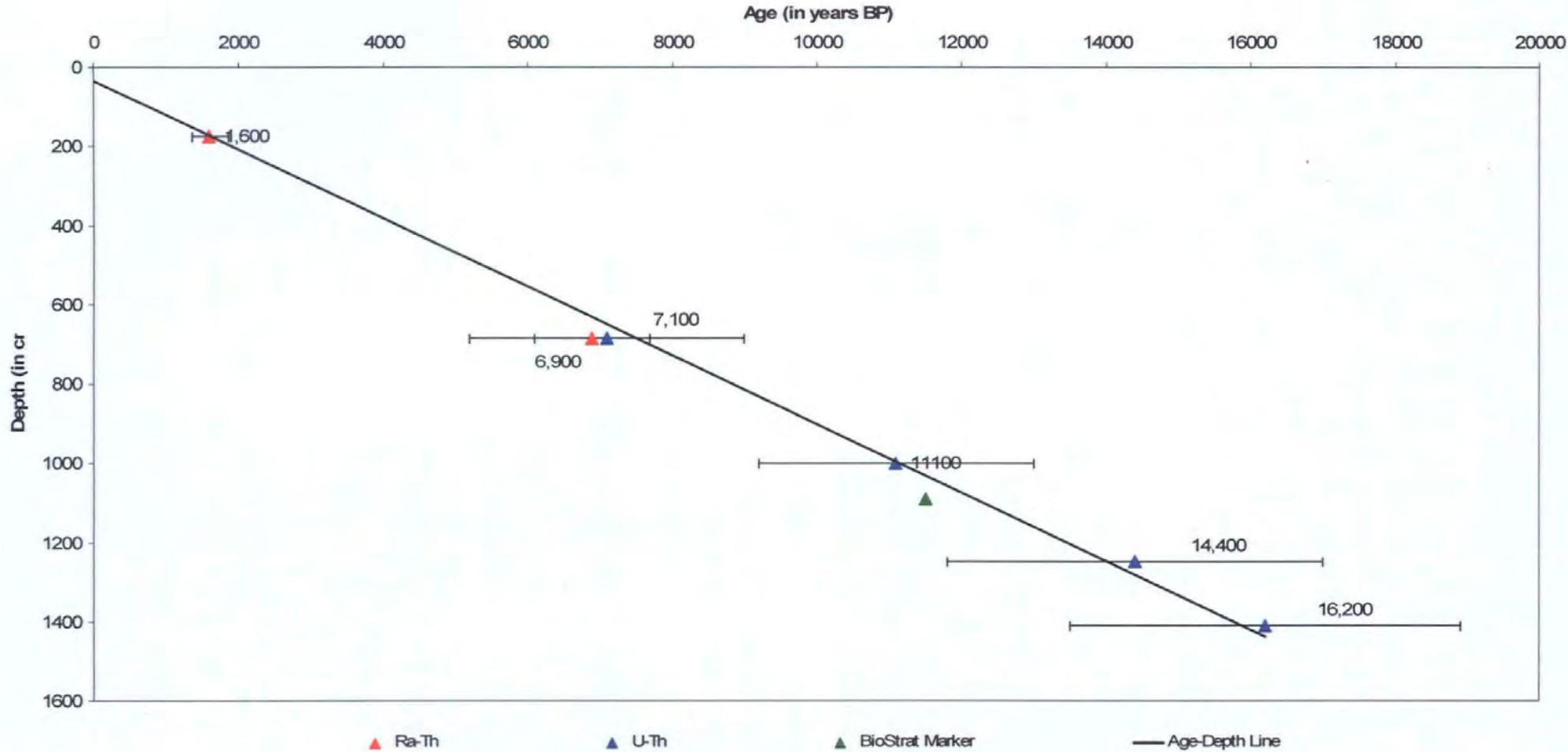
Figure 7.2: ESK96/99 age-depth model

Despite the application of the GRIP age to the Holocene: GS-1 transition, the age-depth model produced ages that are ca.500 to 600 years too old e.g. an age of 12,158 years BP is given for the Holocene: GS-1 boundary rather then the GRIP age of 11,500 years BP. In contrast, the ages extrapolated beyond 1509 cm appear to be an underestimation e.g. the end of the sequence (1566 cm) has an age of 17,600 years BP. Whilst this is within the errors of the fission track dating, it is likely that the basal sediments are older. Therefore the exact chronology of the event stratigraphy could not be applied to this record. Instead transitions between climatic episodes were determined based on lithostratigraphic changes in the sequence (Figure 7.1) e.g. the transition from GS-1 to GI-1 was identified based on change from laminated olive yellow-green silt to dark brown laminated silt at 1240 cm, and the change from GS-2 to GI-1 by the switch from dark olive-yellow laminated silt to very finely laminated silt-marl at 1414 cm. These changes in lithostratigraphy are supported by equivalent changes in the $\delta^{18}O$ data that indicate climatic changes.

(7.4) Influx of microscopic charcoal

Charcoal influx to Eski Acıgöl varies during different climatic episodes (Figure 7.3). GS-2 is characterised by low/zero levels of charcoal influx which begin to increase prior to the onset of GI-1. Charcoal influx remained high but fluctuating during GI-1 until ca.14,740 years BP when it began to decline (Figure 7.3). During GS-1 charcoal influx declined to levels similar to those recorded during GS-2. The GS-1: Holocene transition is marked by a significant sharp rise in charcoal influx to the lake (Figure 7.3). The Early Holocene is characterised by high levels of charcoal influx to the lake, which declined toward ca.9,000 years BP. Following 7,500 years BP influx values increased, with maximum charcoal influx to the lake been recorded ca.5,200 years BP (Figure 7.3). From the Mid Holocene onward, overall charcoal influx to the lake declined. Throughout the Holocene, superimposed on the long-term changes in charcoal influx, there was evidence of cyclic oscillations of charcoal influx to Eski Acıgöl (Figure 7.3).
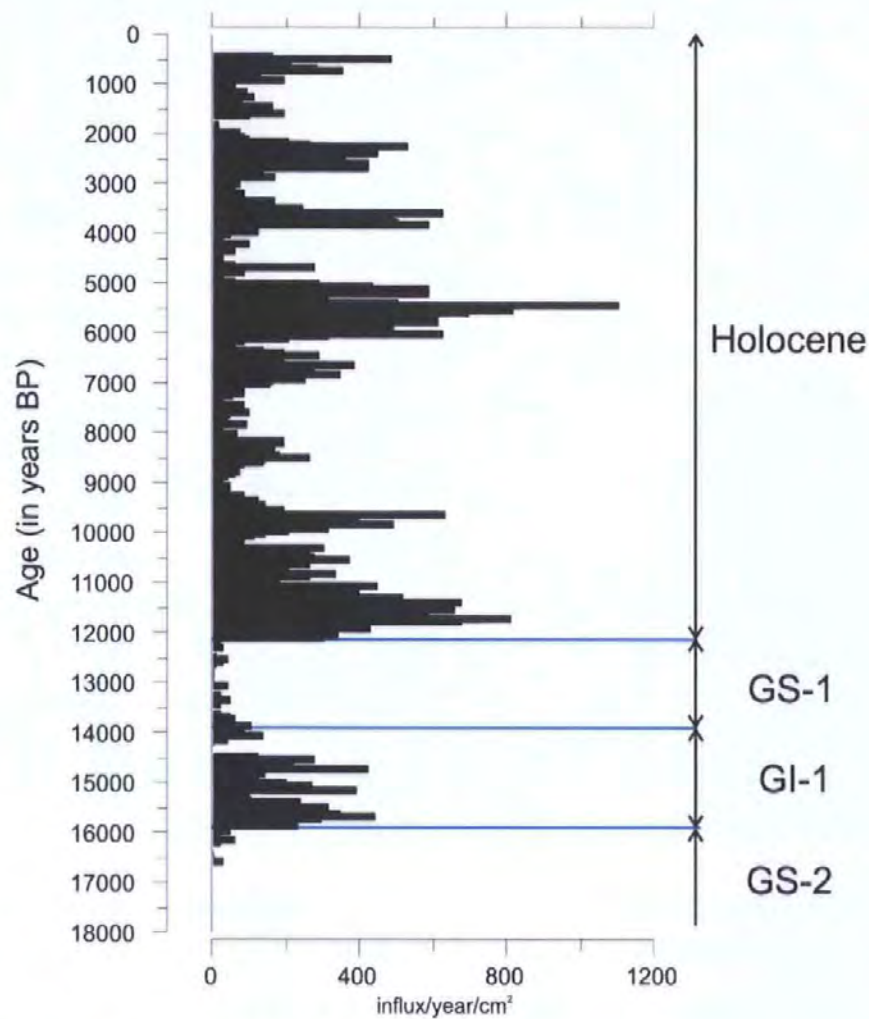
Figure 7.3: Charcoal influx to ESK96/99.

(7.5) Comparison with proxy data

(7.5.1) Pollen (Woldring & Bottema, 2001)

Pollen analysis was carried out on a parallel core sequence (ESK92) taken in 1992. A series of recognisable tie points were identified between the ESK92 and the ESK96/99 sequences that allowed the laminated parts of the two sequence to be correlated with a high degree of confidence (Table 7.2) (Roberts *et al.*, 2001). Two further tie points in the non-laminated section of the core were provisionally identified to enable further correlation between the two sequences (Table 7.2).

Depth of tie point in the ESK92 sequence (cm)	Depth of tie point in the ESK96/99 sequence (cm)
140*	200
290*	350
722	628
865	753
925	816
1017	908.5
1162	1052
1281	1146
1372	1233

* These two tie-points were identified in the non-laminated section of the core therefore do not have the same level of confidence attached to them as the tie points identified in the laminated section of the sequence (722/628 cm onwards).

Table 7.2: Tie points between the ESK92 and ESK96/99 sequences

The ESK92 sequence is shorter then the ESK96/99 sequence therefore no pollen data are available for the end of GS-2 through to the early stages of GI-1 (Figure 7.4). Consequently, pollen and charcoal data were compared form GI-1 onwards. In GI-1 steppic herbs and Gramineae appear to have co-dominated the vegetation community, tree cover was limited, however charcoal influx was high (Figure 7.4). During GS-1 the vegetation community was dominated by steppic herbs, tree cover remained sparse and charcoal influx to the lake was low. The onset of the Holocene is associated with the rapid expansion of Gramineae and a reduction in steppic herbs, which is matched by a sharp increase in charcoal influx to the lake. The Early Holocene is characterised by open grass-parklands, a gradual increase in $Q.$ *robur* and high levels of charcoal influx (Figure 7.4). The increase in $Q.$ *robur* is associated with a gradual reduction in Gramineae percentage abundance. This could be due to either a reduction in Gramineae due to the expansion of trees or a product of using percentage data. From ca.9,650 years BP charcoal influx values declined and remained low for 2,500 to 3,000 years (Figure 7.4). Around the same time $Q.$ *robur* continues to increasd, there were fluctuations in steppic herb abundance.

Maximum $Q.$ *robur* percentage values occurred at ca.5,200 to 5,500 years BP, after which they rapidly decline toward the top of the sequence (Figure 7.4). At the same time the

highest charcoal influx values for the whole sequence are recorded. After this peak charcoal influx values decline overall to the top of the sequence, along with a reduction in both Gramineae and *Q. robur* and an increased abundance of steppic herbs (Figure 7.4).

(7.5.2) Stable oxygen isotopes (Roberts *et al.,* 2001)

$\delta^{18}O$ were analysed on authigenic samples taken from the ESK96/99 sequence. Samples were taken every 16 cm however; the sampling resolution was increased to 8 cm at times of particular interest e.g. the Holocene: GS-1 transition (Roberts *et al.,* 2001). Three gaps are evident in the isotope data (Figure 7.4) at 594.5 to 639.0, 663 to 706 and 813.5 to 845.5 cm. These gaps correlate to anomalous changes in the isotope data which have been attributed to volcanic activity based on the presence of thin basaltic tephra layers below each shift in the isotope data, rather than to climate (Roberts *et al.,* 2001).

During GS-2, higher $\delta^{18}O$ values were recorded along with low levels of charcoal influx. The transition from GS-2 to GI-1 was marked by a negative excursion in $\delta^{18}O$ values that correlated with a rapid increase in charcoal influx (Figure 7.4). The onset of GS-1 was marked by a change to positive $\delta^{18}O$ values and a reduction in charcoal influx. The transition from GS-1 to the Holocene saw the second, major negative excursion in $\delta^{18}O$ values and was matched by an immediate increase in charcoal influx to the lake (Figure 7.4). The Early Holocene was characterised by negative $\delta^{18}O$ values and high levels of charcoal influx. However, as the Holocene progressed and $\delta^{18}O$ values became gradually more positive, charcoal influx to the lake declined (Figure 7.4).

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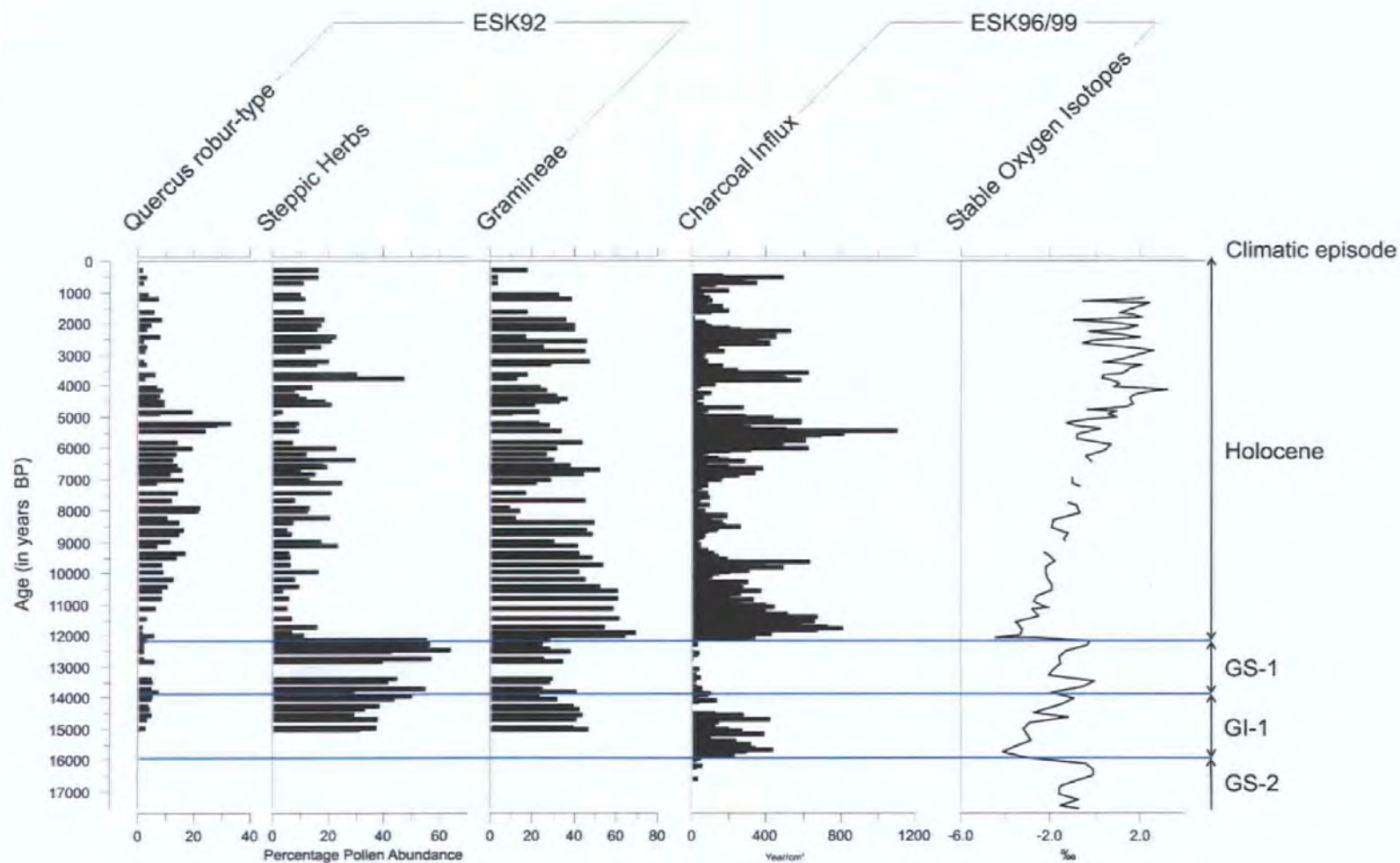
Figure 7.4: Pollen (ESK92) δ¹⁸O and charcoal influx data (ESK96/99) (additional sources Roberts *et al.*, 2001; Woldring & Bottema, 2001)

(7.5) Climate, biomass & fire

Eski Acıgöl was primarily a crater lake with a very small watershed catchment (Figure 4.4); therefore microscopic-charcoal will have entered the lake via aeolian transport processes. The source area of charcoal inputs to the basin is inferred from the modern pollen precipitation data. Woldring & Bottema (2001) recorded *Pinus* sp. pollen in modern surface samples taken from Central Anatolia in 1997, 1998 and 2000. The presence of *Pinus* sp. represents long distance (regional) transport to the lake from the Taurus and Pontic Mountains where contemporary stands of *Pinus* sp. occur as *Pinus* sp. is absent from Cappadocia and scarce in Central Anatolia (Woldring & Bottema, 2001). The hypothesised regional fire history signal is further supported by the absence of macroscopic charcoal particles, none of which were observed during the analysis of this sequence.

Comparisons between the $\delta^{18}O$, pollen and charcoal influx data demonstrate changes in charcoal influx to the lake which follow the major climatic shifts e.g. GS-1 to Holocene, therefore almost synchronous changes are evident between climate, fuel availability and subsequent fire occurrence. The nature of this relationship, how it varies through time and the effects of human activity will be discussed below.

Greenland Stadial 2

The pollen sequence (ESK92) did not extend back to GS-2; however, based on other multi-proxy evidence the vegetation community can be inferred. During GS-2, the $\delta^{18}O$ indicated the prevalence of a cold, arid climate (Roberts *et al.*, 2001; Figure 7.4). This led to reduced evaporation rates resulting in deep water conditions occurring in the lake, as indicated by the diatom flora which was dominated by planktonic species (Roberts *et al.*, 2001). Throughout GS-2 charcoal influx to the lake was low indicating that few fires were occurring in the wider environment. This in turn represents limited levels of biomass, and therefore fuel, a consequence of the harsh nature of the climate. Elsewhere in the Eastern Mediterranean at this time the vegetation community was dominated by steppic herbs (e.g. *Artemisia* sp. and Chenopodiaceae) and tree cover was restricted to isolated pockets of favourable conditions, therefore it is likely that a similar vegetation community occurred in the vicinity of Eski Acıgöl (van Zeist & Bottema, 1991).

Greenland Interstadial 1

The onset of GI-1 was associated with a negative shift in the $\delta^{18}O$ in accordance with a shift to a more favourable climate, a change in the lithostratigraphy of the sequence and a subsequent increase in charcoal influx to the lake (Figure 7.4). The $\delta^{18}O$ data indicate a series of step-wise shifts in climate throughout GI-1. It is possible that they follow the short-lived shifts between warmer and colder climatic episodes recorded in the GRIP ice core, however, due to the chronological problem with the Eski Acıgöl sequence a direct comparison is not possible (Björk *et al.*, 1998).

During GI-1 the pollen data indicates low-levels of *Q. robur* (decidious oak) and Woldring & Bottema (2001) speculated that localised areas of glacial refugia occurred in Cappadocia. The continued presence of steppic herbs despite climatic warming indicates an increase in summer temperatures rather than an overall increase in precipitation (Woldring & Bottema, 2001). However, sufficient climatic warming occurred to allow an increase in biomass (including Gramineae) and therefore fuel and ultimately fire occurrence (Figure 7.4). As GI-1 progressed, the climate became increasingly arid (as reflected by the $\delta^{18}O$ data) resulting in a re-expansion of steppic herbs and a reduction in Gramineae. The change in fuel load led to a reduction in charcoal influx to the lake as the climate deteriorated toward the onset of GS-1 (Figure 7.4). Therefore it can be speculated that in the early stages of GI-1 as Gramineae replaced steppic herbs this supported regular ground fires, however, as steppic herbs increased and fuel availability declined fire frequency reduced.

Greenland Stadial 1

Throughout GS-1 the vegetation community was dominated by steppic herbs and minimum arboreal pollen values were recorded. As a consequence of reduced fuel availability charcoal influx, and therefore fire occurrence, continued to decline throughout GS-1. This further supports the hypothesised importance of Gramineae as a fuel source as opposed to steppic herbs.

The Holocene

The onset of the Holocene is marked by an abrupt climatic ameliorlation reflected by a negative excursion in the $\delta^{18}O$ data indicating a shift to humid conditions. There was also a rapid reduction in steppic herbs followed by the expansion of Gramineae (Figure 7.4). Although there was a delayed expansion of *Q. robur* following the onset of the Holocene,

Pistacia sp. (terebinth) increased (an indication of warmer, potentially frost-free, winters and increased precipitation) and it is hypothesised that *Tilia* sp. (lime), *Crataegus* sp. (hawthorn), *Ulmus* sp. (elm), and *Celtis* sp. (hackberry) also increased, however due to poor pollen productive and dispersal capabilities it is likely that their occurrence is underestimated (Rossignol-Strick, 1995; Woldring & Bottema, 2001). Overall the vegetation community is likely to have been characterised by open, oak-pistacia parkland becoming increasingly mesic in character by ca.8,000 years BP. The shift in the vegetation community and increase in available biomass resulted in a sustained increase in charcoal influx to the lake that lasted until ca.9,500 years BP.

The Early Holocene also saw the establishment of settlements within the vicinity of Eski Acıgöl, of which Aşıklı höyük is one. Aşıklı höyük was a large sedentary settlement located ca.35 km to the southwest of Eski Acıgöl and was occupied for ca.500 years between 10,000 to 9,500 cal. years BP (Esin, 1991). The settlement represented a new model of sedentary life which was based largely on the hunting of sheep and goats and gathering of wild resources, however, there was evidence of the early stages of domestication of wild resources (Esin, 1991). The settlement contained tightly packed houses similar to those seen at Çatalhöyük, yet this settlement pre-dates Çatalhöyük by approximately 500 years (Esin, 1991). Although the settlement was densely populated, the pollen record does not provide any evidence for the impact of human activity on the landscape. For example, there was a continued increase in arboreal pollen values throughout the occupation of Aşıklı höyük. The occupation of Aşıklı höyük does coincide with an increase in charcoal influx to the lake (ca.9,650 years BP), and it is possible that this peak in charcoal can partly be attributed to anthropogenic activity, as the nature of their economy is likely to have required the use of fire to manage or manipulate the landscape (Figure 7.4). However, evidence from other settlements occupied around the same period in Central Turkey (e.g. Pınarbaşı) has shown that the overall impact of people on the environment at this time was limited (Asouti, 2003; Asouti & Hather, 2001). Whilst people would have exploited and manipulated the environment in the immediate vicinity of their settlement, and therefore could have had a local scale impact on the environment, it is unlikely that people would have exerted a large enough impact to be detected at the regional scale. As Eski Acıgöl is thought to reflect regional fire activity, it is unlikely that small-scale, localised fire activity would be detected within the palaeoenvironmental record. Therefore it seems likely that charcoal inputs from Aşıklı höyük was overshadowed by that entering the lake from the wider environment.

Following the abandonment of Aşıklı höyük charcoal influx declined and remained low for ca.2,500 years. Whist there is a slight increase in charcoal at ca.8,500 years BP, the peak is smaller the any other peak in the sequence. This decline in charcoal influx may indicate a reduction in fuel availability. Woldring & Bottema (2001) identify an increase in steppic herbs followed by a decline in Gramineae (Figure 7.4). This shift in the vegetation community and therefore fuel availability may be attributed to the continued expansion of trees leading to a reduction in the amount of water available in the system causing the demise in moisture demanding species (Woldring & Bottema, 2001). There is also an increase in spiny or impalatable species, e.g. *Scabiosa palaestina* and *Centaurea*, that develop in association with human impact e.g. grazing practices (Woldring & Bottema, 2001). Either of these factors could have caused a change or a reduction in fuel availability and therefore fire occurrence.

Around ca.8,000 years BP the maximum extent of mesic woodland occurred which is not as flammable as the open-grass-parklands (Woldring & Bottema, 2001). This is reflected by the decline in charcoal influx to the lake, which continues to fall as steppic herbs and species associated with grazing continue to increase at the expense of Gramineae. Following the maximum extent of mesic woodland from ca.7,100 years BP the diversity of the woodland began to decline although *Q. robur* continued to increase. There was also an increase in the number of grass species with pollen grains greater then 40 μm, perhaps indicating the cultivation of cereals (Woldring & Bottema, 2001). Through this period charcoal influx remains low. The reduction in woodland diversity may be due to the onset or expansion of cereal cultivation in the region, which, through anthropogenic manipulation of the vegetation community may have limited further fuel availability. However these changes in the vegetation community and fire regime may also be linked to climatic changes in the Eastern Mediterranean region (Bar-Matthews *et al.*, 1997). After 6,500 years BP the climate shifted from one of a moisture surplus to a moisture deficit. This shift in the moisture regime could explain the loss of species such as *Corylus* sp. which favour more temperate conditions whilst *Q. robur*, which is more tolerant of drought, continued to expand (Woldring & Bottema, 2001).

As with the onset of the Holocene, this climatic change was recorded synchronously in several different proxies. The shift to moisture deficit led to a drastic fall in lake levels resulting in an end to the formation of laminated sediments (Roberts *et al.*, 2001). There

was also a shift in the diatom assemblage from a predominately freshwater and planktonic to a saline, benthic flora (Roberts *et al.,* 2001). The changes occurred ca.6,600 years BP.

After 5,000 years BP the overall level of charcoal influx to the lake fell. This is clearly linked to fuel availability of which there are two possible explanations for a change in fuel load; climate or people. Maximum *Q. robur* values occurred ca.5,200 years BP which is then followed by a large decline in arboreal pollen values (Woldring & Bottema, 2001; Figure 8.5). The reduction in oak corresponds with a reduction in charcoal influx to the lake, therefore it is unlikely that fire was used to clear the woodland, indicating a demand for wood. Indeed the onset of woodland clearance does correlate with Bronze Age expansion (Woldring & Bottema, 2001). There is widespread archaeological evidence of Bronze Age settlements in Central Anatolia as well as evidence of their metal working (Woldring & Bottema, 2001). Metal working led to an increased demand for fuel and is hypothesised to have led to the large scale woodland clearance evident in the pollen record (Woldring & Bottema, 2001).

Arboreal pollen values fluctuate throughout the rest of the sequence. The reduction in tree cover led to an increase in Gramineae (Figure 7.4), however, this increase is also associated with the expansion of weedy species associated with agricultural activity and grazing e.g. *Plantago lanceolata* and *Sanguisorba minor* (Woldring & Bottema, 2001). Steppic herbs also increase indicating the continued degradation of the landscape. The combined effect of grazing and the shift in the vegetation community resulted in a reduction in fuel availability potentially explaining the progressive overall reduction in charcoal influx to the lake. Limited fuel availability around this time is further exacerbated by climatic aridity from ca.4,500 years BP (Roberts *et al.,* 2001). From around this time the $\delta^{18}O$ data demonstrates a positive excursion, indicating a shift to drier conditions which is supported by a progressive change in the mineralogy of the sequence (e.g. there is a shift from aragonite to high magnesium calcite then to dolomite) (Figure 7.4; Roberts *et al.,* 2001). There is evidence of changes in fire activity following these climatic shifts e.g. prior to this shift the more favourable climate conditions ca.5,200 years BP were associated with an increase in fire activity, whereas following this shift toward climatic aridity there is a considerable fall in charcoal influx to the lake (Figure 8.6). It is likely at this time anthropogenic activity exacerbated the effects of climate change on the landscape.

Charcoal influx continued to decline toward the top of the sequence representing limited fuel availability. This is likely to be the consequence of intensive use of the landscape for cultivation and grazing. The expansion of agriculture and grazing bring with them not only changes in the vegetation which results in reduced fuel availability but also a shift in landscape management practices, which, as will be demonstrated in the next chapter, serve to further retard fire occurrence.

1,500 year periodicity in fire occurrence

Spectral analysis

To assess the nature of the cyclic oscillations evident in the Holocene portion of the ESK96/99 sequence a spectral analysis was conducted using PAST version 1.36 (Hammer *et al.*, 2001). PAST uses the FFT algorithm which is suited to the analysis of palaeoenvironmental data which can be unevenly spaced in time (Hammer *et al.*, 2001). Significant cycles (i.e. at the 0.01 significance level) were identified in the charcoal influx data at periodicities of 6,201, 2,906, 1,937 and 1,524 years (Figure 7.5). The cycles at 6201 and 2,906 years are unlikely to be of importance as they may be a product of the length of the data set (i.e. they represent approximately half and a quarter of the length of the data set). To assess whether the cycles at 1,524 and 1,937 year are evident within the charcoal influx data cycles of high and low charcoal influx values at periodicities of 1,524 and 1,937 were applied (Figure 7.6a and 7.6b). The cycles were anchored at 7,000 years BP as this part of the age-depth model is well-constrained.
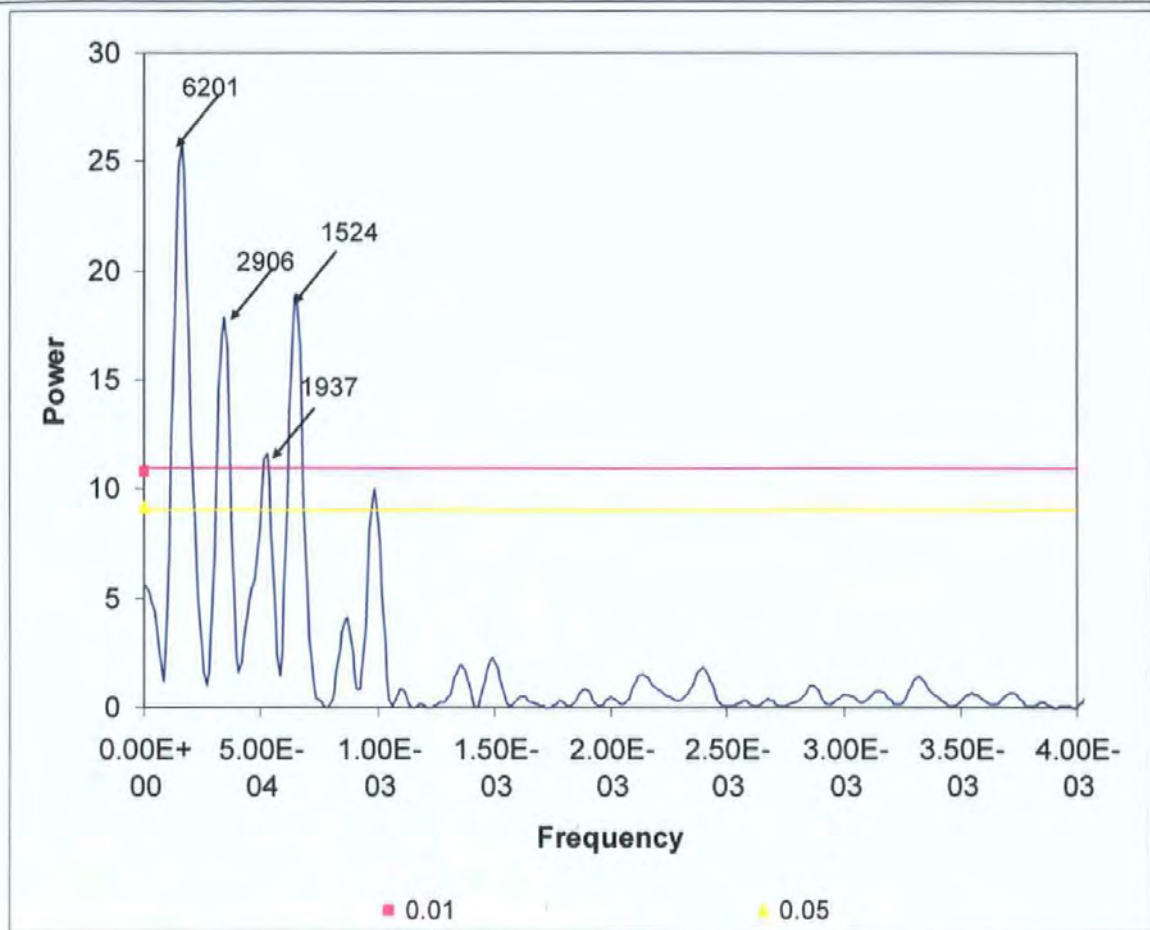
Figure 7.5: Cycles observed in the charcoal influx data using spectral analysis
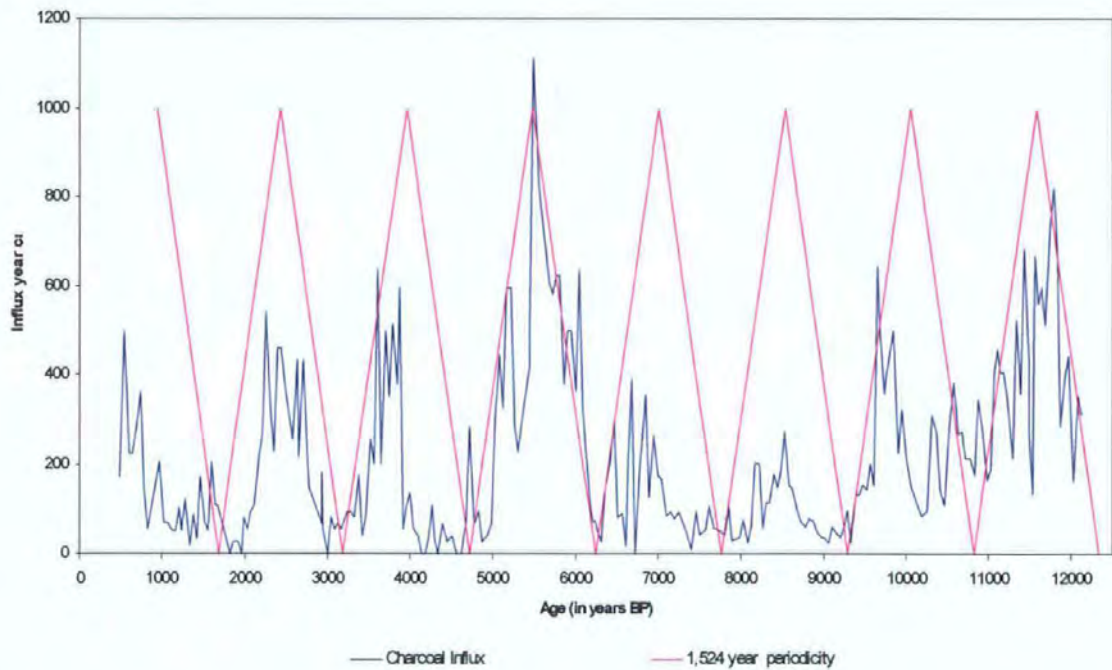
Figure 7.6a: The application of a 1,524 cycle to the charcoal influx data
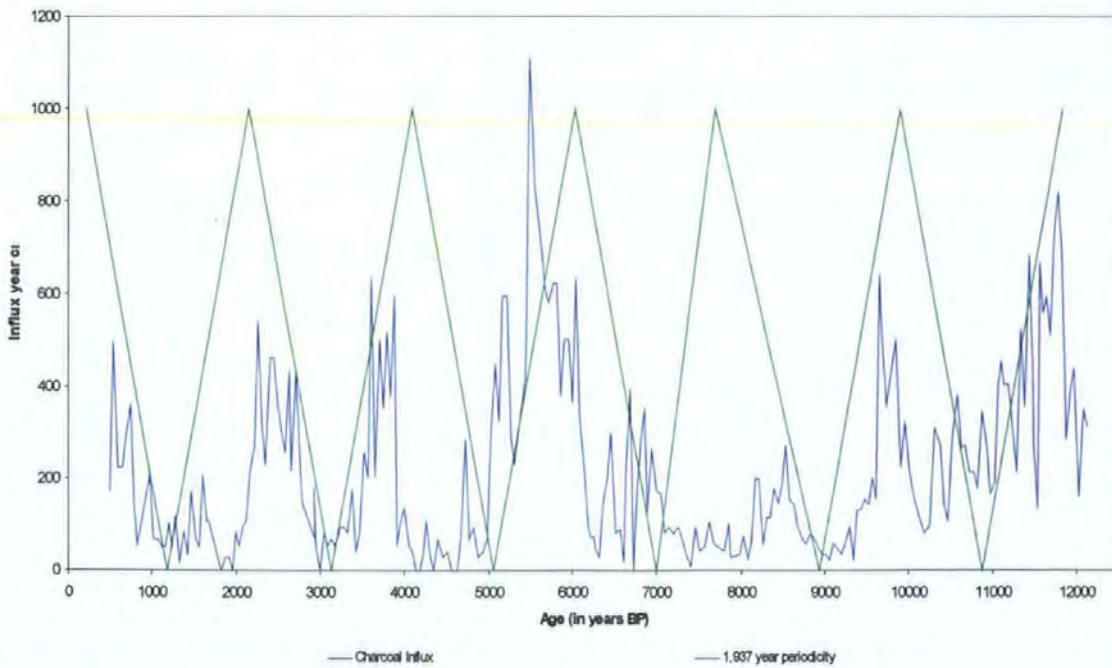
Figure 7.6b: The application of a 1,937 cycle to the charcoal influx data

As evident, through comparisons of Figures 7.6a and 7.6b, the 1,524 year periodicity fits better with the oscillations from high to low levels of charcoal influx for the Holocene portion of the sequence. This periodicity is superimposed on the general changes in charcoal influx to the lake associated with climatic changes and human activity. This

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periodicity is clearly not identified in the other palaeoenvironmental proxies (e.g. pollen or $\delta^{18}O$) analysed from this sequence. This may be due to local-scale factors e.g. climate, exerting an overriding control. The presence of this periodicity in the fire history data may demonstrate the influence of larger-scale, external forcing factors on regional fire activity. This periodicity (exact frequency based on the existing chronology: 1,524 +50/-25 years) is within the error of the 1,470 ± 500 cycle of millennial-scale climatic oscillations identified in the North Atlantic by Bond *et al.* (1997; 2001). Although the 1,524 year periodicity is within the error cited by Bond *et al.* (1997; 2001) it is likely future revisions of the chronology of this site will result in a closer temporal match between these cycles and the 1,470 ± 500 Bond Cycles. "Bond Cycles," as they are known, represent abrupt climatic changes that caused the advection of cool, ice-bearing waters southward resulting in the onset of short-lived cooling events in the North Atlantic. Evidence has shown that these cycles occurred independently of glacial: interglacial climatic states and had a global impact (Bond *et al.*, 1997; Broecker, 1994). Bond *et al.* (2001) identified solar forcing (i.e. the shift between periods of solar maxima vs. solar minima) of climate as a possible driving mechanism for this North Atlantic climatic periodicity. Since the initial identification of Bond Cycles in sediment cores from the North Atlantic, evidence of the 1,470 ± 500 year periodicity and the potential link to solar forcing has been identified in numerous marine and terrestrial record from high to low latitudes (e.g. Campbell *et al.*, 1998; Fleitman *et al.*, 2003; Hu *et al.*, 2003; O'Brien *et al.*, 1995; Verschuren *et al.*, 2000). It is assumed that broad scale teleconnections result in the expression of solar forced climatic changes across all latitudes (Bond *et al.*, 2001; Fleitman *et al.*, 2003; Wang *et al.*, 2005).

Identifying Bond Cycles and therefore solar forcing in palaeoenvironmental data is not straightforward. A proxy needs to be analysed that shows a rapid and directional response to climatic changes. Vegetation data, for example, exhibits both region specific and time-transgressive responses to climatic changes as well as being influenced by abiotic and biotic factors (Willis *et al.*, 2006). Willis *et al.* (2006) cited changes in Holocene fire as a potential proxy due to the clear links between climatic changes and fire history, which have indeed been demonstrated in the Eski Acıgöl sequence (Willis *at al.*, 2006; Figure 7.4). Willis *et al.* (2006) statistically analysed eight charcoal records from lake basins smaller than 1 km^2 in area from Mediterranean, temperate and tropical regions. They identified no clear periodicity in any of the records. This could be attributed to the size of the sites they analysed e.g. they received charcoal from local as well as regional sources,

and therefore the regional pattern could have been masked by the local signal, as was the case at Akgöl. Also, the fire history records were obtained using a spot rather then contiguous sampling strategy and the charcoal was extracted from the sediments using a pollen preparation. Therefore, based on the methodological work presented in Chapter 3, it is possible that a true representation of the fire history record was not always obtained. The Eski Acıgöl sequence provides the opportunity to test the relationship between Bond Cycles, solar forcing and regional fire activity. However, to interpret fully the links between the fire, Bond Cycles and solar forcing it is essential to first fully understand how climatic changes in the North Atlantic can exert an impact on Eastern Mediterranean fire histories. To do this, Eastern Mediterranean climate, the factors that control it and the potential teleconnections to the North Atlantic will be briefly reviewed.

As discussed fire occurrence is closely linked to biomass which in turn is associated with climatic factors. Climatic warming in the Early Holocene saw the replacement of cold-steppe by open-grass parkland in Central Turkey and was associated with an increase in fire occurrence (Woldring & Bottema, 2003; Figure 7.4). The close timing between the change in the main constituents of the herbaceous community and the increased incidence of fires in the region show the importance of the herbaceous vegetation as a fuel source.

Likewise, moisture availability represents the controlling factor on plant occurrence (Zohary, 1973). Therefore vegetation growth will be associated with the seasonality of rainfall, the majority of which (ca.60%) occurs during winter and spring (Turkeş, 1996). Winter storm tracks that determine Eastern Mediterranean rainfall originate in the Atlantic Ocean and pass over Northern and Central Europe whereas the Mediterranean Sea acts as a secondary centre for cyclone formation and moisture uptake (Eshel & Farrell, 2000; Prasad *et al.*, 2004). The path of North Atlantic mid-latitude storm tracks is determined by the North Atlantic Oscillation (hereafter NAO), which acts as a teleconnection between the Eastern Mediterranean and the North Atlantic (Cullen & deMenocal, 2000; Eshel & Farrell, 2000). The NAO represents a range of atmospheric pressure differences between the Icelandic low and the Azores high which dominates winter temperatures and precipitation from the Atlantic to the Eastern Mediterranean (Cullen & deMenocal, 2000; Hurrell, 1995).

Several studies have shown positive correlations between the NAO and precipitation in the Eastern Mediterranean e.g. Cullen & deMenocal, 2000; Cullen *et al.*, 2002; Eskel *et al.*,

2000. Depending on the state of the NAO (i.e. positive vs. negative) it can lead to wetter or drier winters in the Eastern Mediterranean (e.g. positive NAO results in drier winters, negative results in wetter winters) (Cullen & deMenocal, 2000). This is due to the influence of the NAO on the strength of westerlies which carry moisture to the region and the positioning of cyclones (Enzel *et al.*, 2003). However, despite these clear links evident between the NAO and changes in winter rainfall in the Eastern Mediterranean there is still debate as to whether this teleconnection persisted through time. Cullen & deMenocal (2000) state that based on the links between the contemporary North Atlantic and Eastern Mediterranean climates it highly likely that Holocene cooling events, such as those associated with Bond Cycles, would explain millennial scale climate variability in the Eastern Mediterranean region. North Atlantic climate variability (e.g. cooling events) has been associated with drought events in the Eastern Mediterranean due to reduced winter precipitation e.g. Enzel *et al.* (2003) identified links between significant lake levels falls in the Dead Sea and changes in storm tracks between the North Atlantic and the Eastern Mediterranean. However, they stated that the role of the NAO in these shifts in storm pattern was questionable (Enzel *et al.*, 2003). Prasad *et al.*, 2004 identified correlations between climatic deterioration in the North Atlantic during marine isotope stage 2 and a fall in the lake levels due to drought in Lake Lisan, the precursor to the Dead Sea. The NAO oscillation was again cited as a potential mechanism but they also state that the NAO does not explain all winter climate variability in the region and its influence is not fully understood, therefore it is likely that changes in storm tracks exerted a greater control (Prasad *et al.*, 2004). Likewise, Bartov *et al.* (2003) cited inputs of freshwater during the Last Glacial to the North Atlantic during Heinrich Events as inhibiting the formation of deepwater circulation and therefore the transfer of heat from the tropics, which in turn would have resulted in a reduction in the frequency and intensity of storm events reaching the Eastern Mediterranean, and a fall in winter precipitation and, ultimately, regional drought.

Whilst the teleconnections between the North Atlantic and Eastern Mediterranean region may not be fully understood, climatic cooling in the North Atlantic has been linked to drought in the Eastern Mediterranean throughout the present interglacial and during the last glaciation e.g. Bartov *et al.*, 2003; Enzel *et al.*, 2003; Prasad *et al.*, 2004. Likewise, based on the links between Eastern Mediterranean precipitation and climatic cooling in the North Atlantic it is possible that Bond Cycles can be identified in fire history records from this region. Reduced winter precipitation in Turkey as a consequence of climatic cooling in the

North Atlantic would result in reduced biomass availability and therefore a reduction in fire occurrence. Therefore, Bond Cycles should correspond to low or falling levels of charcoal influx to Eski Acıgöl (see Figure 7.7).

Understanding the connections between solar forcing and regional fire activity is less straight forward. Links between solar forcing and climatic change are often made, however it is widely acknowledged that the mechanisms driving solar forcing of climate are highly complex and poorly understood (Beer *et al.*, 2000; van Geel *et al.*, 1999). It is widely accepted that solar minima are associated with climatic cooling whereas solar maxima are associated with climatic warming (Bond *et al.*, 2001; Chambers *et al.*, 1999). Based on the hypothesised links between North Atlantic climatic and solar forcing, times of reduced activity will result in winter drought in the Eastern Mediterranean region and therefore due to a fall in biomass availability lead to reduced fire occurrence, whereas solar maxima will be associated with favourable climate conditions in the Eastern Mediterranean region (i.e. warm, humid conditions) which will result in an increase in biomass availability and therefore an increased incidence of fires. Therefore solar maxima should be associated with higher charcoal influx values to Eski Acıgöl whereas solar minima will be associated with lower influx values. These possible relationships will be assessed by plotting changes in charcoal influx against the timing of Bond Cycles (Figure 7.7a) and solar maxima (Figure 7.7b) and minima (Figure 7.7c).
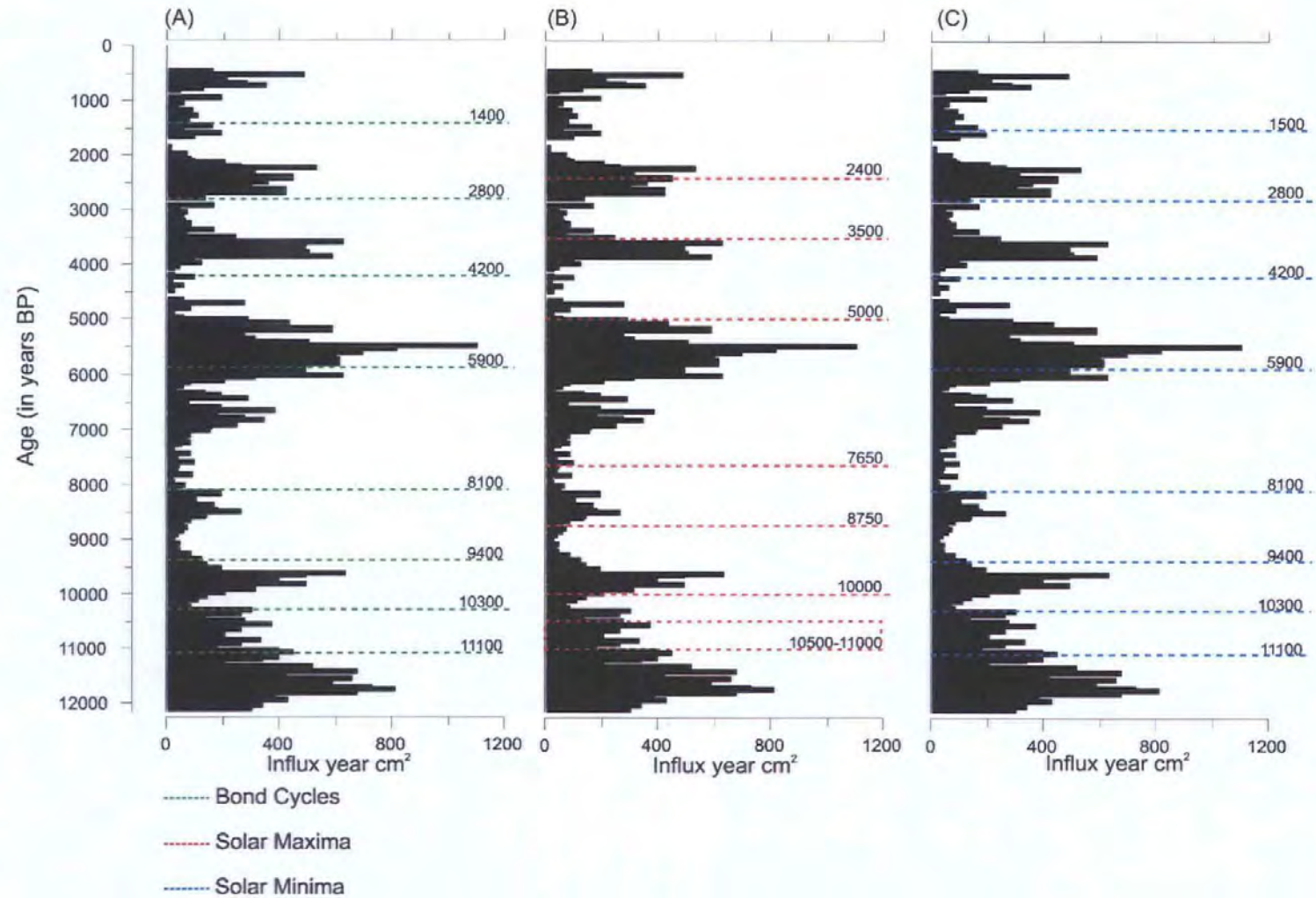
Figure 7.7: (a) Charcoal influx vs. Bond Cycles (IRD maxima), (b) Charcoal influx vs. solar maxima, (c) Charcoal influx vs. solar minima

As evident in Figure 7.7, there is not a consistent relationship between variation in charcoal influx and the timing of Bond Cycles or solar forcing. For example the Bond Cycles and solar minima occurring between 1,400 and 9,400 years BP do correspond to lower or falling levels of charcoal influx entering the lake, whereas the cycles at 10,300 and 11,100 years BP are associated with higher charcoal influx values (Figure 7.7a). Likewise, the solar maxima occurring between 2,400 and 5,000 years BP correspond to higher levels of charcoal influx to the lake; however, solar maxima between 7,650 and 11,000 years BP are associated with lower levels of charcoal influx to the lake (Figure 7.7b).

The lack of a consistent relationship between Bond Cycles, variations in solar activity and fire activity may be partially due to problems surrounding the chronology of this sequence discussed in Section 7.3. As discussed the age model is overestimating the age of the sequence by ca.500 to 600 years in the Early Holocene/GS-1 transition. Therefore it is possible that with an improved age model there may be a stronger relationship between the timing of Bond Cycles, solar forcing and variation in charcoal influx to the lake for the Early Holocene part of the sequence.

The assumed relationship between Bond Cycles, solar forcing and fire occurrence is clearly too simplistic, as exemplified by the complexity of the relationship between the North Atlantic and Eastern Mediterranean climate. Whilst this relationship may affect fire activity indirectly due to the controls it has on moisture availability, vegetation communities and ultimately fuel availability, it is not operating in isolation. Other external forcing factors e.g. orbital forcing or more local scale factors such as local climate or anthropogenic activity are also likely to be exerting a control. Again, until the Eski Acıgöl age model is improved, and the links between Bond Cycles and solar forcing can be assessed more robustly, the potential influence of these factors needs to be considered. It is unlikely, based on the hunter-gatherer practises carried out at settlements such as Aşıklı höyük, that people were exerting a control on the timing of regional fire activity in the Early Holocene. The Early Holocene in the Eastern Mediterranean was characterised by moisture surplus until the Mid Holocene and there was a switch to an environment characterised by water deficit, the influence of teleconnections between Eastern Mediterranean and North Atlantic climate became more pronounced, and therefore, climatic changes in North Atlantic exerted a greater impact in the Eastern Mediterranean.

(7.7) Summary

Changes in the fire history record of Eski Acıgöl follow major climatic shifts, which during GS-2: Holocene transition demonstrate almost synchronous changes in climate, vegetation (and therefore fuel availability) and fire occurrence. From the Mid Holocene onwards, along with the establishment of contemporary climatic conditions in the region, there is evidence within the pollen record of the increasing impact of people on the landscape. However, due to the expression of climatic changes in the North Atlantic in the fires history record of Eski Acıgöl, it is difficult to determine accurately the impact of people on regional fire activity.

Nar Gölü

Nar Gölü is an extant crater lake located within the Anatolia Volcanic Province, Cappadocia. Cores collected in 2001 and 2002 were assembled together to form a master sequence measuring 376 cm. Microscopic charcoal was analysed from contiguous samples taken every 10 (for the first 100 varve years of the sequence) then every 20 varve years (for the rest of the sequence). This chapter will present the charcoal data alongside existing stable isotope and pollen records. Due to the recent age and high temporal resolution of this sequence dates will initially be presented as varve years BP then calendar years (BC/AD).

(8.1) Microscopic charcoal

Variable levels of microscopic charcoal were recorded throughout the sequence (Figure 8.1). Five clear peaks were identified at 1241 to 1260 (9.4 x 10^3 charcoal particles per cm^3), 1161 to 1180 (1.4 x 10^4 charcoal particles per cm^3), 601 to 620 (1.1 x 10^4 charcoal particles per cm^3), 221 to 240 (1.2 x 10^4 charcoal particles per cm^3) and 61 to 70 varve years BP (2.4 x 10^4 charcoal particles per cm^3) (Figure 9.1a). Low, or zero charcoal values were recorded at 1561 to 1580, 1501 to 1520, 1420 to 1381, 761 to 780 and 361 to 380 varve years BP (Figure 8.1)
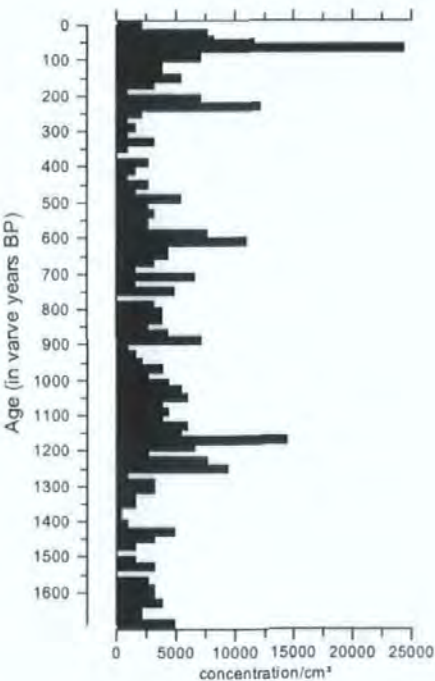
Figure 8.1: Charcoal concentration in Nar Gölü

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(8.2) Lithology

The core sequence is laminated for its entirety. The laminations are couplets of white, carbonate layers and dark layers comprised of organic material and diatoms (Jones, 2004). Occasional thick grey clastic layers measuring between 0.1 and 5.0 cm were present throughout the sequence (Jones, 2004).

(8.3) Chronology

Analysis of contemporary sediments traps and dating of the top 50 cm of the sequence using ^{210}Pb and ^{137}Cs demonstrated that the lamina couplets were annual (Jones, 2004; Jones *et al.*, 2006). The chronology of the rest of the sequence is based on varve counts in varve years before 2001 AD. Varve counting was conducted in 6 cm breaks throughout the whole sequence (Jones, 2004). To ensure accuracy each 6 cm was counted independently by two people, if the varve counts were more then three varves different, the section was recounted until agreement was reached. The varve counting was then replicated on two separate cores from different areas of the basin. Comparisons of these three counts shows that varve ages have a maximum possible uncertainty of 2.5% of the given age (Jones *et al.*, 2006).
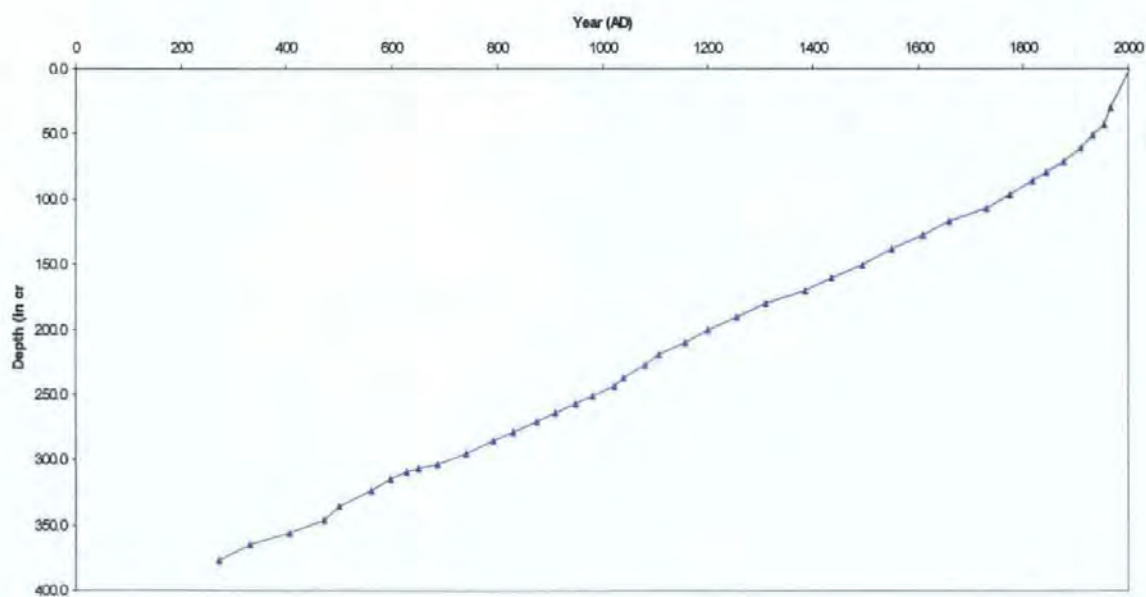
Figure 8.2: Age-depth model for Nar Gölü (Jones, 2004)

(8.4) Influx of microscopic charcoal

Charcoal influx mirrors charcoal concentration (compare Figure 8.1 and 8.3). Charcoal influx is low between 300 and 700 AD corresponding with the latter stages of the Beyşehir Occupation Phase (Figure 8.3). After the Beyşehir Occupation Phase there are two peaks in charcoal influx (at 746 and 826 AD), followed by a gradual decline in influx values to ca.1100 AD. Between 1100 and 1400 AD charcoal influx fluctuates until ca.1400 AD when influx values increase to ca.600 partical/year/cm^2 (Figure 8.3). This increase is followed by a gradual decline in charcoal influx to ca.1630 AD. Influx values remain low until the peak at ca.1770 AD and then they decrease slightly prior to the occurrence of maximum charcoal influx values at ca.1930 AD (Figure 8.3). Low charcoal influx values are recorded at the top of the sequence.
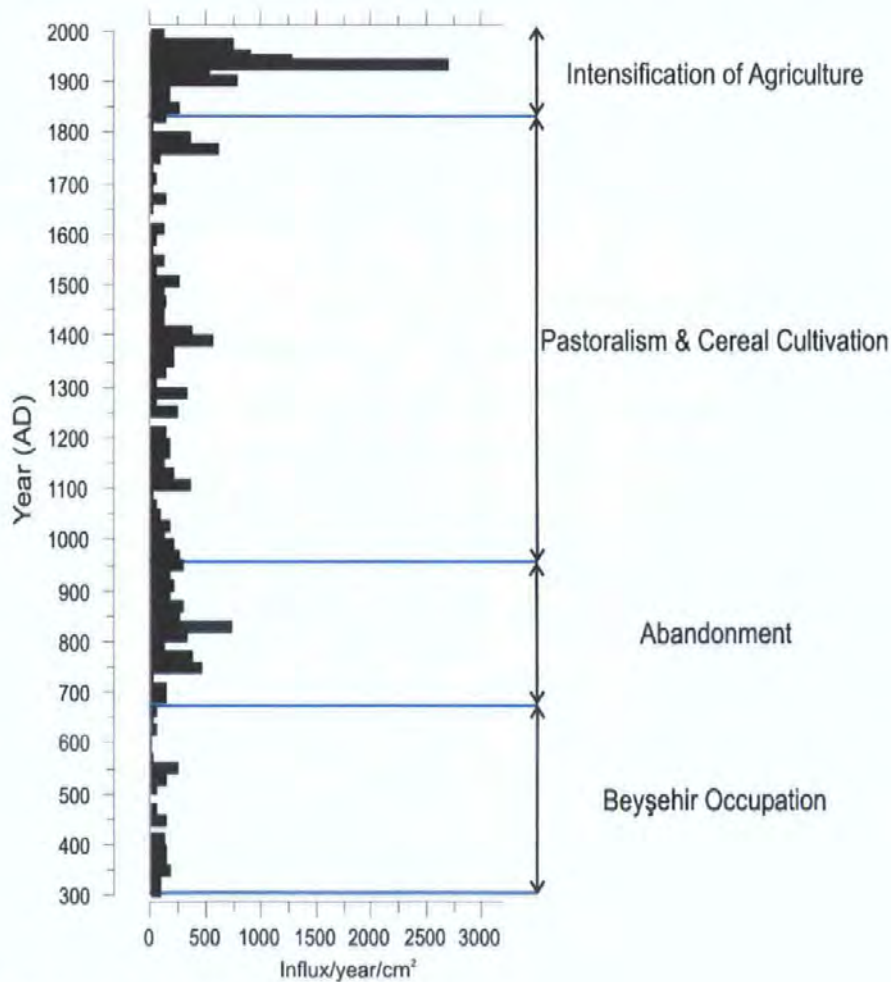
Figure 8.3: Charcoal influx to Nar Gölü

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(8.5) Comparison with proxy data

(8.5.1) Stable oxygen isotopes

Analysis carried out by M. Jones (Jones, 2004; Jones *et al.,* 2006)

$\delta^{18}O$ measurements were determined on authigenic carbonates. The first 900 varve years were analysed annually, whereas bulk samples of five varve years were analysed for the rest of the sequence (Jones *et al.,* 2006). Jones *et al.* (2006) identified positive shifts in the $\delta^{18}O$ values at 300 to 500 AD, ca.800 AD and 1400 to 1960 AD to drier conditions (i.e. increasing summer evaporation and decreased winter precipitation) and negative shifts at 560 to 750 AD and 1000 to 1350 AD to wetter conditions (indicating the reverse climatic relationship) (Figure 8.4). The charcoal data show no clear relationship between either positive (drier/arid conditions) or negative (wetter/humid conditions) isotope values. For example, charcoal influx was low during the 300 to 500 AD dry interval; however, peaks were recorded at 826 AD, corresponding to the dry interval around 800 AD (Figure 8.4). On the other hand, a peak in charcoal influx (at 1387 AD) also occurred at the end of the period of wetter climatic conditions from 1000 to 1350 AD (Figure 8.4). The apparent lack of correlation between charcoal influx and $\delta^{18}O$ data is emphasised by a canonical correspondence analysis (Figure 8.5) which plots charcoal and $\delta^{18}O$ on opposite sides of the ordination bi-plot supporting a lack of a direct link between charcoal influx and $\delta^{18}O$ data.

(8.5.2) Pollen

(8.5.2.1) Percentage pollen data

Analysis carried out by A. England (2006) (unpublished data)

Pollen samples were taken every 20 varve years, and each sample spanned three varve years (England, 2006). The charcoal and percentage pollen data are compared based on the pollen zones identified by England (2006), which relate to the different phases of human occupation and landscape use (Figures 8.3 and 8.4). Between 300 and 670 AD, when low charcoal influx values were recorded, *Pinus* sp. and *Quercus* sp. values were also low. Tree and shrub species associated with the harvesting and collection of fruit and nuts (e.g. *Olea* sp., *Castanea sativa, Juglans regia* and *Vitis vinifera*) and secondary anthropogenic indicators (e.g. *Plantago lanceolata*) were present (Figure 8.4). As charcoal influx increased between 650 and 670 AD, there was an increase in *Pinus* sp. and *Quercus* sp. whilst there was a decrease in both fruit and nut trees, and plants associated with anthropogenic activity also decline (Figure 8.4). From 950 to 1830 AD charcoal influx values fluctuate i.e. there is no clear trend of high or low influx values. This corresponds

to the re-appearance of cereals (*Secale cereale, Avena/Triticum* and Hordeum) in the pollen record. From 1830 AD there was an increase in cereals and the subsequent reappearance of *Olea* sp. in the pollen record which has been associated with the intensification of agricultural activity. At the beginning of this zone to ca.1930 AD high charcoal influx values were recorded with maximum values of the whole sequence being recorded at 1932 AD. Following 1932, influx value decline toward the top of the sequence (Figure 8.4).

These patterns are summarised in the Canonical Correspondence Analysis (CCA) bi-plot of percentage pollen, $\delta^{18}O$ and charcoal influx data (Figure 8.5). The CCA was carried out using PC-ORD (McCune & Mefford, 1999). Interestingly, woodland taxa e.g. *Quercus* sp. which are associated with periods of reduced human activity are located in close proximity to the charcoal data. Furthermore, *Pinus* sp. exhibits the closet association to charcoal influx. The plant species that are associated with greater levels of anthropogenic activity e.g. cereals and cultivated trees are located on the opposite side of the ordination bi-plot to both the woodland taxa and charcoal data (Figure 8.5). The charcoal and $\delta^{18}O$ data plot on opposite sides of the bi-plot.

Figure 8.4: Pollen, δ^{18}O and charcoal influx data from Nar Gölü (England, 2006; Jones *et al.*, 2006). A five fold exaggeration factor was applied to the *Juglans regia*, *Castanea sativa* and Hordeum.
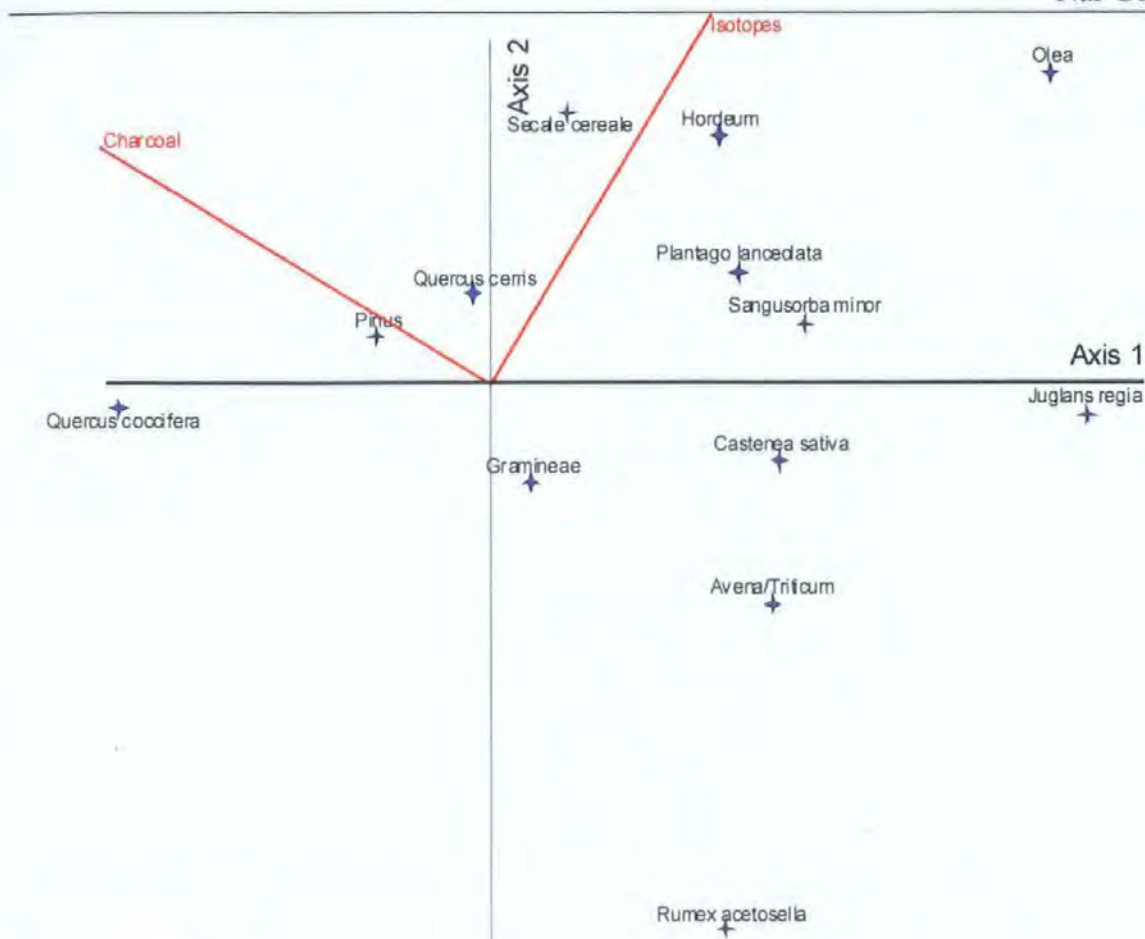
Figure 8.5: CCA bi-plot of pollen, charcoal and $\delta^{18}O$ data

(8.5.2.2) Pollen influx data

The pollen influx data follow the same trends as the percentage pollen data and therefore the pollen influx data are not presented here. However, pollen and charcoal influx values were compared for the three main vegetation groups for each of the four pollen zones identified by England (2006). The vegetation groups were woodland trees (*Pinus* sp. and *Quercus* sp.), cultivated trees (*Castanea sativa, Jugalns regia* and *Olea* sp.) and cereals (*Avena/Triticum,* Hordeum and *Secale cerale*). Gramineae was not included in the comparisons as they encompass natural and cultivated grasses therefore the relationship between charcoal and Gramineae influx values may be more complex then for the chosen species. The pollen and charcoal influx data were compared by calculating the Pearson Correlation values using MINITAB version 13.2 (MINITAB Inc, 2000).

Although the Pearson correlation values between each of the vegetation groups and charcoal influx are low (Table 8.1), they do serve to reinforce the qualitative patterns evident in Figure 8.4. The low comparison values may not be due to the absence of a relationship between the groups of species and charcoal influx, instead it may reflect

factors such as the lack of a linear relationship between changing patterns of pollen and charcoal influx i.e. other factors that are not considered or measured here also exert a control on fire or species occurrence. It could also be due to noise (e.g. outliers from the overall trends) in the data set.

Of the three vegetation groups investigated there is evidence of a relationship between woodland trees and charcoal influx (Table 8.1). In contrast cereals, cultivated trees and charcoal influx consistently produce lower correlation values. The r^2 values vary with each vegetation group and aid in explaining the relationship between changing land use and fire occurrence throughout the sequence.

During the Beyşehir Occupation and Abandonment Phases of the sequence the woodland pollen and charcoal influx values explained between 10.57% and 15.68% of the variation whereas the cereal pollen and charcoal influx values explains only 0.04% and 1.93% of the variation in the data set (Table 8.1). This indicates a link between woodland abundance and fire occurrence (i.e. increased cereals results in reduced fire activity). Over the same timeframe, whilst there is no clear relationship between cultivated tree pollen and charcoal influx these variable explaining 24.15% of the variation in the data set, indicating a link between cultivated tree abundance and fire occurrence i.e. there is a reduction in fire occurrence during periods associated with the cultivation of trees.

Following the reduced importance of cultivated trees after the end of the Beyşehir Occupation Phase, the variation in cultivated tree pollen explained by charcoal influx declines to 14.67% whilst the variance explained by charcoal influx increases to 15.68% for woodland trees (Table 8.1). The variance in the cereal data explained by charcoal remains low (1.93%).

Throughout the pastoralism and cereal cultivation phases, the variation in the charcoal influx data is not explained by changes in the vegetation groups (e.g. cereals or woodland trees) analysed here, therefore the changes evidence in the vegetation community are unlikely to be directly related to fire activity (Table 8.1). This indicates a greater influence of factors not represented directly here e.g. land clearance or grazing that may have increased as a result of the expansions in anthropogenic activity.

Following the intensification of agricultural activity there is an increase in the amount of variation explained in woodland and cultivated tree pollen influx and charcoal indicating a link between these two variables. The r^2 value for cereal pollen and charcoal influx remains low. The changing relationships through time with the different vegetation groups and charcoal influx will be discussed below in the wider context of the human history of Nar Gölü.

	Beyşehir Occupation Phase	Abandonment	Cereal cultivation & pastoralism	Intensification of agricultural
Woodland trees	0.325	0.396	0.214	-0.341
	0.1057	0.1568	0.0459	0.1161
Cultivated trees	0.033	-0.383	0.107	-0.280
	0.2415	0.1467	0.0115	0.0784
Cereals	0.0019	-0.082	-0.129	-0.143
	0.0004	0.0193	0.0166	0.0203

Table 8.1: Comparisons between the changing pollen and charcoal influx values in relation to the different phases of anthropogenic activity (the top cell gives the Pearson correlation value, the bottom cell the percentage of variance explained (r^2 value))

(8.6) Comparison of the charcoal influx records reconstructed using the density separation and pollen preparation procedures

As in Chapter 6, the presence of charcoal counts obtained from the quantification of charcoal on pollen slide by A. England provides the opportunity for further assessment of the density separation extraction procedure. Again, this comparison further substantiates the findings of the methods investigation presented in Chapter 3. Overall the two records produce similar fire history reconstructions, however, the pollen preparation consistently recorded less microscopic charcoal then the density separation (Figure 8.6). However, unlike the results from the methods investigation and the evidence from Akgöl, the difference between the two counts was not as large. This is exemplified through comparisons of the mean values of charcoal influx and the main trends in charcoal influx (Table 8.2). During the Beyşehir Occupation Phase, both records demonstrate low levels of charcoal influx to the lake, with the pollen preparation recording lower influx then the density separation (Table 8.2). During the cereal cultivation and pastoralism phase there is a clear contrast between the density separation and pollen preparation fire history

reconstructions. The density separation records variable levels of charcoal influx throughout this phase whereas the pollen preparation records zero influx values for the majority of this period (Figure 8.6). The upper part of the sequence also produced contrasting fire history reconstructions. The density separation recorded maximum charcoal influx values at 1932 AD, whereas not only did the pollen preparation samples not record this peak, low or zero charcoal influx values were recorded throughout this zone (Figure 8.6).

Vegetation Zone	Pollen Preparation (particles/year/cm^2)	Density Separation (particles/year/cm^2)
Intensification of agriculture	165.2	688.5
Pastoralism & cereal cultivation	100.1	189.7
Abandonment	139.9	297.6
Beyşehir Occupation Phase	89.5	109.6

Table 8.2: Mean charcoal influx values recorded by the pollen and density separation extraction procedures during the different vegetation zones

The contrasts between the two fire history reconstructions can be partly explained by the contrasting mechanical and chemical severity of each preparation technique (see Chapter 3). Likewise, the sampling strategy and resolution may have also caused differences between the two fire history reconstructions. The pollen analysis was based on the analysis of spot samples taken every 20 varve years and each sample spanned three varve years. In contrast, the fire history reconstruction was based on the contiguous sampling of 10 or 20 varve years. A "scrape" of sediment was removed and homogenised to provide an overview of fire activity during the time period sampled. This means that any peaks in charcoal were averaged out using the sampling procedure over a greater temporal interval then the pollen samples, which may have resulted in peaks in charcoal at 1842 and 982 AD appearing smaller then those identified by the pollen preparation (Figure 8.6). It is also possible that there were changes in the biomass/plant matter that was being burnt, which in turn may produce charcoal particles that are more fragile and therefore exhibit greater vulnerability to fragmentation during preparation. Such a change could reflect a shift from vegetation communities that contained a greater proportion of woody shrubs and trees (such as those that prevailed during the Beyşehir Occupation, the abandonment and early

part of the cereal cultivation and pastoralism phases) to a grass/cereal dominated community or the shift to stubble burning following the intensification of agriculture.
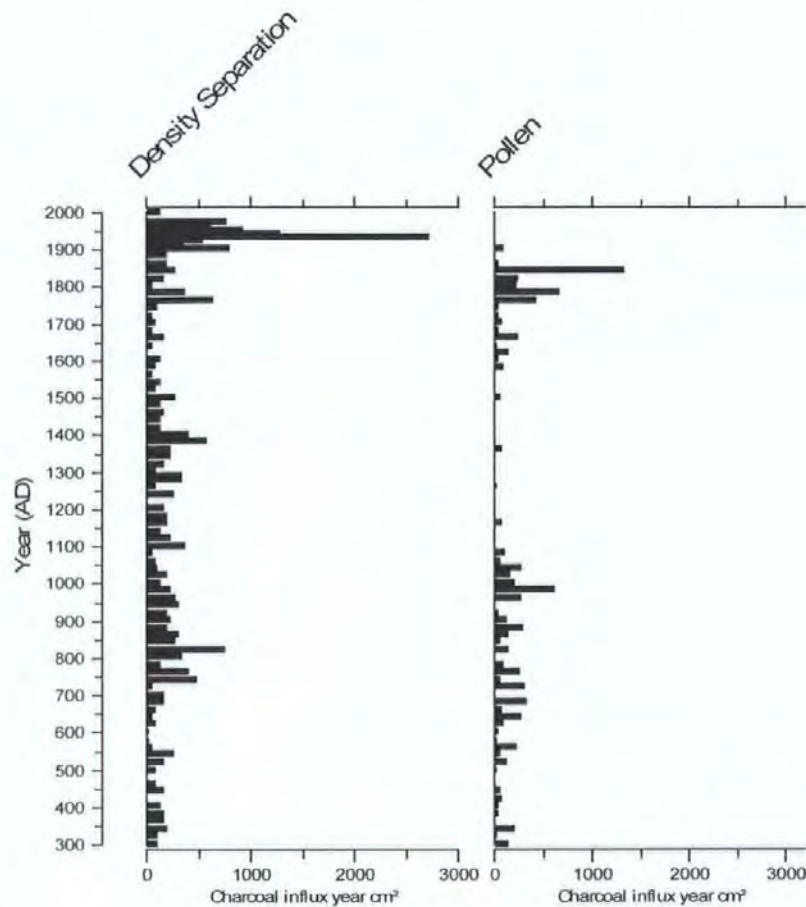
Figure 8.6: Charcoal influx reconstructions using pollen and density separation preparation procedures

(8.7) Climate, biomass, people and fire

As with Eski Acıgöl, Nar Gölü is located within a crater lake and therefore material deposited within the lake will have entered mainly though aeolian transport. Consequently the reconstructed fire history record will almost entirely represent a regional record of fire activity. This hypothesis is based on the assumed analogy between pollen and microscopic charcoal transport processes discussed in Chapter 2. The analysis of pollen grains trapped on moss samples taken from the Nar Gölü crater rim recorded the presence of *Pinus* sp. pollen despite recent vegetation surveys demonstrating the absence of *Pinus* sp. from Cappadocia (England, 2006; Woldring & Bottema, 2001). This indicates the long distance transport of pollen grains to the lake, notably from the Taurus and Pontic Mountains where *Pinus* sp. is common. This analogy is further supported by the correlation between charcoal and *Pinus* sp. in the CCA, as they may reflect similar source areas (Figure 8.5).

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Furthermore, no macroscopic charcoal particles were noted during the preparation of samples, indicating the absence of charcoal from within the immediate area and a consequently a local record of fire activity does not appear to have been recorded in this lake basin.

As evident in Figures 8.4 and 8.5 there is no direct relationship between fire occurrence and the $\delta^{18}O$ inferred climate. Whereas there is clear evidence of the impact of people on the landscape during the last two millennia. This is supported by the arrangement of the plant species associated with higher levels of anthropogenic activity on the opposite side of the CCA ordination plot to woodland taxa which are associated with reduced anthropogenic activity (Figure 8.5). Therefore this theoretical relationship identified between climate, biomass and fire occurrence (see Chapter 1) in this sequence has been altered due to human impact. This will be considered below through discussion of the changing land uses and management practices identified through the pollen analysis and their possible impact on the fire history of Nar Gölü.

Beyşehir Occupation Phase

Between 500 and 1,000 BC anthropogenic activity became widespread throughout the Eastern Mediterranean, as indicated by evidence from northwest Greece (e.g. Lakes Khimaditis and Vegoritis), Israel (Birkat Ram) and many sites in southwest Turkey (Bottema & Woldring, 1990; Eastwood *et al.,* 1998; 1999; Schwab *et al.,* 2004). In southwest Turkey anthropogenic activity was associated with the Beyşehir Occupation Phase, which is a clear phase of anthropogenic activity identified in numerous pollen records from lake and marsh sequences in the region (Beyşehir Golu, Gravgaz near Sagalassos, Gölhisar Gölü, Pınarbaşı and Söğüt Gölü) (Bottema & Woldring, 1986; 1990; Eastwood *et al.,* 1998; 1999; Vermoere *et al.,* 2000; Waelkens *et al.,* 1999a; 1999b). The Beyşehir Occupation Phase, so-called based on the lake record this occupation event was first identified from, Beyşehir Gölü, began ca.1,000 BC and lasted until around ca.670 AD (Bottema & Woldring, 1990). It marked the sudden appearance of anthropogenic activity in the pollen record of southwest Turkey. The beginning of the Nar Gölü sequence corresponds with the latter stages of the Beyşehir Occupation Phase.

The Beyşehir Occupation Phase was associated with the widespread clearance of primary woodland to make way for the cultivation of fruit trees, which included *C. sativa* and *J. regia*. The presence of these species has been attributed to anthropogenic activity as some

of these species have poor pollen dispersal capabilities and therefore their presence in the pollen record indicates a population above natural levels (Behre, 1981; 1990; Bottema & Woldring, 1990; Neef, 1990). There is also supporting archaeological evidence of the use of the cultivated trees (e.g. olive stones and presses have been found at Sagalassos) indicating their close association with people (Vermoere *et al.*, 2000; Waelkens *et al.*, 1999). Vermoere *et al.* (2000) speculated that the cultivation of fruit trees represented a well-organised society as it takes many of the tree species identified in the palynological record several years to produce a first harvest.

Alongside arboriculture, cereal cultivation and grazing were also taking place. *Avena/Triticum, Hordeum,* and *S. cereale* were all recorded in the pollen record from Nar Gölü, alongside high levels of Gramineae, which may include some cultivated grasses that cannot be distinguished palynologically (Figure 8.4). Ruderals and weedy plants species that often grow as a consequence of the disturbance associated with grazing and cultivation e.g. *P. lanceolata, Sanguisorba minor* and *Rumex acetosella* were also present throughout the Beyşehir Occupation Phase (Figure 8.4). Grazing animals would provide an extra food source and also aid in the maintenance of an open landscape, as it is likely that grazing would retard the re-expansion of unwanted tree species.

Throughout the Late Beyşehir Occupation Phase charcoal influx levels were low at Nar Gölü (Figure 8.4). Fires would be unwelcome within an economy dependant on arboriculture and cereal cultivation as they would threaten food resources. Grazing would also serve to reduce the fuel load and subsequently limit fire occurrence. This may explain the low r^2 values identified between cereals and charcoal influx. On the other hand, Bottema & Woldring (1990) have cited fire as being a potentially important tool to promote grazing at the time of the Beyşehir Occupation Phase; however, the nature of a fire event strongly determines the amount of charcoal that is produced, with smouldering ground fires producing less charcoal than larger conflagrations (Lynch *et al.*, 2004; Ohlson & Tryterud, 2000). Therefore, based on the regional source area of charcoal and pollen inputs to Nar Gölü smaller-scale fires may not have been recorded. It is possible that fire was used in the initial woodland clearance but the sequence does not currently extend back to the onset of the Beyşehir Occupation Phase. A combination of landscape management, limited fuel availability and the spatial resolution of the Nar Gölü basin may explain the low levels of charcoal influx during the Late Beyşehir Occupation Phase.

Abandonment

At around 670 AD the Beyşehir Occupation Phase came to an abrupt end throughout the region. Based on varve counting it has been estimated that within 14 varve years, agricultural indicators completely disappeared from the pollen record and there was an increase in arboreal pollen (England, 2006). Over the same time frame, there was also a gradual increase in charcoal influx (Figure 8.4). The sudden end to what has been speculated to represent a well organised and ordered society, indicates widespread societal collapse. Several theories have been proposed in an attempt to identify the factors that led to the demise of the Beyşehir Occupation Phase, these include:

   i.   *Climatic change*

   ii.   *Environmental pressures associated with the longevity of human activity*

   iii. *Earthquakes*

   iv. *Regional warfare & unrest*

The end of the Beyşehir Occupation Phase coincided with a period of political unrest and warfare throughout which Cappadocia was a frontier and vulnerable to attack. From 400 to 1077 AD the region was under Late Roman/Byzantine rule. From 600 AD the Empire was under constant attack by Arab forces from the southeast of Anatolia. Sustained attacks from the Arab forces led to destabilisation of the Empire and resulted in a 700 km retreat of the Roman/Byzantine frontier to Cappadocia (Whittow, 1996). Abandonment of these settlements and continued unrest resulted in an alternate way of life being adopted whereby sedentary agriculture ended and was replaced by smaller scale, subsistence farming and establishment of underground cities (Bottema & Woldring, 1990; England, 2006). Political unrest and abandonment of settlements was regionally widespread and has been traced in pollen records throughout the Eastern Mediterranean (Schwab *et al.,* 2004).

The end of intensive landscape management and the subsequent regeneration of secondary woodland saw a rise in charcoal influx to the site. This increase in charcoal influx is likely to be the consequence of both an increase in fuel availability, associated with regeneration of secondary woodland, and also an end to the possible fire management strategies practiced throughout the Beyşehir Occupation Phase which, for example, may have suppressed natural fire occurrence, as during the "abandonment" phase, higher levels of charcoal influx were recorded (Figure 8.4).

Pastoralism

Around 950 AD, after almost 300 years of political unrest, stability retuned to Cappadocia. This is followed by a period of woodland clearance as indicated by a fall in arboreal pollen (Figure 8.4). Fire was apparently not used to clear the woodland as no peaks in charcoal influx were recorded. This may indicate the importance of wood as a natural resource for use as a fuel or building material. Following the decline in woodland, there is evidence of the widespread cultivation of cereals (e.g. *S. cereale* and *Hordeum*) on the Anatolian Plateau.

Throughout this period there were several political shifts (Figure 8.4), however, unlike the Arab raids on the Roman/Byzantine Empire they did not have a long-lasting, negative effect on the population of Cappadocia. In 1071 AD the Selçucks fought the Byzantines; the Selçucks won the battle and expanded into Cappadocia (England, 2006). The Selçucks were primarily nomadic pastoralists, however, in Anatolia they adopted agricultural practices of the current inhabitants of Cappadocia which led to a further expansion of cereal cultivation. From 1450 AD the Ottoman State was established in Cappadocia (England, 2006). The Ottomans placed a further emphasis on cereal cultivation. Throughout this time the population of Cappadocia continued to increase and was exerting greater pressures on natural recourses. This resulted in the eventual collapse of cereal cultivation between 1600 and late 1700 AD (England, 2006). These political and social changes are evident in the pollen and charcoal records of Nar Gölü e.g. the decline of agriculture at ca.1600 to late 1700 AD results in a reduction in cereals in the pollen record and a fall in charcoal influx to the lake (Figure 8.4). Likewise, prior to the increase in cereals following the agricultural crisis, there is a peak in charcoal influx, supporting further the link between fire and anthropogenic activity in Cappadocia.

Recent fire history and vegetation change

The final zone identified by England (2006) began at 1830 AD and was associated with the intensification of agricultural activity (Figure 8.4). This zone was marked by an initial increase in cereal cultivation (particularly *S. cereale*) followed by the appearance of *Olea* sp. pollen from ca.1930 AD. Once again, the vegetation and fire history of Nar Gölü follow societal change on the Anatolian Plateau. The early 19th century is associated with a significant political shift as the Ottoman Empire collapsed and the Republic of Turkey was established in 1923 (England, 2006). The establishment of the Turkish Republic saw further expansion and intensification of agriculture. This manifested itself in Cappadocia

with the expansion of the cultivation of fruit trees and vines, as reflected by the increase in *Olea* sp. Maximum charcoal influx values to the lake were also recorded prior to this increase in fruit tree pollen. This suggests fire was used to clear vegetation to make way for the olive groves. Following the establishment of *Olea* sp. trees, charcoal influx rapidly falls. This may indicate management of the landscape to retard fire occurrence, limited fuel availability, or the presence of less flammable vegetation communities. The intensification of agriculture resulted in more land being given over to agriculture. Therefore it is possible that the availability of fuel to support fire events became increasingly limited therefore restricting (natural) fire occurrence further and explaining the reduction in charcoal influx to Nar Gölü toward the top of the sequence.

Patterns of charcoal influx into Nar Gölü throughout the 20th century can be compared to records of fire occurrence complied by the Turkish Meteorological Service from 1937 (IFFN, 1995; 1997). Since records began, there has been an overall increase in the number of fires recorded within Turkey yet the area burned each year has declined since the late 1950s (Figure 8.6). This may reflect a reduction in fuel availability or the success of fire management strategies, however, it does follow the overall trend of declining charcoal influx to Nar Gölü in recent times (Figure 8.4). However, this is not a direct comparison to fire occurrence on Cappadocia, as this data is likely to represent primarily fire occurrence in Mediterranean forest in south and west Turkey.
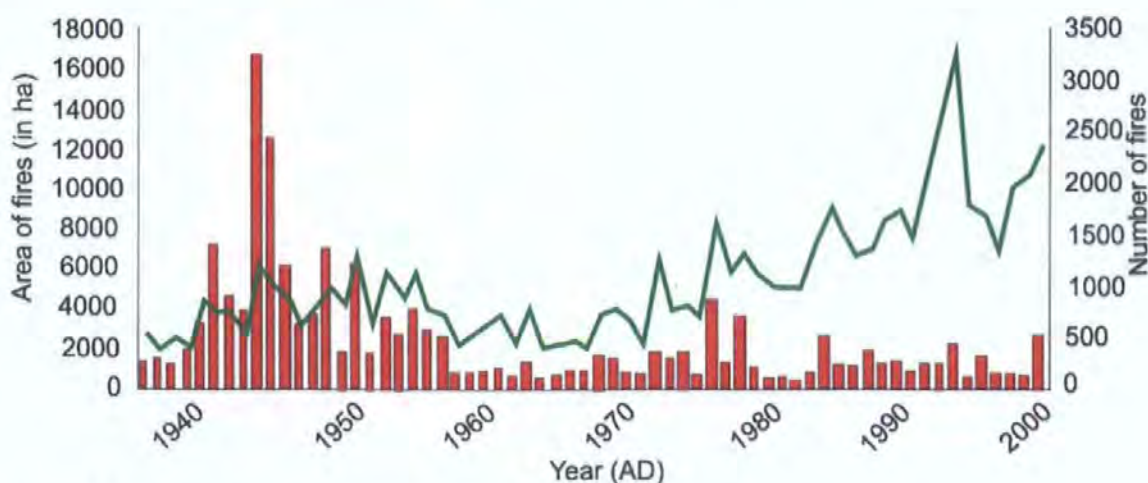
Figure 8.6: Number of fires in Turkey (Erkan, unpublished data)

Detailed records compiled on the cause of fires in the 1990s show that only 3% of fires can be attributed to natural causes (i.e. lightning) therefore people, through arson, negligence or accidents, are the main agents of fire occurrence within Turkey (IFFN, 1997). This adds

further weight to the link between biomass, people and fire occurrence throughout the Nar Gölü record.

(8.8) Summary

Discussion of the fire history record of Nar Gölü sequence in relation to the changing vegetation communities and the climatic record has demonstrated that people rather then climate were the main driving mechanisms underlying the fire history record here during the last two millennia. There is a close relationship between changing land use and charcoal influx values indicating the use of fire by people to manage the landscape. Finally comparison of charcoal influx values reconstructed using the pollen and density separation extraction procedure agrees with the findings presented in Chapter 3. This further demonstrates the suitability of the density separation procedure as a technique to extract microscopic charcoal particles from lake sediments.

Discussion & Conclusions

The overall aim of this research was to produce a fire history reconstruction for the Eastern Mediterranean region from the Late Glacial through to the present day. To achieve this, four specific objectives were identified. This chapter will present an overview of the research conducted to reach these objectives and ultimately reconstruct Eastern Mediterranean fire histories. Issues relating to the development of a robust sampling protocol and the influence of site type on the spatial resolution of fire history reconstruction will first be considered. Then a regional synthesis of fire activity from GS-2 to the Late Holocene will be presented. This synthesis will first discuss fire activity in the context of potential driving mechanisms and how they have changed through time, then compare the reconstruction of Eastern Mediterranean fire activity to published studies from a) a global syntheses of Holocene fire activity (e.g. Carcaillet *et al.*, 2002), b) fire activity in the Western Mediterranean and c) the Eastern Mediterranean region (Wick *et al.*, 2003; Yasuda *et al.*, 2000). Following this, the potential role of natural or anthropogenic fire activity in delaying woodland recolonisation to the region in the Early Holocene will be evaluated. Finally limitations to this research and future work will be considered.

(9.1) The development and application of a robust laboratory procedure and sampling protocol for the analysis of microscopic charcoal preserved in lake sediments.

Based on a thorough review of the published literature concerning microscopic charcoal analysis a comprehensive investigation into methods of microscopic charcoal extraction and analysis was deemed necessary, prior to reconstructing Eastern Mediterranean fire histories. Although such an investigation had been requested in the past (e.g. Tinner & Hu, 2003) only limited comparisons of extraction techniques (whereby only two techniques, usually the pollen preparation and one other) had been made (e.g. Carcaillet *et al.*, 2001). Therefore a systematic experimental investigation was conducted that tested five extraction techniques (three published and two new approaches based on the use of density separation) and three quantification techniques (see Chapter 3 for further details). The results of this investigation clearly demonstrated the effects of different extraction and quantification techniques on fire history reconstruction. This is largely due to the vulnerability of charcoal particles to fragmentation, meaning that mechanically and chemically stringent techniques would not produce a true representation of the charcoal

content of a sample being obtained. In terms of quantification techniques the total abundance measures gave a robust and rapid indication of the concentration of charcoal in samples, and as will be demonstrated in the next section, allow inferences regarding the spatial resolution of the fire history reconstruction to be made without the need for time consuming particle area measurements. For the analysis of local fire events, represented by larger charcoal particles, the Oregon Sieving Technique is the most effective extraction technique. However for regional fire events, this investigation identified the need for a two step extraction procedure, stage one to capture the larger meso/macroscopic charcoal particles and stage two the application of a heavy liquid separation to extract microscopic charcoal particles. Chemical and mechanical treatments were kept to a minimum. Due to the comprehensive nature of the investigation conducted in Chapter 3, this two-step extraction procedure should have wide potential applicability in fire history reconstruction.

Further assessment of the heavy liquid separation extraction procedure was possible as counts of microscopic charcoal had previously been made during the analysis of the pollen for the Akgöl and Nar Gölü sequences (see Chapter 6, Section 6.5.1.3 and Chapter 8, Section 8.6). In the experimental investigation the pollen preparation recorded microscopic charcoal counts that were significantly lower then those obtained from the density separation procedure (e.g. the mean number of charcoal particles quantified on pollen slides measured 55.7 vs. 687.7 on the density separation slides). However, the charcoal counts from pollen and density separation preparations samples from Akgöl and Nar Gölü demonstrate the difference in the counts were not as great (e.g. at Nar Gölü during the Beyşehir Occupation Phases the pollen preparation recorded a mean charcoal influx of 89.5 particles/year/cm^2 vs. 109.6 particles/year/cm^2 by the density separation; see also Tables 6.2 & 8.2). This may reflect differences in the biomass consumed during fire events as is evident in the Nar Gölü data. Broad agreement was evident between the two counts for the majority of the Nar Gölü reconstructions with the exception of the last 150 years of the sequence. The period from 1850 AD saw expansion of cereal agriculture, and a possible shift in the biomass burnt. It has been hypothesised that this may reflect the contrasting fragility of grass compared to wood charcoal which, due to the chemical and mechanical severity of this procedure, could be damaged during the preparation (see Chapter 9, Section 8.6). If this hypothesis were to be true, it could have wide-reaching implications for fire history reconstruction obtained from pollen slides. Pollen slide reconstructions may provide a better measure of charcoal produced by the burning of trees rather than fire events involving non-woody biomass.

A novel, high resolution sampling strategy was also devised and applied to the sites where a full core sequence was available (Akgöl, Eski Acıgöl and Nar Gölü). This strategy was based on the sampling scheme used in the analysis of tephra preserved in peat and lake sediments (e.g. Pilcher & Hall, 1992). Rather than spot samples being taken contiguous samples were removed from the core. The value of a high resolution sampling strategy was demonstrated by the replication experiment conducted on the 3 cm thick charcoal horizon preserved in the Akgöl sequences (AGL95A/B) (see Section 6.7).

Overall the methodological investigation and fire history reconstructions presented in this thesis have demonstrated the value of microscopic charcoal as a palaeoenvironmental proxy in its own right. Through the application of a new sampling protocol and extraction procedure robust interpretations of the fire histories of the lake sites analysed during this research have been produced. When interpreted alongside existing multi-proxy environmental data these reconstructions can be placed in the context of wider environmental changes.

(9.2) Examination of the influence of site type on fire history reconstruction, and in particular the detection of local and regional scale burning events

The fire history reconstructions presented in this thesis were obtained from a range of open and closed lake basins of varying size (see Tables 4.1 & 4.2 for further details). The basin type and size appears to have a clear influence on the spatial resolution of the fire history reconstruction that is produced. The mean and range of charcoal influx values have been compared from the study sites (excluding Çatalhöyük) over the different climatic episodes[1] to gain an insight into the effect of site type on the spatial resolution of the fire history reconstruction (see Tables 9.1a to 9.1d). These values can also be used as a measure of the effect of changing biomass and fuel availability on fire occurrence. Clearly, due to the problems associated with the dating of most of the sites presented in this thesis (with the exception of Nar Gölü and the laminated section of Eski Acıgöl), which in turn has an impact on the reliability of the influx values that have been calculated, these comparisons should be treated as tentative. Improved chronological control will be needed to test and refine the correlations proposed here. However, despite the obvious limitations associated

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[1] Unless otherwise stated the Early Holocene covers the time from 11,500 to 8,000 cal. years BP, the Mid Holocene covers 8,000 to 4,000 cal. years BP and the Late Holocene covers 4,000 cal. years BP to present.

with these data they are presented here as they demonstrate the possibility of using multi-site microscopic charcoal records to infer the source area of a fire history signal.

	Mean influx year/cm^2	Range	
		Lower	Upper
GI-1 without large peak	621.7	154.4	2312.9
GS-1	224.9	43.5	676.4
Early Holocene (up to 9,716 cal. years BP)	797.4	169.7	2775.1
Mid Holocene	445.2	88.0	888.5

Large charcoal peak at ca.13,000 cal. years BP: influx of 9517.7 particles year cm^2 recorded.

Table 9.1a: Charcoal influx to Akgöl – open, shallow marsh lake

	Mean influx year/cm^2	Range	
		Lower	Upper
GS-2	11.4	0	67.0
GI-1	186.5	10	449.0
GS-1	22.0	0	112.0
Early Holocene	254.0	23.8	821.9
Early Holocene to 9,200 cal. years BP*	319.7	23.8	821.9
Mid Holocene	237.6	0	1109.6
Late Holocene	167.9	0	636.0

* The full timescale of the Early Holocene in Akgöl and Lake Hula is not represented therefore to make the Early Holocene charcoal influx comparable at these sites the mean and upper/lower influx ranges are presented for the same timeframe as covered by Akgöl and Lake Hula.

Table 9.1b: Charcoal influx to Eski Acıgöl – closed, crater lake

	Mean influx year/cm^2	Range	
		Lower	Upper
Late Holocene	259.9	0	2725.5
Late Holocene – prior to 1850 AD	190.2	0	762.9
Late Holocene – 1850 to present	688.5	0	2725.2

* Charcoal influx to Nar Gölü increases dramatically in the 20th century, and due to the potential impacts of this on the measures of the range and mean influx, these values are also presented excluding the 20th century.

Table 9.1c: Charcoal influx to Nar Gölü – closed, crater lake

	Mean influx year/cm^2	Range	
		Lower	Upper
GI-1 *	1240.0	982.4	1497.0
GS-1	524.0	85.4	1076.0
Early Holocene (up to 9,200 cal. years BP)	960.0	118.6	3439.8
Mid Holocene	506.4	18.1	1271.2
Late Holocene	300.2	62.7	725.4

*GI-1 is only represented by two samples therefore they must be interpreted with caution.

Table 9.1d: Charcoal influx to Lake Hula – open, marsh lake

The Eski Acıgöl and Nar Gölü sequences were both obtained from crater lakes (now drained and extant) >400 metres in diameter. These sediments were deposited in closed basins with no perennial surface in or outflows, therefore the majority of the charcoal deposited in these lakes will have entered via aeolian transport mechanisms. Although charcoal influx to these lakes is lower than at other sites, the influx values of Eski Acıgöl and Nar Gölü show clear variations through time and therefore these records are likely to provide a robust indication of regional fire activity (Table 9.1c & 9.1d). Also closed basins will experience complete retention of the charcoal entering the lake compared to open basins as charcoal particles could be potentially lost through outflows from the lake. Likewise very large influx values may represent local scale fire events, notably the events recorded in Akgöl (e.g. the large fire peak at ca.13,000 cal. years BP), as these events are consistent with local scale burning events of either natural or anthropogenic origin that

overwhelm the regional signal. Transport of charcoal within a lake catchment will be associated with the open basins and may result in either inputs of secondary charcoal or remobilisation of charcoal which is ultimately incorporated within the stratigraphic record of fire events. This is exemplified by comparing charcoal influx values for Akgöl and Lake Hula to the values for Eski Acıgöl and Nar Gölü e.g. during GI-1 mean charcoal influx to Akgöl is ca.60% greater than that entering Eski Acıgöl (Table 9.1a, 9.1c and 9.1e). Based on the contrasting levels of charcoal influx and how they have changed through time it has been possible to infer the spatial resolution of the lake sites for the duration of their records (Table 9.2).

	Akgöl	Eski Acıgöl	Nar Gölü	Lake Hula
Late Holocene	-	Regional	Regional	Extra-local/regional
Mid Holocene	Extra-local/regional	Regional	-	Extra-local/regional
Early Holocene	Extra-local/regional	Regional	-	Extra-local/regional
GS-1	Extra-local/regional	Regional	-	Extra-local/regional
GI-1	Local/extra-local and regional	Regional	-	Extra-local/regional
GS-2	-	Regional	-	-

Table 9.2: Inferred spatial resolution of the fire history records preserved in the study sites

Based on the charcoal source area theory presented in Chapter 2, it seems most likely that the lower charcoal influx values recorded by the crater lakes and the absence of meso or macroscopic charcoal particles in the sediments, the crater lake sites provide a regional fire history reconstruction. The open basins (Akgöl and Lake Hula) probably provide extra local to regional fire history reconstructions, based on the amount of charcoal quantified in relation to the crater lakes and also the presence of mesoscopic particles in the sediments provide an extra-local to regional fire history reconstructions. Although numerous researchers have previously used microscopic charcoal to either reconstruct local scale fire events or infer the spatial resolution of fire history reconstruction (e.g. Asselin & Payette,

2005; Innes *et al.*, 2004; Pitkänen, 2000), microscopic charcoal is still widely interpretated as representing primarily a regional or background level of fire activity (e.g. Carcaillet *et al.*, 2001; Clark, 1988a; 1988b; Clark & Patterson, 1997; MacDonald *et al.*, 1991; Tinner *et al.*, 1998; Whitlock and Anderson, 2004). It is also generally argued that to infer accurately the spatial resolution of a fire history record, meso or macroscopic charcoal particles should be analysed and particle area measured (Clark, 1988a; Whitlock and Anderson, 2004). However, where results are available from multiple sites within a region, differences in the charcoal records may be used to speculate a source area of charcoal. As has been demonstrated by comparing and contrasting the level of charcoal influx into the lake basins analysed in this thesis. Therefore highlighting the potential use of microscopic charcoal to infer the spatial resolutions of a fire history records, echoing the findings of Asselin & Payette (2005), Innes *et al,* (2004) and Pitkänen (2000).

(9.3) A reconstruction of Eastern Mediterranean fire activity from GS-2 to the present day based on microscopic charcoal records from a range of different site types

In Chapter 1 (section 1.4) it was proposed that under natural circumstances climate, through the influence it exerts on biomass availability, has an overriding control on fire activity (this Figure is presented again in Figure 9.1). It was also stated that people alter this relationship through their manipulation and management of vegetation communities. In this model therefore, under natural and anthropogenic conditions, biomass should play a central role in fire occurrence as it represents the fuel matter that is available to burn (Figure 9.1).
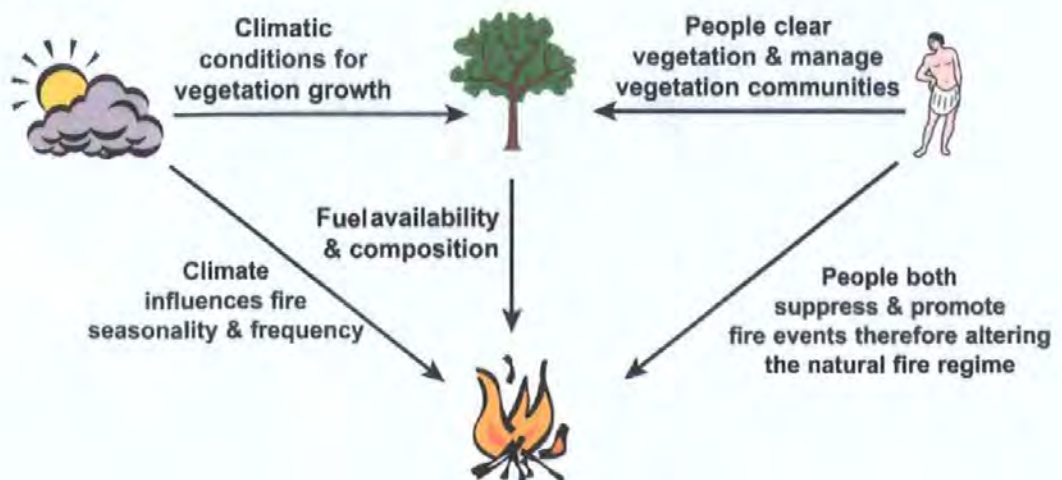
Figure 9.1: The relationship between climate, biomass availability, people and fire occurrence

The applicability of this model, and the inferred role of climate and people in driving fire activity through biomass availability will be assessed by comparisons of changing charcoal influx with measures of climatic changes and anthropogenic activity in the Eastern Mediterranean region. By using multi-proxy data to infer these natural and anthropogenic controls it may be possible to gain an understanding of how regional fire activity in the Eastern Mediterranean has changed since GS-2. A summary of the timescales of the archaeological and climatic records used to infer the changing driving mechanisms underlying regional fire activity is presented in Figure 9.2 and an overview of regional fire activity, including the published records of Wick *et al.* (2003) and Yasuda *et al.* (2000) are presented in Figure 9.3. To assess the effects of changing biomass (due to natural and anthropogenic factors) the mean and inter-quartile charcoal influx values derived from this investigation are presented in Figure 9.4 alongside information concerning the nature of the vegetation community associated with each climatic episode, in order to assess the effects of changing biomass availability on charcoal influx. Throughout this thesis (Chapters 5 to 8) climatic changes have been inferred from $\delta^{18}O$ records. Identifying changes in fire activity that are driven by climate will be achieved by identifying shifts in fire activity which follow the isotope-derived climatic signal. Shifts in fire history records that could be attributed to human influence on fire activity may be identified by shifts in fire activity that are "out of phase" with the climatic signal and are associated with evidence of human impact on the environment. This approach has been previously used by Carcaillet (1998) and Clark & Royall (1995) to trace potential human impacts on fire activity. Identifying a proxy for human activity is less straightforward. In the Eastern Mediterranean, despite there being abundant archaeological evidence of human impacts on the landscape, there is little unambiguous evidence for human manipulation of vegetation communities until ca.4,000 years BP when widespread woodland clearance began (Bottema & Woldring, 1990; Eastwood *et al.*, 1998; Roberts *et al.*, 1997). Therefore a combination of archaeological (particularly during the time of the GS-2: Holocene transition) and palynological evidence will be used to infer anthropogenic impacts on regional fire activity.
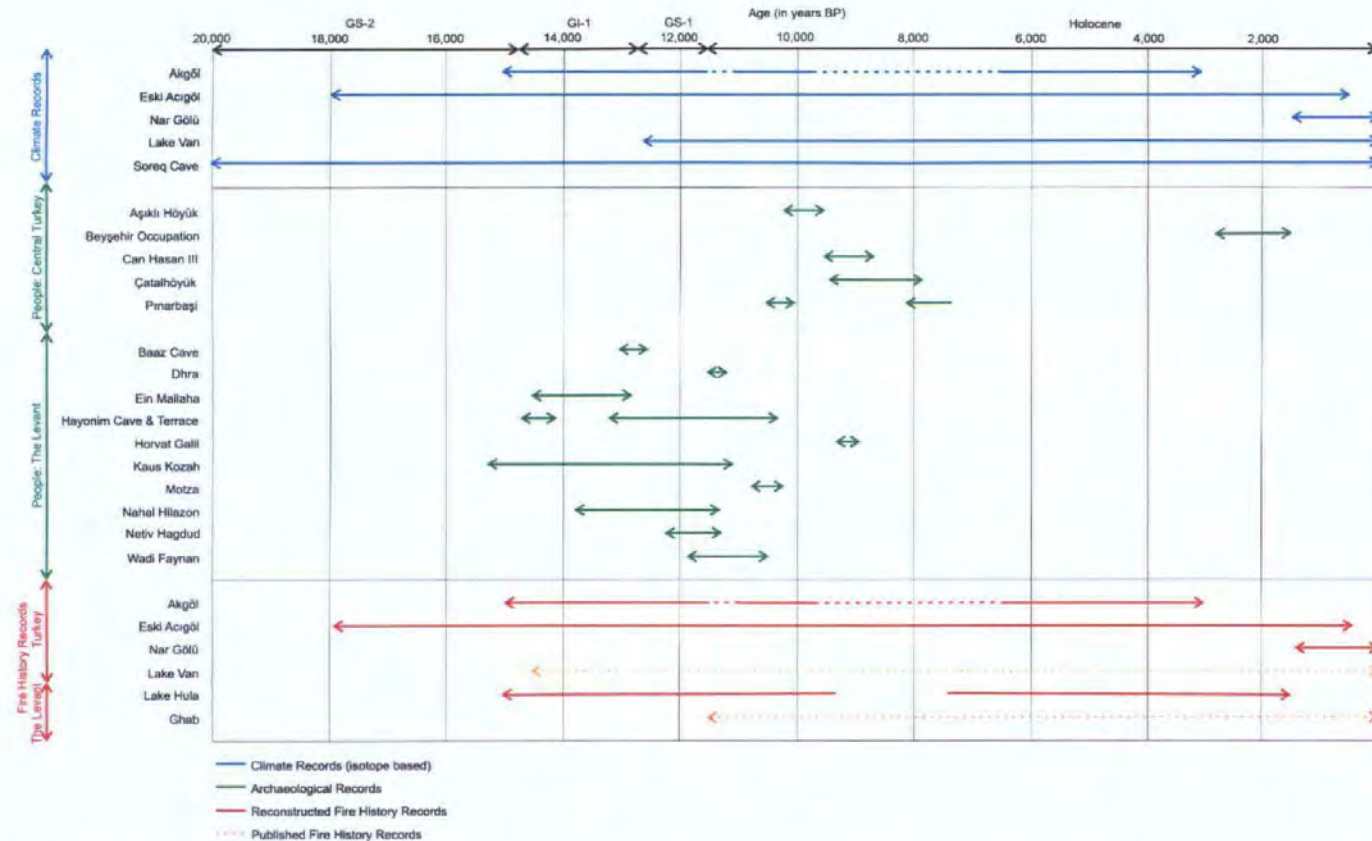
Figure 9.2: Time line of the climatic and archaeological records used to infer the driving mechanisms underlying Eastern Mediterranean fire activity (sources: Bar-Matthews *et al.*, 1997; Bar-Yosef, 1998; E. Jenkins pers. comm.; Leng *et al.*, 1999; Roberts *et al.*, 2001; Wick *et al.*, 2003; Yasuda *et al.*, 2000). NB This diagram represents only a brief overview of PPNA/B sites in the Levant, there are many more that are not shown on this diagram see Bar-Yosef (1998) for more details.
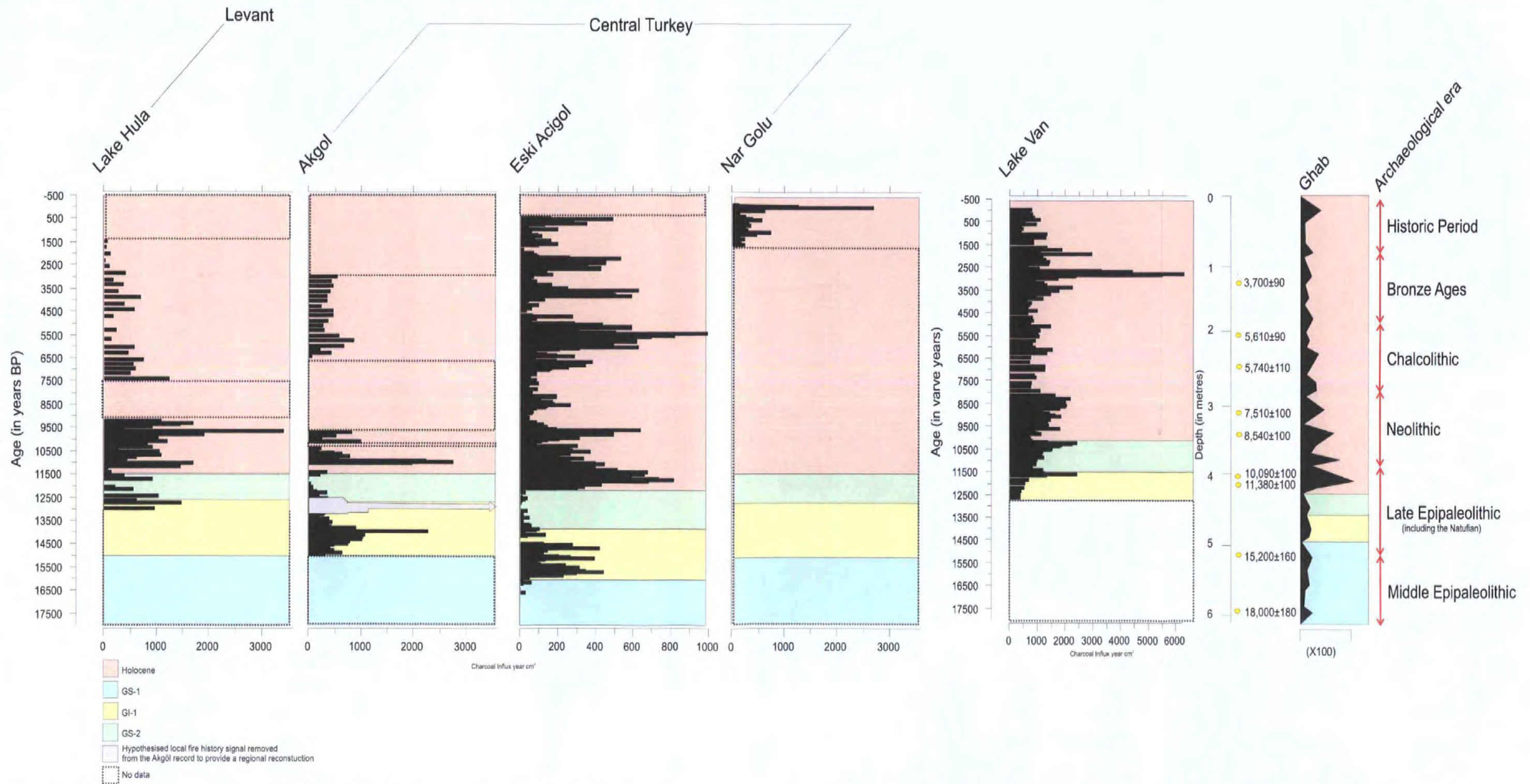
Figure 9.3: Reconstruction of Eastern Mediterranean fire history. Includes the published fire history reconstructions of Yasuda *et al.* (2000) & Wick *et al.*, (2003). The radiocarbon dates and depth scale relate to the Ghab sequence only and the placement of the climatic episodes for the Ghab sequence is approximate. The scale for the Eski Acıgöl diagram is different to that used for the rest of the study sites analysed in this thesis.
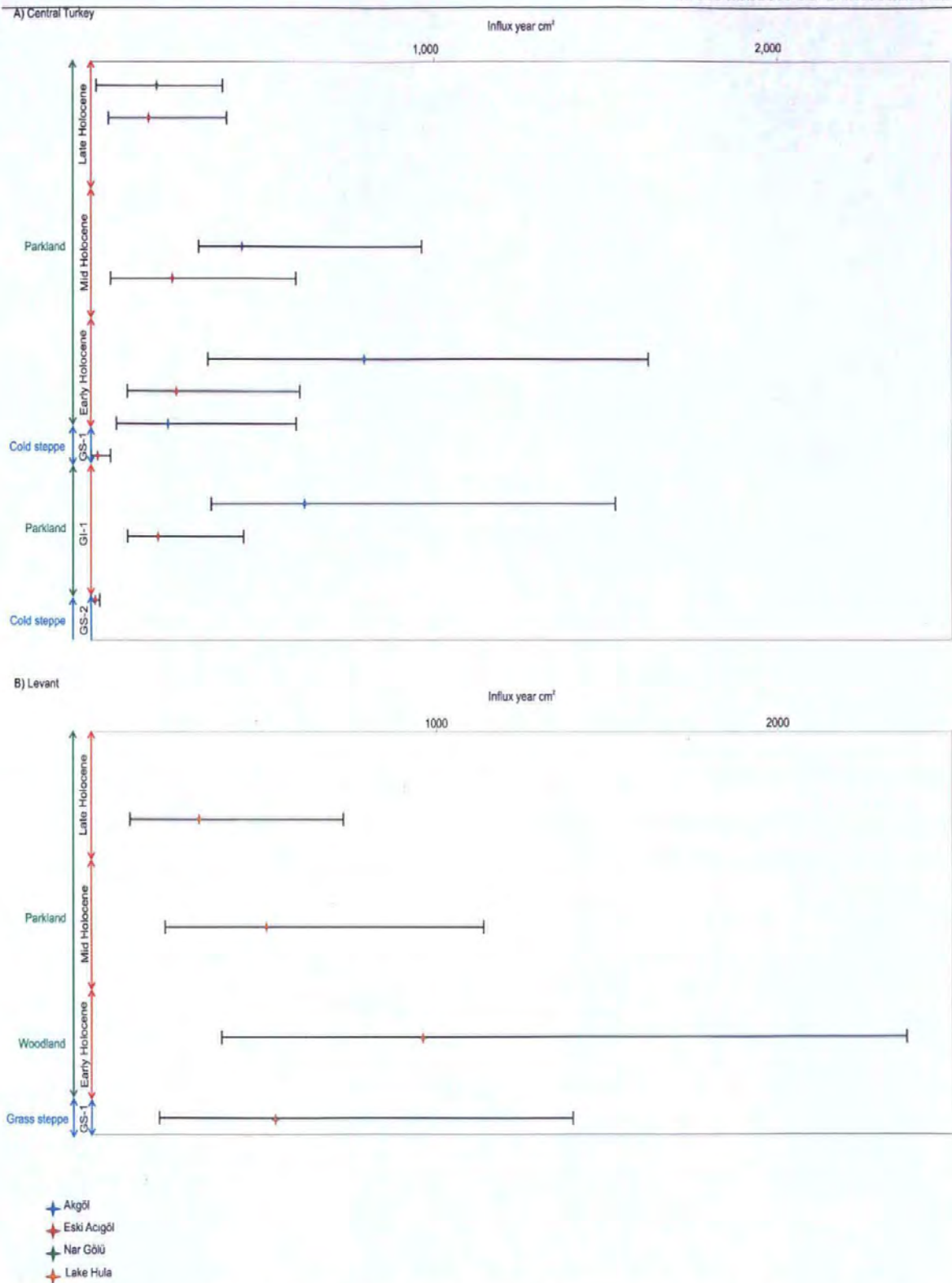
Figure 9.4: Changing charcoal influx & biomass from GS-2 to the Late Holocene in the Eastern Mediterranean. The diagrams show mean and inter-quartile influx values

Greenland Stadial-2

Of the sequences analysed, only Eski Acıgöl definitely extends back to the GS-2 and therefore inferences concerning regional fire activity at this stage are restricted to Central

Turkey. Existing palaeoclimatic evidence from the Eastern Mediterranean demonstrates the prevalence of a cold, arid climate and vegetation communities characterised by cold steppe (*Artemisia* sp. and Chenopodiaceae) with sparse tree cover restricted to areas of glacial refugia (Robinson *et al.,* 2006; van Zeist & Bottema, 1991). The harsh climate and restricted vegetation cover meant there was limited biomass available to burn and therefore limited fire occurrence (Table 9.1c; Figures 9.3 and 9.4). Based on the low biomass availability and the absence of archaeological evidence of people in Central Anatolia, climate is likely to have controlled regional fire activity.

Greenland Interstadial 1

Climatic warming associated with the termination of the GS-2 saw the partial replacement of cold steppe with grass-steppe in Central Turkey (e.g. Figures 7.4 & 8.6) and the expansion of open, oak-parkland in the Levant (Figure 6.7). Climatic changes led to an increase in grasses, fuel availability which supported fire occurrence throughout the region. The Levantine open-oak-parkland contained an understory vegetation of annual and perennial grasses which included cereals (van Zeist & Bottema, 1991; Zohary & Hopf, 2001). The change in the availability of wild resources has been hypothesised to represent the catalyst that led to a cultural shift (see also Section 1.3) from mobile bands of hunter-gatherers to the establishment of larger, sedentary settlements (Bar-Yosef, 1989; 1998; Bar-Yosef & Goren, 1973; Henry *et al.,* 1981) (Figure 9.2). It has been speculated that fire was an integral part of this new mode of life, as has been supported by limited archaeological evidence from southwest Turkey and Northern Iraq (Emery-Barbier & Thiébault, 2005; Naveh & Carmel, 2003; Solecki, 1963). However, the role of fire in this new way of life has been contested, due to fire having potentially deleterious effects on some wild grasses (Blumler, 1991; Byrd, 2005; Hillman, 1996). Instead fire may have been used to maintain open grasslands to prevent the encroachment of trees and to promote the growth of vegetation for grazers (Emery-Barbier & Thiébault, 2005). Although there is evidence of anthropogenic activity in southwest Turkey, the focus of this new mode of life was the Levant. However, the Lake Hula sequence probably only covers the tail end of GI-1, and it is unknown as to whether or not people were exerting an influence on fire activity. In Central Turkey there is still clear evidence of simultaneous changes in climate, biomass and fire occurrence, which in the absence of archaeological evidence of people supports the continued role of climate as the driving mechanism underlying regional fire activity.

Greenland Stadial 1

The reversion to quasi-glacial conditions at this time had a significant impact on regional fire activity (Figure 9.3). In Central Turkey fire occurrence declined soon after the onset of GS-1. This indicates the speed with which cold steppe replaced the grass steppe and the subsequent impact of the vegetation shifts on fire occurrence, which is emphasised by the fall in charcoal influx to Akgöl and Eski Acıgöl (Figure 9.3 and 9.4; Tables 9.1a and 9.1c). It implies the continuing, overriding impact of climate on fire activity in this region. In Northern Israel where climate modelling has shown climatic cooling to have been less severe than in Central Turkey, there was a less marked decline in fire occurrence throughout this period (compare the influx rates for Akgöl, Eski Acıgöl and Lake Hula Tables 9.1a, 9.1c and 9.1e) (Jones *et al.,* in review). The climatic deterioration associated with GS-1 appears to have had an impact on human activity in the Eastern Mediterranean. In the Levant there was wide scale abandonment of the sedentary settlements established during GI-1 and a return to small, highly mobile bands of hunter-gatherers (see Section 1.3 for a detailed explanation) (Harris, 1998; Hillman *et al.,* 2001). However, in some areas it has been hypothesised that the climatic deterioration and reduction in wild resources acted as a stimulus for the onset of the cereal cultivation (see Section 1.3; Hillman *et al.,* 2001). The abandonment of sedentary settlements may have led to a reduction in human induced fire activity in the southern Levant. Equally, the re-expansion of steppic herbs and reduction in biomass availability (see Table 9.1e and Figure 9.4) would have also reduced fuel availability and therefore natural fire occurrence. In Central Turkey climate underlay the decline in regional fire activity whereas in the southern Levant climatic and anthropogenic factors may have both exerted an impact.

Early Holocene

The rapid climatic ameriolation associated with increasing temperatures and precipitation at the onset Holocene was quickly followed by the replacement of cold steppe with open Gramineae-dominated parkland in Central Turkey and the return of oak-parklands to the Levant (Figure 9.4) (van Zeist & Bottema, 1991). There was also an associated rapid increase in fire occurrence throughout the region (Figure 9.3). Enhanced moisture availability is likely to have promoted vegetation growth resulting in ample fuel being available, reflected by the increase in fire occurrence for approximately the first 1,000 years of the Holocene (Tables 9.1a, 9.c, 9.d and 9.e; Figure 9.4). Similar relationships have been identified within the North American Prairies and the Boreal forests of Alaska whereby positive links have been identified between precipitation, vegetation productivity

and fire occurrence (Camill *et al.*, 2003; Lynch *et al.*, 2004). The close association between climatic warming and the regional increase in fire activity which substantiated by evidence from North America highlights climate as the overriding control on fire activity. This is further supported by the lack of archaeological evidence of human activity in Central Turkey during the opening millennium of the Holocene. The earliest evidence of human activity in Central Turkey does not appear until after this initial Early Holocene burning phase ended and is associated with the seasonally used rockshelter, Pınarbaşı, occupied between 10,300 to 10,000 years BP and Aşıklı Höyük, a hunter-gatherer settlement used between 10,000 and 9,500 years BP (Asouti, 2003; Esin, 1991; Todd, 1980; Figure 9.2). These settlements were based on the use of wild plant and animal resources available in the wider environment. Analysis of botanical remains from Pınarbaşı has suggested that people exerted limited pressure on local resources and therefore it is likely that they exerted a modest impact on regional fire activity (Asouti, 2003).

In the southern Levant there is archaeological evidence for the reappearance of sedentary hunter-gatherer settlements as well as the development of larger, food producing villages that were widely distributed throughout the region (e.g. in the Jordan Valley, the Damascus Basin, and along the shores of the Euphrates and Tigris Rivers) (Bar-Yosef, 1998; Byrd, 2005). It has been hypothesised that the cultivation practices developed during GS-1 continued for several thousand years alongside traditional practices before being widely adopted and spreading out from the Levant into Anatolia and beyond (Bar-Yosef, 1998). The coinciding changes in climate and human activity in the Early Holocene makes accurate determination of the overriding controls on fire activity impossible. However, the increase in fire activity detected in Central Turkey is also recorded here, therefore it may be possible, particularly in the very Early Holocene that whilst people are still adapting to the climatic warming, that fire is controlled to a greater extent by natural rather then anthropogenic factors (Figure 9.3).

Unlike the GS-2:Holocene transition whereby clear links are evident between climate, biomass and fire, the gradual spread of cultivation and people throughout the Eastern Mediterranean meant that people also began to have a greater impact on regional fire activity. Asouti & Hather (2001) hypothesised for the Early Holocene that although it was likely that the immediate environment around settlements such as Can Hasan III and Çatalhöyük (Central Turkey) was intensively used, it is possible that people would not

exert a detectable impact on the regional vegetation community. Therefore whilst manipulation of the vegetation community would have clearly influenced fuel availability at the local scale, and may have influenced natural fire occurrence at these sites, at the regional scale it is unknown as to whether or not anthropogenic impact was exerting a control on fire activity. Therefore the controls on fire activity at this time and throughout the Mid Holocene cannot be identified with confidence.

Mid Holocene

The Mid Holocene is associated with the onset of regional climatic aridification. This resulted in a shift from a regime of water surplus to water deficit (Roberts *et al.,* 2001). Clearly this would have exerted a significant impact on the vegetation community with the replacement of mesic species with more drought-tolerant species. Following this shift in the climatic regime the cyclic oscillations evident in Eski Acıgöl become more pronounced, which would be consistent with a climatic control on fire activity (Figure 9.3). However, in Central Turkey and the southern Levant there is also widespread evidence of the intensification of anthropogenic activity (Figure 9.2). In the Levant this is associated with the onset of olive cultivation which resulted in widespread land clearance (e.g. Lake Kinneret, the Dead Sea, Birket Ram) (Baruch, 1986; 1990; Liphschitz *et al.,* 1991; Neef, 1990; Schwab *et al.,* 2004). In Central Turkey the intensification of cultivation and grazing practices may have exacerbated the effects of climatic aridification on the vegetation community and potentially reduced fuel availability (Figure 9.4). Similar trends toward anthropogenic activity aggravating the effects of climatic changes have been identified from research conducted in the Western Mediterranean (e.g. Carrión & Dupré, 1996; Jalut *et al.,* 2000; Magri, 1996). Therefore in the Mid Holocene climatic and anthropogenic factors were both exerting an impact on Eastern Mediterranean fire activity, and it is impossible to state which had the greatest influence.

Late Holocene

The Late Holocene was characterised by the further intensification of anthropogenic impacts on the landscape. There is evidence in lake sediments from ca.4,000 years BP of the emergence of complex societies in southwest Turkey (e.g. Beyşehir Gölü, Gravgaz near Sagalassos, Gölhisar Gölü, Nar Gölü, Pınarbaşı and Söğüt Gölü) (Bottema & Woldring, 1986; 1990; Eastwood *et al.,* 1998; 1999; Roberts, 1990; Vermoere *et al.,* 2000; Waelkens *et al.,* 1999a; see Section 8.6 for a detailed review). The intensification of human activity was marked by widespread woodland clearance, a marked shift in the

vegetation community, and a change in landscape management practices as people began to exert an overriding control on the ecosystem. This had a clear impact on fire activity as is evident in the Nar Gölü sequence, with periods of intensive landscape management experiencing limited fire occurrence compared to periods of reduced activity (see Section 8.6). In the Levant, further intensification of anthropogenic activity occurred. From ca.3,000 years BP there was another phase of extensive woodland clearance associated with the increased demand for wood for fuel (due to increased metal production) and for construction (Schwab *et al.*, 2004). Sustained clearance and management of the landscape in Northern Israel is reflected by the continued reduction in charcoal flux rates (Table 9.1d; Figure 9.4). Therefore in the Late Holocene there is clear evidence of changes in fire activity relating primarily to people rather than climate.

Over the last 18,000 years the driving mechanisms controlling Eastern Mediterranean fire activity have not remained static. From GS-2 through to the Early Holocene climate exerted the greatest influence on regional fire occurrence which is likely to reflect the influence of climate on fuel availability (Figure 9.5). In the Mid Holocene when people were beginning to exert a greater impact on the Eastern Mediterranean landscape identifying the role of climate vs. people is less straightforward. It is likely that climatic factors and anthropogenic activity were both exerting an impact on regional fire activity; yet identifying which exerted the greatest control might not be possible. From the Late Holocene onward, people rather than climate appears to have exerted the overriding control on regional fire activity (Figure 9.5).

Relationship between climate, biomass, people & fire during the GS-2:
Early Holocene transition
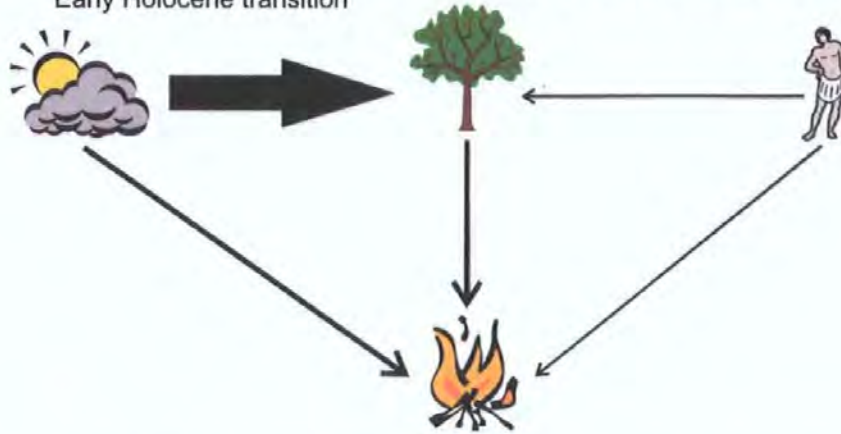
Relationship between climate, biomass, people & fire in the Late Holocene
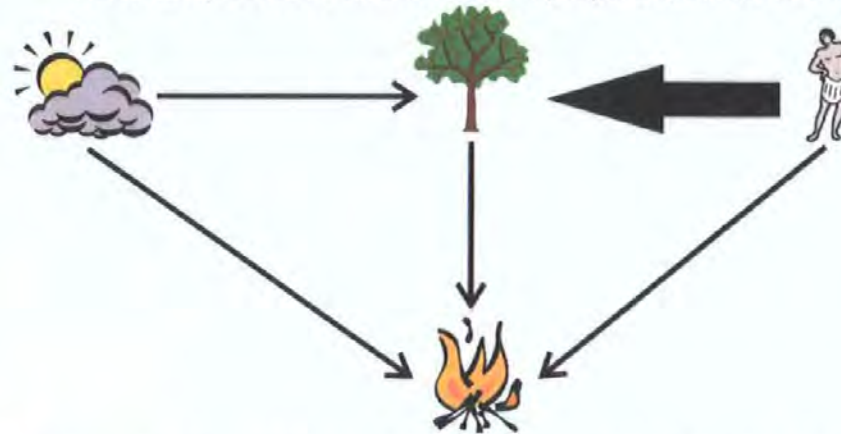
Figure 9.5: Summary of the changing driving mechanisms influencing Eastern
Mediterranean fire history over the last 18,000 years

Comparisons with published fire history reconstructions

Comparisons can be made with fire history reconstructions made at the global, continental
and regional scale to assess how the changes in fire activity identified in the Eastern
Mediterranean relate to existing knowledge of fire histories since the end of the GS-2.
Based on Carcaillet *et al's.* (2002) global synthesis of Holocene fire activity, depending on
the region, it was concluded that with the exception of the north-east of North America, the
first half of the Holocene was characterised by low-levels of biomass burning which
increased in the Mid Holocene, whereas the Late Holocene was characterised by
significant biomass burning (Carcaillet *et al.*, 2002). These changes in biomass burning
have been related to climatic changes and anthropogenic activity. The global trend of
increased biomass burning shows a different pattern to that evident in the regional fire
history reconstructions presented in this thesis. However, Carcaillet *et al.* (2002) did note
the lack of fire history records from the Mediterranean in general; therefore it is unlikely
that a true representation of Mediterranean fire activity was presented in this synthesis.

Evidence from fire history studies conducted in the Western Mediterranean region demonstrates similarities to the fire history reconstructions presented in this thesis. In contrast to Carcaillet *et al.* (2002), but in agreement with this research, fire history reconstructions produced from the Western Mediterranean show the occurrence of fire in the Early Holocene (Carrión & van Geel, 1999; Carrión, 2002; Pantaléon-Cano *et al.*, 2003). In the Western Mediterranean the Early Holocene vegetation was characterised by pine forests and grassland scrub which readily promoted fire (Carrión, 2002). The Mid Holocene saw expansion of broadleaved, deciduous woodland which is hypothesised to have developed in response to the shift to colder winters and an increase in moisture availability during the growing season (Jalut *et al.*, 2000; Carrión, 2002; Carrión *et al.*, 2001). The vegetation shift in response to climate resulted in a reduction in the availability of flammable fuel and therefore a decline in fire occurrence. As discussed a decline in fire activity was recorded following the peak in Early Holocene fire activity which may be linked to either changes in the vegetation community relating to the expansion of woodland, or as the Holocene progressed, climatic induced vegetation shifts or anthropogenic activity. Unlike the Eastern Mediterranean, but in agreement with Carcaillet *et al's* (2002) synthesis, the Late Holocene in the Western Mediterranean was associated with a significant increase in fire activity (Carrión *et al.*, 2001; Carrión, 2002; Carrion & van Geel, 1999). This increase in fire activity has been primarily associated with the demise of deciduous woodland and expansion of xerophytic, sclerophyll vegetation communities due to the spread of what is now classed as a typical Mediterranean climate throughout the area (Carrión *et al.*, 2001; Carrión, 2002; Jalut *et al.*, 2000). The presence of a summer drought and the increased availability of flammable fuel led to an increase in fire occurrence. In the Western Mediterranean the arrival of human activity was later than in the Eastern Mediterranean (Carrión & van Geel, 1999; Jalut *et al.*, 2000).

Two fire history reconstructions have previously been conducted in the Eastern Mediterranean, these are from the Ghab Valley (in Syria) and Lake Van (in Turkey) (Figure 9.3; Wick *et al.*, 2003; Yasuda *et al.*, 2000). These reconstructions were produced through the analysis of microscopic charcoal on pollen slides. This method of microscopic charcoal analysis has been demonstrated to considerably underestimate the amount of charcoal present in a sample compared to the heavy liquid separation (see Chapter 3). There are also chronological problems associated with the dating of these sites which may further hinder the comparison. The current chronology of the Ghab is based on a series of

^{14}C dates on mollusc shells (Yasuda *et al.*, 2000). It is highly likely, based on the chronological issues presented in this thesis regarding the dating of lake sediments, that these dates contain a hard water or old carbon affect, despite this being disregarded by Yasuda *et al.* (2000). Therefore it is likely that the current chronology may over predict the age of the sediments, as was the case for Lake Hula. Likewise, in Lake Van there is evidence of ca.1,100 missing varves resulting in the GS-1:Holocene transition being placed at 10,460 varve years BP rather then the globally accepted 11,500 years BP.

The methodological differences between the fire history reconstructions and chronological problems clearly limit the extent to which these records can be compared. However, general changes are evident in the record from the Ghab which follow the regional reconstruction presented in this thesis. The Ghab fire history reconstruction records generally low levels of charcoal throughout the GS-2: Holocene transition. As in the records present in this thesis, the onset of the Holocene is associated with a rapid increase in charcoal entering the Ghab (Figure 9.3). Again elevated charcoal concentrations persist for the first few thousand years of the Holocene then begin to gradually decline toward the Late Holocene.

The comparison between Lake Van and the records presented in this thesis does not show the same level of agreement. This disagreement may be related to the size and source area of Lake Van. Lake Van is the largest salt lake in the world with a depth of 458 m and surface area of 3,570 km^2 (Wick *et al.*, 2003). Based on charcoal transport theory, Lake Van may receive charcoal particles from a regional to continental, or event global source area (Clark, 1988a). Therefore changes in fire activity that are occurring within the Eastern Mediterranean region may not be accurately represented in Lake Van due to the source area of charcoal inputs. This may result in a contrasting fire history reconstruction that does not follow closely the regional signal reconstructed in this thesis. For example, during GS-1 charcoal influx into Lake Van does not decline as sharply as in the rest of the Eastern Mediterranean. Likewise, charcoal influx does increase in the Early Holocene but not as significantly as in the records presented in this thesis (Figure 9.3). Whilst the Early Holocene has been widely acknowledged as being a time of optimum climatic conditions (i.e. increased humidity) Wick *et al.* (2003) hypothesised that this increase in fire occurrence reflected climatic aridity. However, climatic aridity is not clearly visible in the δ^{18}O record (see Wick *et al.*, 2003). Likewise, during the Mid Holocene (6,000 to 4,000 varve years BP), when charcoal influx to Lake Van declines Wick *et al.* (2003) concluded

that this was due to regional climatic optima which resulted in an increase in moisture availability and favoured the expansion of woodland. However, elsewhere in the Eastern Mediterranean region the Mid Holocene is associated with a shift to increasingly arid conditions (Bar-Matthews *et al.*, 1997; Roberts *et al.*, 2001). It may be possible that, as has been speculated for the Eski Acıgöl sequence (see Section 7.5), the gradual expansion of mesic woodland and *Quercus* sp. and the subsequent shift in the dynamics of the vegetation community and fuel load, led to a fall in fire occurrence. Lake Van also experienced the delay in woodland recolonisation recorded in Central Turkey, therefore it is possible that similar vegetation changes were exerting an impact in the vicinity of Lake Van, particularly as biomass availability has been demonstrated to be exerting a considerable control on fire activity (see Figure 9.4). Finally in the Late Holocene charcoal influx to Lake Van increases, indeed ca. 2,700 varve years BP the largest charcoal peak of the whole sequence was recorded (Figure 9.3). This large peak in charcoal influx was not commented upon by Wick *et al.* (2003); however they do link the overall increase in fire occurrence to the shift toward arid conditions.

Overall the reconstructions presented in this thesis identified a reduction in fire activity toward the Late Holocene as human manipulation of the vegetation communities influenced fuel availability and fire occurrence. There is limited evidence of human activity in the vicinity of Lake Van until ca.600 years ago and therefore there is a clear contrast in the overriding controls on fire activity on these records in the Late Holocene explaining the discrepancies between the two records at this time.

(9.4) An evaluation of the role of natural and anthropogenic fire activity in the delayed woodland recolonisation of parts of South West Asia during the Early Holocene

Based on the evidence obtained from the fire history reconstructions, existing multi-proxy and archaeological evidence, people appear to have exerted a limited impact on regional fire activity during the GS-2: Holocene transition at least in Central Anatolia. Discussion of the driving mechanisms controlling regional fire activity has identified climate, through the influence it exerted on biomass availability, as an overriding control on fire occurrence at this time. This is due to near synchronous changes in climate, vegetation and fire occurrence observed (Figures 7.5 & 9.3).

Likewise, the importance of fire to hunter-gatherer/early agro-pastoralist communities has been questioned (see above: Blumler, 1991; Byrd, 2005; Hillman, 1996). Whilst Lewis (1972) and Naveh & Carmel (2003) cited fire as representing an essential tool to these communities that allowed them to manipulate and manage wild resources, Hillman (1996) and Byrd (2005) cited the negative effects of fire on some wild cereals. Even if fire was used by these communities, palynological and archaeological evidence has shown the limited impact of people on the landscape of Central Turkey at this time (Asouti, 2003; Asouti & Hather 2001; Bottema & Woldring, 1986). The apparently limited impact of hunter-gatherer/early agro-pastoralist communities demonstrates the ability of the environment to buffer the effects of low level anthropogenic activities; a critical threshold still had to be crossed whereby people, rather than environmental factors, exert the overriding control on the landscape. It is only once this threshold has been crossed that there is clear evidence of people within palaeoenvironmental records, as exemplified by the widespread evidence from southwest Turkey of the Beyşehir Occupation Phase (Bottema & Woldring, 1990; Eastwood *et al.,* 1998; 1999). The limited evidence of human impacts on the environment during the Early Holocene echoes Messerli *et al's* (2000) discussion of the relationship between people and nature. Messerli *et al.* (2000) viewed the Early Holocene as being a time of "nature dominated environmental changes" which was characterised by people's vulnerability to environmental changes and their processes of adaptation, mitigation and migration in response to the prevailing environmental conditions.

It is also possible that natural fire occurrence was serving to retard the expansion of woodland in the Eastern Mediterranean region. Throughout Central and Eastern Anatolia the Early Holocene was characterised by grass parkland resulting in a readily available supply of flammable fuel that would have supported low intensity ground fires and quickly regenerated following fire events. As discussed in Chapter 7 (Section 7.5) the expansion of trees into grassland shifts the dynamics of the ecosystem (Clark *et al.,* 2001). Young trees in particular can have a considerable impact on the productivity of vegetation communities (Grove & Rackham, 2001). Young trees consume significant amounts of water which can have a negative impact on surrounding vegetation, especially in areas such as the Eastern Mediterranean which are characterised by a deficit in water supplies. Therefore the expansion of trees can result in a decline in the productivity of grasslands, a reduction in fuel availability and the incidence of fires (Clark *et al.,* 2001). In Eski Acıgöl and Lake Van periods of reduced charcoal influx during the Mid Holocene correspond to

the expansion of mesic woodland in Eski Acıgöl and increasing abundance of *Quercus* sp. in Lake Van (see Figure 7.5; Wick *et al.*, 2003). Under a regime whereby ground fires regularly occur, both fire and competition with grasses may serve to retard the establishment or expansion of trees. Consequently, to allow trees to establish and spread within Anatolia, a shift in the dynamics of the vegetation community would have needed to occur that reduced the fuel load and therefore the frequency and intensity of fire events. Similar patterns have been identified through the study of the interactions of grassland and woodland boundaries in the Northern Plains of North America. The replacement of grasses with woody plants and trees in northwestern Minnesota resulted in a fall in fire activity due to the reduction in the fine fuel load which supported regular ground fires (Clark *et al.*,2001). Such a shift may relate to a shift in the climatic regime i.e. changing humidity, which in the case of Cappadocia could be linked to a reduction in the length or severity of summer droughts that were necessary to dry the vegetation and increase its flammability. In Cappadocia this would have favoured the expansion of mesic woodland.

However, caution is also attached to the role natural and anthropogenic factors play in retarding the spread of woodland. It may not, due to a variety of reasons, be possible to answer this question fully with the fire history reconstructions presented here. Of the four records only the Eski Acıgöl sequence provides an (almost) complete fire history reconstruction for the GS-2: Holocene transition. As discussed, the onset of the Holocene was associated with a short hiatus in sedimentation in the Akgöl sequence and, due to the limited amount of material available and the gaps in the core sequence, only a low resolution fire history reconstruction was possible for the Lake Hula sequence. Also, there is a large distance between these sites, therefore whilst a comprehensive understanding of fire activity has been obtained for Central Turkey only one fire history record was produced for the Levant. As demonstrated, the cultural, climatic and vegetation histories of these two areas of the Eastern Mediterranean vary. Therefore to gain a thorough understanding of regional fire activity ideally sites are needed to "fill in" the gaps between these two areas, particularly to enhance existing understanding relating the postglacial woodland recolonisation, as whilst a delay was evident in Central Turkey, trees persisted throughout GS-1 in the Levant.

Another factor that may have affected the rate of woodland recolonisation in the region is changing atmospheric carbon dioxide concentration [CO_2] during the Last Glacial-Early Holocene transition (Bennett & Willis, 2000). CO_2 is essential for plant growth as it

represents one of the two materials necessary for photosynthesis to take place, the other being water (Bennett & Willis, 2000; Cowling & Sykes, 1999). The availability of atmospheric CO_2 is known to have varied over geological timescale, yet despite this palaeoclimatic reconstructions based on pollen records typically assume that plant-climate interactions have remained constant through time (Cowling & Sykes, 1999; Polley, 1997). Recent research has demonstrated that variations in atmospheric $[CO_2]$ exert a direct control not only on plant growth, but also on the composition of vegetation communities (e.g. Bond & Midgley, 2000; Bond et al., 2003; Cowling, 1999; Cowling & Sykes, 1999). Lowered atmospheric $[CO_2]$ results in increased photorespiration reducing the efficiency of CO_2 uptake by C_3 plants (Cowling & Sykes, 1999). Therefore during periods of reduced atmospheric $[CO_2]$ the rate of C_3 plant growth declines, which may result in a community increasingly dominated by C_4 plants (Cowling & Sykes, 1999). Under conditions of reduced $[CO_2]$ woody plants, such as tree saplings, have slower growth rates, retarding their postburn recovery after fires (Bond et al., 2003). Such slow sapling recovery rates during periods of low $[CO_2]$ may favour the spread of fire-tolerant grasses, and the maintenance of relatively open conditions, since samplings are more likely to remain trapped in the 'topkill' zone of wildfires (Bond & Midgley, 2000).

During the Last Glacial Maximum atmospheric $[CO_2]$ measured 200 $\mu mol \ mol^{-1}$ (Smith et al., 1997). The Holocene saw an increase in atmospheric $[CO_2]$ to ca.280 $\mu mol \ mol^{-1}$ at a rate of approximately 11 $\mu mol \ mol^{-1}/1,000$ years, shifts which are likely to have had significant impacts on growth rates in C_3 plants (Anklin et al., 1997; Sage, 1995). Therefore it is possible that the initially low levels of atmospheric $[CO_2]$ contributed to the observed delay in postglacial woodland recolonisation in the Eastern Mediterranean region. This as yet untested hypothesis clearly warrants further exploration, especially as the palaeoclimatic evidence has demonstrated that regional rainfall regimes were apparently suitable for woodland regeneration (Roberts, 2002). Likewise the potential role of people in retarding woodland recolonisation in Central Turkey has not been supported by the current study. Therefore reduced atmospheric $[CO_2]$ in the early postglacial, the effects of which may or may not have been exacerbated by natural fires, may have contributed to the delayed postglacial woodland recolonisation in the Eastern Mediterranean.

(9.5) Limitations

As with any research problems arose during the course of this work which affected the methods that were applied, the results that were obtained and the ultimate interpretation of the data. These will be briefly reviewed and approaches taken to overcome them.

Availability of sample material

The benefits of applying a contiguous sampling regime have been advocated throughout this thesis; however this was not always possible due to the limited availability of material associated with Çatalhöyük and Lake Hula sequence. This was due to these sequences already having been heavily sampled for previous multi-proxy analysis. Therefore samples were taken at the highest resolution possible and caution was taken not to over interpret the data when interpretations were made.

Dating

Problems associated with the dating of sediments from the Eastern Mediterranean region are widely acknowledged (e.g. Bottema & van Zeist, 1991; Byrd, 2005; Cappers *et al.,* 1998; 2002; Meadows, 2005). Many core sequences from the Eastern Mediterranean are clay rich and therefore there can be a lack of sufficient organic matter to date to provide a robust chronology. Likewise many of the organic matter samples dated contain "old carbon" due to the incorporation of carbon originating from older sediments into tissues resulting in localised reservoir effects which need correcting (Cappers *et al.,* 1998). These problems were experienced in the analysis of the core sequences used in this research.

With the exception of the Çatalhöyük sequence all the lake sediment records contained an old carbon effect which resulted in ^{14}C dates being overestimated (Jones, 2004; Meadows, 2005; Roberts *et al.,* 1999; 2001). In the Nar Gölü sequence this was not a problem as a robust varve chronology was also available. The detailed chronologies for the Eski Acıgöl and Lake Hula sequences still need resolving but unfortunately this was not possible during the course of this research.

^{14}C dates conducted on the Eski Acıgöl sequence contained an age offset of between 3,000 and 5,000 years due to the presence of old carbon within the system and volcanic degassing (Roberts *et al.,* 2001; Woldring & Bottema, 2001). U-Th dates were also obtained but these contained large standard errors.

The problems surrounding the chronology of Lake Hula have already been discussed in detail (see Section 4.2.2.1). The revision of Meadows (2005) was used to analyse the charcoal influx data. Whilst Meadows does provide a convincing argument for the correction applied to ten of the originally ^{14}C dates presented by Baruch & Bottema (1991; 1999) the chronology of this site is still debated.

The charcoal concentration data were converted to charcoal influx to gauge how charcoal influx varied throughout time. Clearly the chronological issues surrounding most of the sequences limit the validity of these calculations (and the spectral analysis applied to the Eski Acıgöl data). In an attempt to overcome this, general trends in charcoal influx were discussed rather then placing an emphasis on specific peaks. Clearly, if improvements are made to the chronologies of any of these sites prior to publication these will be considered and where appropriate applied.

(9.6) Future work

One of the aims of this research was to understand whether or not early agro-pastoralists delayed woodland recolonisation through their use of fire. Although the evidence presented in this thesis points to human-induced fire not playing the dominant role in delayed woodland recolonisation, the analysis of further sites is necessary to support this conclusion further. By reconstructing the fire history of sites located between Central Turkey and the Levant it may be possible to gain a full understanding of the postglacial spread of woodland. Ideally a multi-proxy approach should be taken whereby climatic and vegetational data are also analysed to allow the subsequent fire history reconstruction to be placed into the context of changes occurring within the wider environment. One possible approach is to re-analyse sites where multi-proxy reconstructions have already been produced where charcoal was either not analysed or analysed on pollen slides.

In Chapters 6 and 8 differences were identified between the fire history reconstructions produced by the analysis of microscopic charcoal extracted using a pollen preparation to that extracted using heavy liquid separation. It was hypothesised that this was due to a change in the plant matter that was been regularly burnt, which in turn may produce charcoal particles that were more fragile and therefore exhibit greater vulnerability to fragmentation during preparation, i.e. wood charcoal vs. grass charcoal. By conducting a series of experiments where different plant matter (e.g. wood and barley) are burnt and then put through pollen and heavy liquid separation preparations it may be possible to test

this hypothesis. This experiment would also offer the opportunity to test the use of morphological measurements of charcoal particles (length: width ratio) to infer vegetation type. Umbanhowar & McGrath (1998) identified clear morphological differences between the length: width ratio of microscopic charcoal particles produced under controlled conditions from grass, leaves and wood. It would have been useful in this research to apply such measurements to infer the source of the charcoal analysed and enhance understanding of the vegetation community. However, due to concerns surrounding the possible effects of particle fragmentation during preparation this was not conducted. By measuring the particle length and width on charcoal from a known fuel source the diagnostic potential of these measurements, once charcoal has been extracted from lake sediments, could be assessed. The results of this work could have implications for the interpretation of fire history reconstructions produced using different extraction techniques and allow wider application of the work of Umbanhowar & McGrath (1998).

(9.7) Summary & conclusions

This research has successfully used microscopic charcoal analysis to produce a robust reconstruction of Eastern Mediterranean fire activity from GS-2 through to the Late Holocene. This reconstruction has suggested that the factors controlling regional fire activity have changed throughout this time. Biomass appears to be the key factor controlling fire occurrence as this represents the fuel consumed during fire events. Biomass availability is in turn controlled by climate factors from GS-2 through to the Early Holocene and anthropogenic activity in the Late Holocene. There is clear archaeological evidence of the presence of people in the Levant and along coastal areas of Turkey over this timeframe; therefore in these regions it is possible that people may have, along with climatic factors, exerted an impact on regional fire activity. However, despite thorough archaeological surveys been conducted on the Anatolian Plateau these surveys have failed to show the presence of any pre-Holocene occupation of this area until the time of Aşıklı höyük and Pınarbaşı (see Figure 9.4). This may reflect the absence of people in this region, yet it may also reflect the limited impact of people on the environment at this time, as the palaeoenvironmental record indicates that the environment appears to be responding primarily to natural factors e.g. climatic and vegetation changes. However, in the lack of any reliable evidence of people in Central Turkey over the GS-2: Holocene transition means that people were not actively retarding the spread woodland in the early post glacial in favour of the naturally available wild resources that supported the expansion of people throughout South West Asia at this time. However, it is has being speculated that natural

fire activity may have served to maintain the open-grass parklands and retarded the establishment of woodland in the area.

Evidence has also been identified of links between climatic changes in the North Atlantic which are recorded in Eastern Mediterranean fire activity. It has been speculated that these links reflect the 1,470 year periodicity identified by Bond *et al.* (1997; 2001) in the North Atlantic climate change associated with cooling events and potentially the solar forcing of climate.

This research has demonstrated the importance of microscopic charcoal as a palaeoenvironmental proxy in its own right. The thorough investigation of charcoal extraction and analysis techniques resulted in new methods of microscopic charcoal extraction using heavy liquid separation and a novel, high resolution sampling regime being applied to the study sites analysed in this thesis.

In addition the results of the investigation into Eastern Mediterranean fire history highlighted the potential of inferring the spatial resolution of the fire history signals using microscopic charcoal. Commonly such inferences are limited to the analysis of meso/macroscopic particles.

Finally this work has advocated the value of a multi-proxy approach to the interpretation of fire history data. Through the comparison of the charcoal data to available $\delta^{18}O$, pollen and phytolith data robust interpretations of the data have been made which have considerably enhanced existing understanding of Eastern Mediterranean fire history.

A critical assessment and experimental comparison of microscopic charcoal extraction methods

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Abstract

Microscopic charcoal analysis has been used to reconstruct past fire activity over a range of spatial and temporal scales in Europe, the Americas and Australasia. Despite this, no uniform method of microscopic charcoal analysis has been adopted. This paper presents the results from a systematic experimental investigation into a range of charcoal extraction and quantification techniques. Existing techniques including a standard pollen preparation and the Oregon Sieving Technique were rigorously tested on a series of "control" lake sediments that contained a known added weight of charcoal. Two further techniques were developed during the course of this investigation that used heavy liquid to extract charcoal from lake sediments. Particles were quantified using the Point Count Method, total abundances and size measurements. The results suggest the need for a two-stage procedure, the first stage removing the more fragile meso and macroscopic particles and the second stage utilising heavy liquid separation to extract microscopic charcoal. The separation of different sized particles reflects their contrasting vulnerability to fragmentation during processing. Heavy liquid separation extracted the highest quantity of charcoal from the sediments. The quantification techniques highlighted the spatial resolution required by the study to be considered when deciding the quantification procedure. Total abundance counts are more suited to the analysis of microscopic charcoal, whereas area measurements are better suited to the analysis of meco and macroscopic charcoal particles.

Introduction

A major issue in microscopic charcoal analysis is the lack of a universally accepted method of charcoal extraction and quantification (Patterson *et al.*, 1987; Rhodes, 1998). Unlike other palaeoenvironmental proxies e.g. pollen or testate amoebae, no specific and widely agreed extraction procedure have been developed or adopted. Micro-charcoal is often counted by palynologists interested primarily in vegetation change rather then fire activity.

Charcoal analysts have realised the constraints on analysing charcoal on pollen slide, due to the fragility of charcoal and the mechanical and physical severity of this procedure (Whitlock & Larsen, 2001). Yet, despite other extraction techniques having been developed e.g. thin section analysis and Oregon Sieving Technique, pollen preparation remains the most frequently used extraction procedure. Furthermore, the lack of universal agreement on charcoal extraction procedures means that a range of techniques (alongside the pollen preparation) are now applied to the extraction of microscopic charcoal. Each of these techniques varies in the size range of particles analysed and the chemical and mechanical stress particles experience during processing. As a consequence, fire history records can be produced that may not be directly comparable. To date, a thorough investigation into charcoal extracting procedures has been called for but not conducted (Carcaillet, *et al.*, 2001; Tinner & Hu, 2003). This paper presents an investigation based on controlled laboratory experiments conducted using published extraction techniques, and test a new method of charcoal extraction based on density separation. Issues of charcoal identification and quantification are also addressed.

Charcoal extraction

Three commonly used extraction procedures have been selected from the published literature to test the effects of preparation procedures on the fire history that is reconstructed. The methods selected are a standard pollen preparation (Moore *et al.*, 1991), bleaching and filtering (Rhodes, 1998) and the Oregon Sieving Technique (Millspaugh & Whitlock, 1995). Other methods of charcoal analysis are available e.g. thin section analysis, but they are not investigated as they are not directly commensurable and therefore not amenable to comparison under controlled laboratory experimental conditions.

Pollen preparation

The extraction and quantification of microscopic charcoal on pollen slides is widely used as it allows pollen and charcoal to be obtained simultaneously with no extra sample preparation. However, this technique does have several limitations. The pollen preparation procedure focuses on particles between 10 µm and 180 µm. Particles larger the 180 µm are removed by sieving in the early stages of the processing. This creates a size bias toward the smaller size fractions and therefore over-represents extra local and regional source areas of charcoal inputs. The pollen preparation procedure is also chemically and mechanically rigorous which can result in fragmentation of charcoal particles (Clark, 1984). This increases the abundance of smaller size fractions resulting in an

overestimation of the total charcoal concentration and further shifting the size bias (Clark, 1984; Saramaja-Korjonen, 1991).

Oregon Sieving Technique

Millspaugh & Whitlock (1995) developed this technique to extract charcoal from lake sediments. A sample is disaggregated and then washed through a series of nested sieves. This gentle extraction technique limits potential sources of damage that can fragment charcoal particles. Likewise the emphasis on larger charcoal particles means that the background component has been removed and therefore a reconstruction of localised fire activity is produced.

Bleaching & Filtering

Rhodes (1996; 1998) developed this technique of charcoal extraction based on the bleaching and filtering of lake sediments. It aimed to provide a cheap, quick and gentle method of charcoal extraction minimising physical and chemical stress. This methods has no upper size limit and therefore no size bias, hence it produces a record of fire activity spanning a range of spatial scales. This technique is also gentle and so limits the amount of mechanical damage.

Quantification procedures

Similar to the extraction procedures, several quantification techniques exist which convey different information concerning past fire activity.

Absolute abundance

This measure involves all charcoal particles, regardless of their size, being quantified (Patterson *et al.*, 1987). This assumes that all particles contribute an equal level of information to the fire history record.

Point count

Charcoal abidance is recorded based on the number of "hits" particles scored on a standard number of points on an eyepiece graticule (Clark, 1982). Particles presenting the field of view, but which do not "hit" a point are ignored. Again this assumes that all particles contribute an equal level of information to the fire history record.

Particle area

This measurement can be used to infer transport distance of particles. Particle measurements e.g. longest axis or area can be taken using an eye-piece graticule or using image analysis techniques, and then particles can be placed in predetermined size classes. Area measurements allow greater emphasis to be placed on the importance of larger vs. smaller particles due to their contrasting transport potential (Batterson & Cawker, 1983). However, these measures are strongly influenced by the extraction procedure used. Mechanically and chemically rigorous techniques, e.g. pollen preparations, potentially alter the size distribution of particles (Clark, 1984). This may result in the misrepresentation of the charcoal record particularly if the analysis primary interest is to reconstruct the spatial scale of past fire events.

Charcoal identification

Correct identification of charcoal is a problem associated with the optical analysis of microscopic charcoal. Although charcoal is described by many analysts as been jet black, angular and opaque, (Clark, 1984; Clark, 1988b, Patterson *et al.*, 1987; Swain, 1973; 1978; Tinner & Hu, 2003), the actual identification of charcoal is subjective depending strongly on the experience of the analyst. Accurate identification of charcoal can be difficult for several reasons. There are many particles present in lake sediments that can resemble charcoal e.g. pyrite, dark plant fragments and insect cuticles (Clark, 1984. Partial combustion also hinders identification problems; it results in a spectrum of particles presents that span from charcoal to unburnt. Therefore to ensure accuracy in charcoal identification diagnostic criteria were applied to each particles, namely 1) jet black, (Figure 1a, 1b and 1c), 2) angular, straight edges (Figures 1a and 1b), 3) straight but fuzzy edges (Figure 1c), 4) blue hue (Figure 1a and 1c) and 5) the presence of cellular structure (Figure 1b) and represented the most commonly observed characteristics (Figure 1). Particles that included a combination of these characteristics were classified as charcoal. All other particles were ignored.

Figure 1: Diagnostic characteristics of charcoal
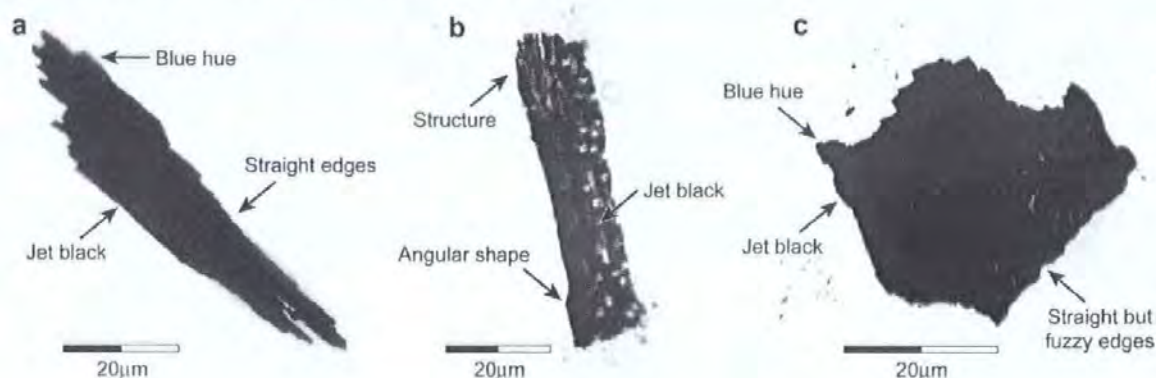
Sample material

Fossil samples contain an unknown quantity of charcoal, and therefore the record of charcoal produced could reflect either the processing techniques or the abundance of charcoal in the sample. Therefore, for this investigation artificial lake sediments were produced. The control samples were comprised of a known volume of modern charcoal combined with sterile lake sediments. The charcoal used in the control samples has been manufactured from a mixture of hardwoods, using traditional methods, by the Forest of Dean Museum Heritage Trust, UK. The charcoal was sieved through a series of nested sieves (mesh sizes: 250 µm, 125 µm, 63 µm, 50, µm and 25 µm) for five minutes using a Wretsch Vibro sieve shaker. These size classes were selected to be representative of the charcoal particles preserved in lake sediments that had extra-local to regional source area. Each sample contained 0.7 g of sterile lake sediment. The sediments used were Late Pleistocene lake marls from the Konya Basin, Turkey, taken from near the archaeological site of Çatalhöyük. These sediments had previously been sieved to <250 µm and cleaned by P Boyer during preparation for particle size analysis. To each sample 0.1 g of 50 to 63 µm and the 25 to 50 µm size fractions were added along with 0.5 g of the 125 to 250 µm and 63 to 125 µm size fractions. Each preparation technique was thoroughly tested using ten replicate samples.

Extraction procedures

Pollen preparation

Pollen extraction followed the standard protocol of Moore *et al.* (1991).

1) 30ml of 10% Hydrochloric acid was added to the sample to dissolve the carbonates.

2) Potassium hydroxide digestion to remove humic acids and disaggregate organics

3) Fine sieving through a 10 µm mesh.

4) Acetylation

5) The sample was stained with safranin and then 2 ml of molten glycerol jelly added. 20 µl of the mixed sample was placed on a slide.

6) The slide was then analysed at 400x magnification.

Bleaching & Filtering

1) 0.2 g of sediment was placed in 20 ml of distilled water and left for 24 hours to rehydrate.

2) 20 ml of 6% Hydrogen Peroxide was added then the sample was placed in an oven at 50°C for 48 hours.

3) The sample was then filtered through Whatman Number 1 filter paper to remove fine particles.

4) The filtrate was washed into a glass evaporating dish using a minimal amount of distilled water, and then placed in an oven at 50°C to evaporate the excess water.

5) The beaching stage was repeated.

6) The sample was then washed into 30 ml tubes and 2ml of glycerol added.

7) 100 µl of glycerol was placed on a glass slide to which 10 µl of the processed sample added and mixed. A cover slip was placed on the sample and sealed with clear nail varnish.

8) The sample was then analysed at 200x magnification.

Oregon Sieving Ttechnique

1) 1 cm^3 of sediment was placed in a 60 ml solution of 10% Sodium Hexametaphophate and left for three days to disaggregate.

2) The samples were then gently washed through a series of nested sieves (mesh size: 63, 125 and 250µm) with distilled water.

3) Each size fraction was then washed into a 30 ml plastic tube of ml of glycerol added.

4) A 100 µl sub-sample was taken and placed on a glass slide, and a cover slip placed on top. The cover slip was then sealed with clear nail varnish.

5) The samples was then analysed at 100x magnification.

Density Separation

The use of heavy liquid separation to extract charcoal was first suggested by Clark (1984) but to date this technique remains undeveloped. Therefore heavy liquid separation was tested as an alternative method of charcoal extraction. Heavy liquid uses Lithium Hereopolytungstate (LST) with a known specific gravity. LST is used in pollen analysis with a specific gravity of 2.2 (Vandergoes & Prior, 2003). Particles e.g. mineral matter, with a specific gravity greater then that of the LST sink and can be discarded. Particles with a lower specific gravity, e.g. pollen and charcoal, float on the surface of the liquid. The actual specific gravity of charcoal varies depending whether the particles are saturated or dry e.g. the specific gravity of dry particles is 0.3 to 0.6 (Renfrew, 1973). It is hypothesised that saturated particles have a similar specific gravity as pollen grains. Therefore using the same specific gravity as used for the pollen preparation would be suitable for charcoal. This was tested by applying a range of specific gravities (from 1.1 to 2.6) on artificial samples. The experiment showed that a specific gravity in excess of 2.2 was suitable. LST with a specific gravity of 2.2 was used in this procedure.

1) 10 ml of 10% Hydrochloric acid was added to 1 cm^3 of sediment to remove the carbonates and disaggregate the sample.

2) The sample was the washed through a 250 μm mesh with distilled water.

3) 10 ml of LST was added to the sample and then it was centrifuged at 2000 rpm for 10 minutes. The samples were then decanted into beakers. 200 ml of distilled water was added and the samples were then left to settle. Once settled the water was removed with a disposable pipette. This stage was repeated twice.

4) The sample was then washed onto a 30 ml plastic tube and 2 ml of glycerol added. 100 μl of glycerol was then placed on a slide and 10 μl of sample added. This was then mixed and a glass cover slip placed on top. The cover slip was then sealed with clear nail varnish.

5) The sample was then analysed at 200x magnification.

Density Separation & Bleaching

This technique was developed based on observations made during the course of this investigation. In the bleaching and filtering the hydrogen peroxide successfully digested organic material. Likewise the density separation removed mineral matter from the samples. Therefore two categories of particles that could potentially misidentified as charcoal could be removed from the sediments if these techniques were combined. Therefore this technique was tested as a further alternative to the published methods.

1) 10 ml of 6% hydrogen peroxide was added to 1 cm^3 sample and left for 24 hours to react. The sample was then left to settle and the hydrogen peroxide was then removed with a disposable pipette.

2) The sample was then washed using distilled water through a 250 μm mesh. The particles left on the mesh were retained.

3) 10 ml of LST was added to the sample and then it was centrifuged at 2000 rpm for 10 minutes. The sample was then decanted into beakers. 200 ml of distilled water was added and the sample was left to settle. Once settled the water was removed with a disposable pipette. This stage was repeated twice.

4) The sample was then washed onto a 30 ml plastic tube and 2 ml of glycerol added. 100 μl of glycerol was then placed on a slide and 10 μl of sample added. This was then mixed and a glass cover slip placed on top. The cover slip was then sealed with clear nail varnish.

5) The sample was then analysed at 200x magnification.

Quantification procedures

To standardise the quantification procedure across the preparation techniques one slide from each preparation was counted. On each slide 66 fields of view across 11 traverses were analysed. To each field of view the three quantification techniques were applied, namely absolute abundance, particles area (estimated using a grid square graticule), and point counts made along 11 points along a graticule (Clark, 1982).

Results

Absolute abundance

Although all the control samples contained the same amount of charcoal there was considerable variability in the number of charcoal particles measured using each extraction procedure (Table 1). The lowest charcoal counts were produced by the Oregon Sieving Technique. In contrast the density separation and the density separation plus bleaching preparations recorded the greatest number of particles. Differences in the amount of charcoal quantified by each extraction procedure were evident in the results of the one-way ANOVA. This indicated a highly significant difference between the extraction procedures (F-value: 70.62; *P*-value: <<0.001). A Fisher's pairwise comparison was conducted to identify which if the preparations were significantly different from one another (Table 2). The results indicate that the density separation, density separation & bleaching and he bleaching & filtering preparations produced charcoal counts that were significantly different from one another.

Table 1: Absolute abundance of charcoal particle counts for the different preparation methods.

Extraction procedure	Charcoal particles counted	Standard deviation
Pollen Preparation	55.7	18.4
Oregon Sieving Technique	22.4	6.4
Bleaching & Filtering	186.4	49.5
Density Separation	687.7	185.0
Density Separation & Bleaching	577.9	172.3

Table 2: Fisher's pairwise comparison

	Bleaching & Filtering	Density Separation	Density Separation & Bleaching	Oregon Sieving Technique
Density Separation	**			
Density Separation & Bleaching	**	*		
Oregon Sieving Technique	NS	**	**	
Pollen Preparation	NS	**	**	NS

NS: non-significant, *:significant, **highly significant

Point Count

The point count method repeatedly underestimated the charcoal abundance; therefore this was not carried out on all the samples analysed.

Particle size measurements

The pollen, bleaching & filtering, density separation and density separation & bleaching preparations all record the greatest abundance of particles in the smallest size fraction (<625 μm^2) (Figures 2a & 2b). The particles sizes quantified in the Oregon Sieving Technique contrasts with the other preparation techniques (Figure 2b), where the majority of particles were found in the larger size fractions.

Figure 2a: Particles per size fraction (at 100x magnification)
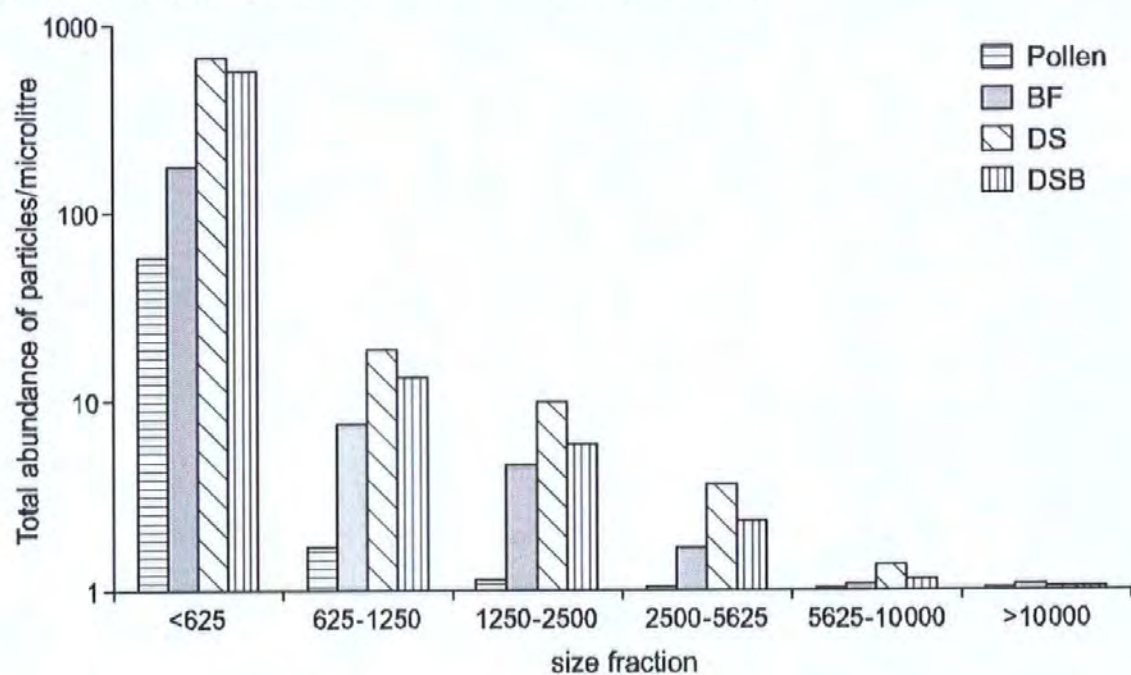
Figure 2b: Particles per size fraction (at 200x magnification)
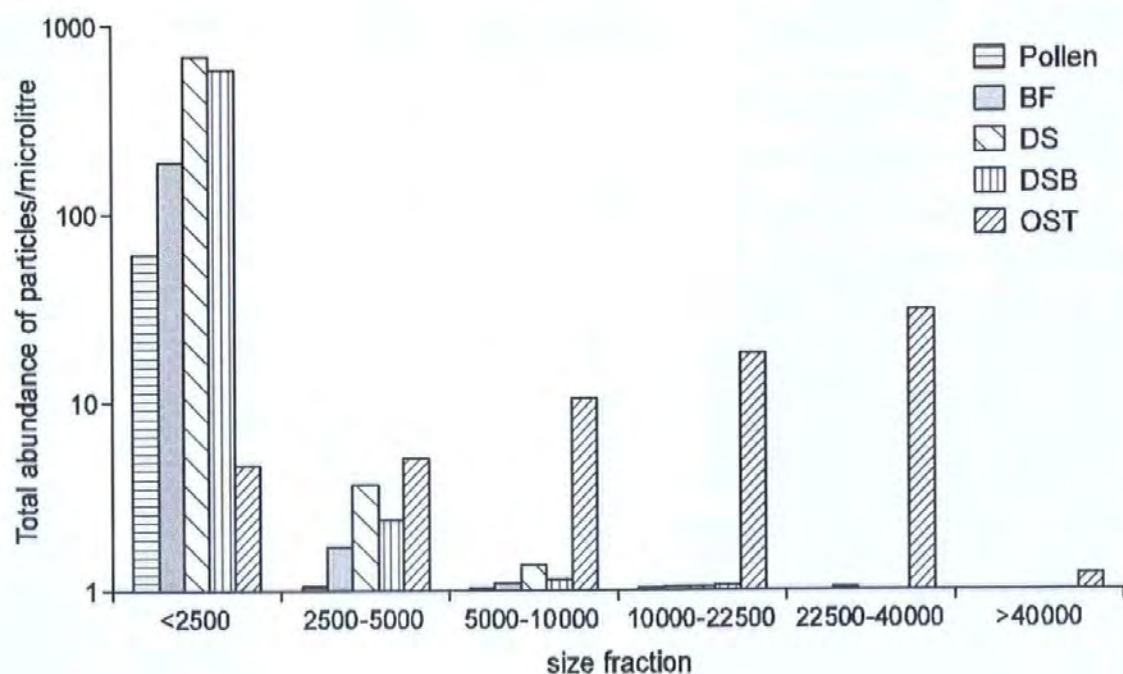
Discussion

The extraction and quantification procedures do have a clear impact on the results of charcoal analysis, and the specific method(s) used will therefore have an influence on the fire history that is reconstructed. Each extraction and quantification technique is now reviewed to identify the causes of the large variation in the amount of charcoal recorded (see also Table 3). This information along with factors including ease of identification and preparation time will be central to the development of the recommendations for further charcoal analysis.

Pollen preparation

This preparation involved three different chemical treatments (excluding the HF acid treatment was not conducted) and mechanical treatments which included micro-sieving, repeated centrifuging (high speed/short time: minimum of 13 times) and mechanical mixing. Furthermore this preparation was biased toward the smaller size fractions, all particles greater then 180 μm being removed. Therefore there were many potential sources of particle loss with this procedure. As a result, the counts of charcoal made from samples processed with a pollen preparation produced significantly underestimated the actual content of charcoal.

Bleaching & Filtering

This technique was mechanically gentle, therefore minimised the sources of particles fragmentation. However, it did include two chemical treatments with 6% hydrogen peroxide. This technique is not biased toward any size fraction i.e. there is not a maximum size cut-off and although the samples are washed through an 11 μm filter paper the amount of charcoal lost is thought to be minimal (Rhodes, 1998). Therefore this technique should provide a count of charcoal particles in a similar magnitude to the heavy liquid separations. However, the charcoal counts produced by this preparation were lower then the heavy liquid separation techniques (Figures 3.2a). Hydrogen peroxide has been used previously in the extraction of charcoal from solids (White & Hannus, 1981) and was applied in this method as it has been hypothesised tat due to charcoal being chemically and biologically inert; it should not react or be digested by hydrogen peroxide (Rhodes, 1998' White & Hannus, 1981). Yet the lower then expected charcoal counts may indeed reflect the removal of charcoal by hydrogen peroxide, and the effect of hydrogen peroxide on charcoal may need further investigation.

Oregon Sieving Technique

The technique was both chemically and mechanically gentle therefore minimising particle fragmentation. The size ranges of particles analysed (greater then 63, 125 and 250 μm) were biased toward the larger size fractions. Therefore this method would provide a local rather then a regional record of fire activity. Hence this method is better suited to the analysis of meso and macroscopic charcoal. Consequently, the record produced of fire activity using this technique is not directly comparable to that produced by the procedures that focus on microscopic particles.

Density Separation

Although chemical and mechanical treatments were conducted during this analysis, the severity of these treatments was minimised. The samples were sieved at 250 μm to remove larger particles that may have a specific gravity higher then 2.2 and therefore not be separated from the denser material. The chemical treatment was limited to 10% hydrochloric acid to remove carbonates and particles could have potentially been fragmented during reaction with the analysis. The mechanical treatment involved a long, slow speed centrifugation (2000 rpm for 10 minutes). Initially it was hoped that the samples would separate without the need for centrifuging but even after samples were left over night, the separation was not successful and centrifuging was essential. The density separation resulted in the highest charcoal counts. Furthermore the samples were only centrifuged once, If the high counts were due to the centrifuge causing particles fragmentation the samples processed using a pollen preparation, where a minimum of 13 short, fast centrifugations were applied, charcoal counts produced by a pollen preparation should be similar or larger then those of the density separation. However the pollen preparation counts of the control samples are significantly lower then the density separation samples; therefore it is likely that particle recovery is greater with the density separation.

Density Separation & Bleaching

The application of a bleaching stage to the density separation was designed to improve identification accuracy by removing organic matter. However, this procedure, despite being otherwise identical to the density separation, it recorded fewer charcoal particles then the density separation, although recording more charcoal then the other extraction procedures. This again raises concerns over the effect of hydrogen peroxide on charcoal.

Quantification Techniques: absolute abundance vs. area measurements

The suitability of each old these techniques for quantification of charcoal depends on the information required from a study, the size range of particles that are being analysed (e.g. micro, meso or macroscopic particles) and the extraction procedure used. Microscopic particles are hypothesised to represent an extra-local to regional source area (Clark, 1998a). Therefore when the size bias (e.g. toward the smaller particles) of the preparation techniques used to extract the charcoal and the time taken to measure microscopic charcoal particles are balanced against the limited amount of information that is obtained in relation to transport distances, absolute abundance measures appear to be the most appropriate technique of charcoal quantification. In contrast, meso and macroscopic charcoal particles which have a hypothesised local to extra-local source area (Clark, 1998a), if extraction by the Oregon Sieving Technique (which is biased toward larger particles), can offer useful information concerning the distance of charcoal inputs and will require measurement of particle area as well as frequency.

Table 3: Extraction procedure overview

Extraction Procedure	Chemical treatment	Mechanical treatment	Size bias?		Preparation time/intensity of procedure	Identification ease
			Size range	Spatial scale		
Pollen Preparation	HCl, KOH, Glacial acid, Conc. Sulphuric acid, Acetic anhydride	Centrifuging (x13), mechanical stirring, micro-sieving	>10 to <180 μm	Extra-local to regional	5 to 7 days Labour intensive	Still contains mineral matter & organics
Bleaching & Filtering	H_2O_2	None	>11 μm	Local, extra-local to regional	6 days Not labour intensive	Organic material removed. Still contains mineral matter
Oregon Sieving Technique	None	None	>63 μm	Local	3 to 5 days Not labour intensive	Still contains mineral matter & organics
Density Separation	HCl	Centrifuging (x1)	<250 μm	Extra-local to regional	4 days Not labour intensive	Mineral matter removed. Still contains organic matter.
Density Separation & Bleaching	HCL, H_2O_2	Centrifuging (x1)	<250 μm	Extra-local to regional	5 Not labour intensive	Mineral matter removed. Still contains organic matter.

Conclusions and recommendations for the further analysis of microscopic charcoal

The techniques investigated here demonstrated varying levels of suitability to the analysis of microscopic charcoal. Ideally, a technique should be selected that minimises the amount of articles fragmentation. This can be achieved by limiting the number of chemical and mechanical treatments samples experience during preparation. Likewise the technique applied needs to be suited to the size fractions that are being analysed e.g. Oregon Sieving Technique is best suited to the analysis of particle that have a local source area. Also the extraction procedure selected should represent an attempt to analyse the full range of size fractions present in a sample. Therefore a two-step extraction procedure may be more useful. A sieving stage in the earl preparation procedure can remove larger particles which exhibit the greatest vulnerability to particle fragmentation and can, if they are fragmented, lead to overestimation of the charcoal content of a sample. This would leave the smaller size fractions to go through a more rigorous preparation. The suitability of this approach was demonstrated by the density separation repeatedly producing the highest charcoal counts. This investigation have also clearly shown charcoal is a separate palaeoenvironmental proxy and as such it is essential to use an extraction and quantification procedure that focuses solely on charcoal extraction if maximum information is to be derived. Applying such a procedure would ensure fire history records are produced that are reliable and comparable between different analysts.

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