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Living with a changing landscape: Holocene climate variability and socio-evolutionary trajectories, central Turkey

by

Samantha Lee Allcock

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Abstract

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Collaborative studies between Quaternary scientists and archaeologists increasingly provide new and informative discussions about the nature and timing of cultural change and links with variation in the natural world (particularly climate). In the Eastern Mediterranean region, connecting the human past with palaeoclimate is an important research theme but the complex interactions between them are still poorly understood and past climate records have often been collected from regions distant from the human record. The thesis aims to derive a record of past climatic and environmental changes from lake sediment cores and synthesise this with archaeological data in order to reconstruct human-climate interactions at the regional scale. Annually laminated sediment data collected from Nar Gölü crater-lake and archaeological archives from the same region, Cappadocia (Turkey) allow problems of chronological uncertainty between records of the human past and palaeoclimatic archives, and spatially variable datasets to be addressed.

New sediment cores collected from Nar Lake in 2010 cover the last ~14000 years based on varve counting and climate-stratigraphic correlation. The changing chemical composition of these sediments has been obtained using high-resolution Itrax XRF core scanning, mainly at 200µm resolution over 21.6m. Temporal differences in Ca and Sr are interpreted as a record of regional moisture levels, while Ti and Fe are elemental proxies that detail changes in catchment in-wash. These and other sedimentary data (e.g. total carbon analysis) document lake evolution from a predominately stable and moist early Holocene climate dominated by high authigenic Ca precipitation to a drier and less stable late Holocene dominated by increased authigenic Sr and Mg (and higher lake salinity levels). The most arid climatic conditions occurred during Bronze and early Iron Age times, but frequent and intense centennial-scale climatic shifts between wet and dry are also evidenced during the last 2600 years from Ca/Sr data.

Peaks in Fe and Ti, along with Si, K and Rb indicate two distinct phases of increased sediment influx into Nar Lake, namely ~9200 to ~8000 yr. BP (ceramic Neolithic) and again – more importantly – during the last 2600 years (Iron Age and later). These appear to be related primarily to increased human impact on vegetation and soils in the lake-catchment, but volcanic activity and intense rainfall events and/or water deficits may also have played a role.

To determine the degree to which climatic variability and cultural change are interlinked, the geochemical record from Nar Lake is correlated against long-term settlement histories which have been derived from systematic archaeological site survey and excavation data from Cappadocia. One of the key outcomes of the project is an examination of periods of climatic stability and instability which are identified by amplitudinal changes from the mean state using correlation of coefficient statistics on the Nar Lake geochemical record. This information about the predictability of climate has been coupled to data in settlement density and location within the resiliency model framework of Holling and Gunderson (2002). Together these data suggest that a series of four long-term adaptive cycles (Neolithic, Chalcolithic-Bronze Age, Iron Age-Classical, Byzantine-Ottoman) characterise the dynamic inter-play between people, climate and their environment. In each adaptive cycle, environmental change contributed (both positively and negatively) to community resilience, although at no point during the Holocene is climatic variability seen as the sole driver of societal change. There were times such as the post-Roman Dark Age (1300 to 1100 yr. B.P.) when increased climatic variability and environmental degradation may have heightened social vulnerability.

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1. Introduction

1.1. Research context

1.1.1. Climate and culture interactions

Attempts to link natural change events with past societal changes date back as far as the early 20th century when key figures such as Raphael Pumpelly, Ellsworth Huntington and V. Gordon Childe were influential in advocating a climatic/environmental cause for shifting characteristics of human cultures (e.g. Childe, 1926, 1952; Huntington, 1915; Pumpelly, 1905). In more recent years, since the development of more accurate scientific data from proxy indicators, the role of climatic/environmental change in the development of human populations has become an important research theme. The identification of ‘rapid climate change’ events which appear to coincide with significant social transformations throughout the Holocene has drawn particular interest. This has resulted in a number of studies which propose, in a rather deterministic sense, climate change as a primary causal factor in the demise of certain human groups (e.g. Cullen *et al.*, 2000; Stanley *et al.*, 2003; Weiss and Bradley, 2001). Other studies see climate as a driver of increased social complexity (e.g. Brooks, 2006) or an explanation for changes in settlement patterns (e.g. Haug *et al.*, 2003).

Most scholars agree that such mono-causal environmental explanations for societal change are too simplistic and ignore the social dimension to change events (see Coombes and Barber, 2005). It is also important to note that the linkages made between cultural and climatic data are often not as contemporaneous as they seem and can be fraught with dating inaccuracies (Berger and Guilaine, 2009). Rosen (2007), by contrast, outlines the non-passivity of Eastern Mediterranean people in tackling climatic perturbations and avoids the classic climatic deterministic approach by conveying past societies as bodies, at least partially, in control of their own outcomes. Whilst modern investigations have shown a nuanced view of these complex interactions (e.g. Cooper and Sheets, 2012; McIntosh *et al.*, 2000; Rosen and Rivera-Collazo, 2012; Wilkinson *et al.*, 2007), research projects have remained at a small scale and deterministic interpretations continue to be in fashion. Even though the comparability and integration of research from differing subject fields is being addressed (e.g. Davies and Watson, 2007; Schulting, 2010), there have been only minor developments in how palaeoclimatic and archaeological or historical data sets should be compared.

A recent development in climate and culture studies has seen the introduction of social science terms which, to some degree, have helped to enhance the understanding of climate/people relationships. The increased use of social science related terms directly relates to our own cultural systems and growing concern with the changing climate system we currently face. Ideas such as adaptive response, vulnerability, resilience, complexity theory, nonlinear change and feedback regimes (Adger *et al.*, 2005; Adger *et al.*, 2009; Byrne, 1998; Janssen *et al.*, 2006; Nelson *et al.*, 2007) are no longer seen as just applicable to modern communities, or as simply ‘current’, but as cultural creations which were just as relevant in the past (Redman, 2005). Such ideas are now represented in discussions (e.g. Ur, 2010) concerning, for example, the Akkadian and Early Bronze Age (EBA) collapse events which, up until present, have primarily been considered from a deterministic perspective (Gophna and Portugali, 1988; Richard, 1980; Staubwasser and Weiss, 2006). Joint archaeological and palaeoclimatic investigations now suggest that climate may not have always been as detrimental to Akkadian culture as first argued, as grain storage systems and water regulatory techniques were used to help combat the effects of climate (Cullen *et al.*, 2000; Kuzucuoğlu, 2007; Ur, 2010). Whilst still in their infancy, these new discussions about how Near East populations had anticipated change and moved towards safe-guarding their lifestyles are developments in understanding these relationships.

It cannot be denied that certain bodies of evidence indicate that periods of cultural transition do occur at times of climatic deterioration or amelioration, linked to episodes of resource scarcity or environmental uncertainty (e.g. Brookfield, 2010; Brooks, 2006, 2010). In this regard, some scholars (e.g. Brooks, 2006) have particularly focused on the mid-Holocene, for example the 6th Millennium B.P, as a large body of data suggests that this time period witnessed widespread climatic drying and reorganisation of many different social groups across the Old World. With the emergence of a new climatic state by 5000 cal. yrs. B.P., it is argued that a new phase of complex social developed began that was significantly different to that which had existed only 1000 years earlier (Brooks, 2010). The problem remains that interpretations of this sort are formulated from research that had been carried out in separation, either in the science or humanities fields, and that relationships were ‘perceived’ rather than ‘understood’. Scholars often struggle to work from the standpoint of social and scientific disciplines but it is through an integrative perspective that the greatest understanding and reconciliation of datasets can be made.

Given this intricate and often confusing latticework of multifaceted interactions between climate, environment and people, this doctoral thesis work seeks to gain a more in-depth understanding of climate change and human response mechanisms for the Holocene. The Holocene is clearly an era of major social development that to some extent is dependent on shifting natural systems, and warrants further research. This research aims to look at different climate states and socio-economic and political adjustments from an integrated perspective. The work presented here explores the influence of changing climatic/environmental variability on past communities and how this is related to the sensitivity and adaptability of past societies during the late Pleistocene and Holocene. An annual-decadal, as well as a centennial-millennial, temporal resolution is used to study climate/culture relations as people will more likely perceive changes in climate e.g. between wet and dry on a year by year basis. Emphasis is placed on climatic variability rather than sudden change events, as it could be hypothesised that sensitivity and adaptability of past people were highly influenced by stable or unstable climate regimes (Rosen, 2007). A comparative analysis of changes in climatic and environmental stability and archaeology will be used to outline relationships between them.

1.1.2. The value of annually laminated lake sediments

Annually laminated or varved sediments are well known recorders of climate and environmental variability due to their changing nature, composition and structure (Gold, 2009). They can provide accurate chronologies based on varve counting and can be analysed at high resolution using a range of proxy indicators (Brauer and Negendank, 2002). Varved lake records have thus been identified as key palaeo-archives for inland regions and in recent decades, many projects have attempted to exploit this potential gain in understanding. Varved lake sedimentary archives offer the potential to reconstruct records of regional climate and environmental change over time, as seen in Jones *et al* (2006), Marshall (2010), Roberts *et al* (2001) and Tiljander *et al* (2003). Their sensitivity to climate is often a consequence of a hydrological system that can be influenced by evaporation and precipitation (P-E) budgets (Street-Perrott and Harrison, 1985). Changes to the P-E ratio can cause a lake’s water balance to fluctuate, which leads to distinct shifts in the physical, chemical and biological processes occurring within a lake, a record of which can be preserved in the lake sediments (Street-Perrott and Harrison, 1985). Studies will often adopt a multi-proxy approach (Lotter, 2003) which encompasses various geochemical and biological components to help reconstruct environmental and climatic change in the lake and catchment over time.

The benefit of using annually laminated lake sediments extends beyond climatic and environmental reconstructions as they can be used to address some of the issues that are prevalent in climate/culture studies. Principally they can offer a stricter and more tightly dated record of palaeoclimatic change which can help to resolve the problems associated with dating accuracy and uncertainty, and provide detail at the yearly or sub-annual temporal resolution which is the scale at which people most readily observe signals of climatic disruption (Akerlof *et al.*, 2013; Biehl, 2012). Moreover, climate reconstructions from lake sediments are often more useful to climate/culture studies because the record of climatic change comes from a site which can be in very close proximity to areas of past human habitation, thus reducing the effective of spatial variability and ensuring that the climate recorded in the lake sediment proxies is the same as that experienced by past communities.

Within this research project, Nar Gölü (Lake) has been identified as a suitable site to study palaeoclimate. Nar Lake is situated within Cappadocia, central Turkey, and is a source of information on the climate history of the Eastern Mediterranean (England *et al.*, 2008; Jones *et al.*, 2006; Turner, 2007; Woodbridge and Roberts, 2011). The study site was chosen for its 1) continuous sediment record throughout the Late Glacial and Holocene, 2) annually-deposited (varved) sequences, 3) possibility to establish a high-resolution (annual) and reliable chronology, 4) existing understanding of the relationships between climate proxies and particular climate variables. As Nar Lake is situated amongst a plethora of archaeological sites, palaeoclimate data can also be compared to changes in human behaviour as evidenced in the archaeological record to investigate how societal changes were mediated, by varying degrees, by climatic and environmental change. Advantageously, synchronisms in the archaeological and palaeoclimatic records can be investigated at the regional scale due to the spatial congruence between the Nar Lake site and past occupational locales.

1.2. Research aims and objectives

<u>Overarching aim:</u> The principal aim of this research is to provide a detailed long-term reconstruction of changes in Holocene climatic and environmental variability for the purpose of comparison to regional past societal changes. Of particular interest are

linkages to human societies in the region of Cappadocia, central Turkey, and how uncertainties in past climate/environment may have influenced the life choices made by past people at various temporal and spatial scales.

Aim1: To build a clear picture of Holocene climatic and environmental variability to assess when natural change occurred in Cappadocia and how.

Objective 1: To evaluate short-term and long-term Holocene climatic and environmental variability from high-resolution sampling and analysis of varved lake sediment archives.

Objective 2: To delineate periods of stability (constant periods) and instability (unsteady periods) in Holocene climate/environment using geochemical elemental records from annual lake sediment deposits.

Objective 3: To combine data from this project to existing Holocene climatic and environmental data to understand the broad picture of natural change in central Turkey and the Eastern Mediterranean.

Aim 2: To assimilate records of Holocene climatic and environmental variability with the past human record to develop new ideas about the integration of climate and cultural data and how ancient social systems developed alongside changes in variability.

Objective 4: To create archaeological and historical data sets to build up a picture of past human occupation in Cappadocia for the Holocene time period, drawing on individual site data as well as large scale regional archaeological survey results.

Objective 5: To produce a timeline of human habitation periods and abandonment periods from the archaeological and historical records to establish when there may have been cultural discontinuities during the Holocene.

Objective 6: To understand the inter-relatedness of climate, environment and culture using sediment and archaeological data to examine the hypothesis that stable climates would have been more advantageous to past communities.

Aim 3: To produce a more research-informed, whole-systems dialogue about the challenges past societies faced and ultimately what actions, if any, they took during times of Holocene climatic and environmental variability.

Objective 7: To understand the types of links and feedbacks which existed between the natural world and people, and how these developed within the limits of Holocene climate change.

Objective 8: To assess how resilient or prepared past communities were and how effective social systems were during times of variability in climate.

Objective 9: To document what happened to past cultures during times of stress and vulnerability created by climate variability. This will use knowledge gathered through objective 8 about the resilience of communities and how well societies coped with changing climate.

1.3. Thesis outline

The remainder of the thesis is comprised of 7 chapters. Chapter 2 includes a summary of the literature on palaeolimnological study, palaeoclimatic patterns in the Eastern Mediterranean, and how past climatic characteristics can be integrated with archaeological research to provide an understanding of climate and culture relationships. Chapter 3 outlines the key methods employed in this study and the reasoning behind their usage. This is followed by a presentation of the project results from Itrax XRF core scanning and other sedimentary investigations (chapter 4), and archaeological data collection (chapter 6). An interpretation of the Nar Gölü geochemical outputs is provided in chapter 5. In chapter 7, the results from both the laboratory investigations and archaeological survey collection are brought together to investigate climate/culture relationships. Firstly, comparisons between the Nar Gölü data and other records of Eastern Mediterranean climate are made to discuss the replicability of the palaeoclimate record established from Nar Lake sedimentary data. Following this, a discussion regarding climatic and environmental variability is made and associated with the history of past human occupation in Cappadocia. Finally, climate and environmental variability and cultural change are understood from a resilience perspective with the aim of highlighting the linkages between climatic change and cultural change. Chapter 8 includes an overview of the conclusions drawn from this doctoral study and makes recommendations for future research.

2. Literature review

Palaeolimnology, Eastern Mediterranean climatic change and climate/culture relationships

2.1. Chapter introduction

This chapter outlines the key background readings conducted which shaped the basis of this thesis. It firstly introduces the subject of palaeolimnology and the advantage of using varved lake sediments for understanding palaeoclimatic change, and it draws on XRF geochemical analysis for extracting climate data from annual lake sediment archives. It also includes a review of the current understanding and literature surrounding Eastern Mediterranean climate change from the Late Glacial period through to present day. The chapter finishes with an overview of climate and culture studies to date, focusing on the development in theory and modern ideas about how we should address such complex interactions.

2.2. Annually laminated lake sediment archives

2.2.1. Palaeolimnology and palaeoclimatology, an introduction

Palaeolimnology is the study of past conditions and processes which occurred within a lake basin (Last and Smol, 2001). Palaeolimnology plays a key role in palaeoclimate studies as processes and conditions can be picked up at high-resolution and inform about how climate may have been interacting with the lake environment at various temporal and spatial scales (Brauer and Negendank, 2002). Data derived from lake sediment archives is generally complex as the information can signify changes in both the limnological and terrestrial environments (Brauer and Negendank, 2002). The climate record established from lake sediment may not therefore represent the exact climatic forcing due to the non-linear and non-stationary nature of deposit formation (Fritz, 2008). Studies of palaeoclimate from palaeolimnological archives demonstrate the usefulness of lake sediment records in understanding past climate change (Cohen, 2003). The geographical distribution of lakes is wide which provides scholars with a global network of sites to choose from and allows for various scales of investigation to be conducted with regard to past climate (Battarbee, 2000). Figure 2.1 from Battarbee (2000) outlines the sorts of processes which occur in lake as the result of climate and demonstrates the physical, biological and chemical responses of the lake system which need to be understood to interpret past climatic change from lake sediment archives.

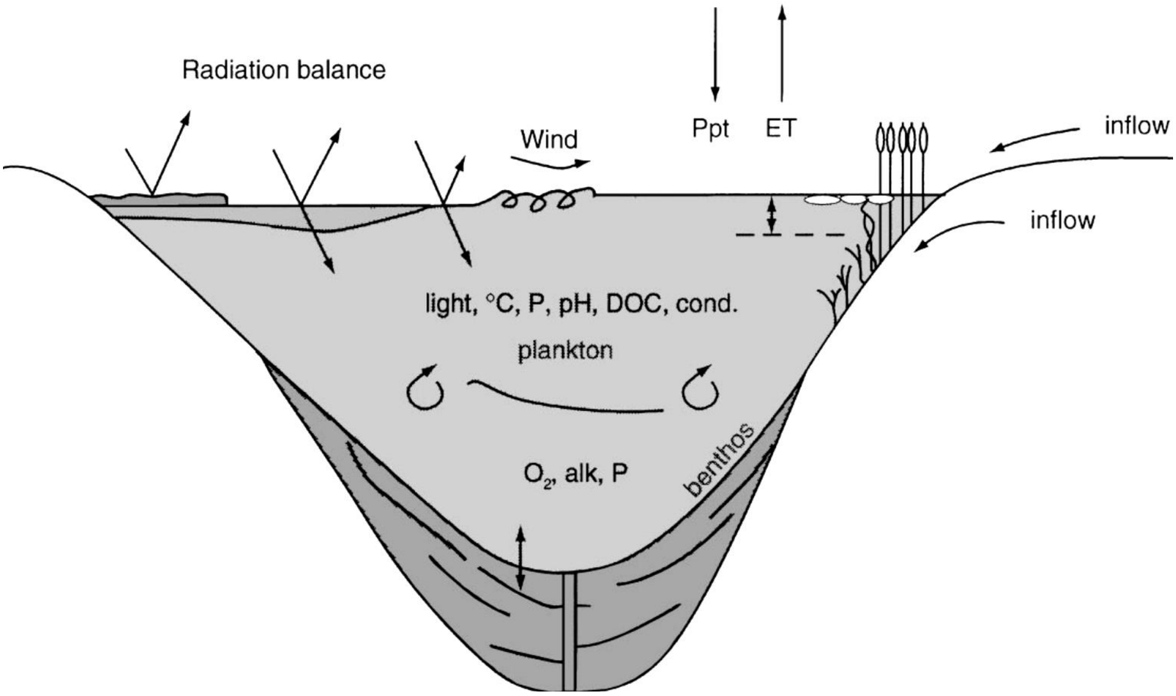


Figure 2.1: Schematic diagram taken from Battarbee (2000) to show examples of the principal physical, chemical and biological responses of lake systems to changes in climate forcing. Permission to reproduce this image has been granted by Elsevier.

The biggest issue with palaeoclimate studies is generating a record of climate which distinguishes between local factors and regional climate variations, and obtaining spatially similar archives (Fritz, 2008). Each lake is different and each lake responds in a unique way to climate forcing which can generate rather conflicting climate reconstructions. Therefore, palaeoclimate records must consider regional environmental variations, basin characteristics and factors driving sediment formation before any detailed reconstruction of climate can be made (O'Sullivan, 1983; Renberg *et al.*, 1984; Simola, 1992). As Battarbee (2000) states and as others have shown (Gasse *et al.*, 1987; Villalba *et al.*, 2009; Zolitschka, 1998), the multi-proxy approach is the best method for understanding lake-catchment and lake-system responses to climate change. Caution must be given to responsiveness and lag times however, as each proxy record will respond differently to a climatic event and interpretations will therefore be dependent on how we understand relations between the two variables (Ingram *et al.*, 1981). Examples of the sorts of studies which have been conducted into past climate from lake sediment archives can be seen in (Anderson *et al.*, 1996; Bradley and Dean, 1993; Hardy *et al.*, 1996; Itkonen and Salonen, 1994; Lotter and Birks, 2000; Ramrath *et al.*, 1999).

2.2.2. Annually laminated lake sediment (varves)

Varves are annually deposited rhythmic formations which generally consist of a summer and winter sediment formed under changing seasonal conditions (Gold, 2009). Varves are derived from both autochthonous and allochthonous material and constitute an array of deposits depending upon the physical, chemical and biological properties which were occurring within and around the lake at the time of formation (Gold, 2009). Catchment clastic sediment input may result from precipitation, runoff, vegetation cover and soil condition whilst in-lake variations can derive from dissolved materials, chemicals and organic matter and are controlled by oxygen content, pH, salinity and water temperature (Anderson and Dean, 1988). Limits to varve formation and preservation are outlined by O’Sullivan (1983) who suggests that deposits need to be undisturbed and flat lying, and that lake water needs to be fairly still to reduce bioturbation and movement of the lake bottom. Deep lakes are ideal for varve creation and stability because they are deep enough to minimize disturbance but they also promote low oxygen levels which discourages the growth of damaging benthic organisms (O'Sullivan, 1983).

Due to their changing nature, composition and structure, varves are good recorders of climate (Gold, 2009). Varved lake sediments are particularly important for high-resolution climate change studies not only because they provide a clear and simple way of defining short and long term natural change but because they can provide a chronology, independent of other dating techniques (Lamoureux, 2001; Renberg, 1983). Chronology formation involves counting individual laminae, replication, cross-dating and cross-correlation with other dated records to determine the age of the stratigraphic sequence (Lamoureux, 2001). Analysis consists of finding a good match between known and unknown sections of varve deposits to assign an age to the stratigraphic sequence (Verosub, 2000). It is also useful to independently check chronologies through radiometric, historical or other incremental dating techniques to validate the determined age-depth profiles (Lamoureux, 2001).

The demand for more accurately dated palaeoclimatic reconstructions from lake sediments in recent years has encouraged the growth in studies on varved deposits, from investigations into the physical properties of varves and changes in fossil assemblages to dating techniques (e.g. Landmann *et al.*, 1996b; Lücke *et al.*, 2003; Ojala and Tiljander, 2003; Romero-Viana *et al.*, 2008; Snowball *et al.*, 2010; Tiljander *et al.*, 2003; Wick *et al.*, 2003). These annually deposited sediment archives usually exhibit visible stratigraphic changes related to regional seasonality and the effects of climatic factors combined with anthropogenic influences and basin characteristics. The sensitivity of the lake system to changing natural and human-induced conditions leads to information about palaeoclimate and environments. Therefore palaeo-reconstructions can be performed through varved sediment analysis.

2.2.3. Annually laminated lake sediments and the advantages of using XRF

One of the more significant improvements in terms of analysing lake sediments has been the introduction of XRF (X-ray fluorescence) core scanning techniques (Francus *et al*., 2009) which allow non-destructive, high-resolution geochemical data to be gathered. This is of particular benefit to varved lake sediment deposits (in fact any annually laminated sequence) where it is necessary to determine climatic or environmental variability over short-term time scales, and there is the need to describe changes that have occurred during individual years. XRF scanners offer many applications for palaeolimnology including estimating erosion intensities, primary productivity and palaeo-redox conditions (Francus *et al*., 2009), which can complement other investigatory techniques, but by far the most useful to studies of annual deposits is the sub-millimetre scale of analysis (Francus *et al*., 2009). High-resolution core scanning also has the advantage of being relatively low cost and requires few preparation steps (Wilhelms-Dick *et al.*, 2012) which is useful when attempting to interpret seasonal changes over long temporal scales. The precise chemical composition of sediment cores is not often needed in palaeoclimate studies where critical boundaries and shifts are of the main interest (Wilhelms-Dick *et al.*, 2012). The fastest way to obtain continuous and accurate measurements at high-resolution is therefore by XRF scanning which details only relative variations in elemental components (Croudace *et al.*, 2006).

As with any investigatory technique, the accuracy of this method for palaeoclimate reconstruction is variable and can be influenced by a number of physical sedimentary properties (Böning *et al.*, 2007; Hennekam and de Lange, 2012; Kido *et al.*, 2006; Richter *et al.*, 2006; Tjallingii *et al.*, 2007; Weltje and Tjallingii, 2008). The consequences of these factors on elemental intensities are important for palaeoclimatic studies and should be adequately considered (Hennekam and de Lange, 2012). As Löwemark *et al* (2011) points out, the dilution effect of organic material on the elemental measurements obtained can be rectified to some extent by normalising using a stable elemental component to better assess relative change. XRF is thus an attractive tool for palaeoclimate studies provided that some of the investigative uncertainties can be limited or quantified (Hennekam and de Lange, 2012).

XRF core scanning at very high-resolution (µm scale) has been conducted on a number of annually laminated lake sequences and proven to be a useful tool for dating annual layers and obtaining palaeo-climate/environmental data. An Itrax XRF scanner used on lake sediments from Japan proved to be a useful instrument in the creation of a varve chronology as the individual varve limits could be precisely marked using a combination of Itrax-derived optical, density (X-radiography) and geochemical properties (Kossler *et al.*, 2011). Combined with thin sectioning and microscopic investigation of micro-facies, an adequate varve based-age model was created (Kossler *et al.*, 2011). In Germany, the same method of using Itrax XRF core scanning on Lake Meerfelder Maar (Martín-Puertas *et al.*, 2012) gave information regarding long-term lake change through Ti (Titanium) and Si/Ti (Silica/Titanium) ratio data. A record of Holocene windiness was documented even though proxy sensitivity to Holocene climatic variation had shifted across time. Itrax scanning on varved sediment cores from Cape Bounty also provided a history of changing lacustrine conditions, in this case related to sediment source changes and environmental variability (Cuven *et al.*, 2011). The applicability of micro XRF scanning is evidently vast.

2.3. Eastern Mediterranean palaeoclimate

2.3.1. Eastern Mediterranean palaeoclimate, an introduction

The Eastern Mediterranean (EM) region is widely discussed in relation to changing climate (e.g. Arz *et al.*, 2006; Bar-Matthews *et al.*, 1997; Finné *et al.*, 2011; Migowski *et al.*, 2006; Roberts *et al.*, 2011a; Roberts *et al.*, 2011b; Schilman *et al.*, 2001; Staubwasser and Weiss, 2006; Weiss and Bradley, 2001; Weninger *et al.*, 2006). The

EM region in this context includes a number of modern European, North African and southwest Asian countries and their surrounding coastlines (figure 2.2). The climate of the region today is highly varied, with each country showing individual climatic characteristics; more generally, the whole Eastern Mediterranean is dominated by drier conditions in the summer with higher rainfall levels during the winter and spring months (Magri *et al.*, 2004). The EM has a complex climatic history due to the influence of atmospheric circulation patterns, oceanic conditions and topography. Modern EM climate is controlled mainly by the North Atlantic Oscillation (NAO), and Indian Monsoon (figure 2.2), but the North Sea Caspian Pattern (NCP), El Niño/Southern Oscillation (ENSO) and Arctic Oscillation (AO) also have important influences on the regions climate (see Kostopoulou and Jones, 2007a, 2007b; Lionello *et al.*, 2006; Mann, 2002; Staubwasser and Weiss, 2006; Xoplaki *et al.*, 2003, 2004). Besides climate, anthropogenic activity has played an important role in shaping the EM landscape. Climatic change coupled with human impact has altered the region’s environment to such a degree that the influences of the two are often hard to disentangle (Roberts *et al.*, 2011b).

The Eastern Mediterranean region, with its long history of human occupation, offers an excellent opportunity to link climatic and environmental variability to the human record of change as outlined by archaeological findings (Finné *et al.*, 2011). The climate of the region has always been a significant influence on the interplay between people and their natural-setting (Finné *et al.*, 2011). The climate and resources available to past people were substantially different from those available today, and this was driven by the evolution of climate over millennia. In contrast to the last 2000 years, Eastern Mediterranean climates of the early and mid-Holocene, and preceding Pleistocene were controlled principally by solar radiation and ice cover forcings that were very different from modern times (Roberts, 2011). The unstable nature of climate over archaeological timescales offers the chance to understand how human societies coped with climatic changes in the past, and bring to the forefront an understanding of the human experience of dynamic environments (Miller and Moore, 2011). In order to address interrelations between past climate and society since the late Pleistocene, a brief outline of palaeoclimate data and reconstructions from the region since the Late Glacial is provided.

Figure 2.2: Map of the Eastern Mediterranean region highlighting the dominating atmospheric circulation patterns (adapted from Woodbridge (2009)).

The Pleistocene period is characterised by major shifts in global climate between glacial and inter-glacial episodes which continued until around 11700 years ago with the commencement of the current warm inter-glacial phase called the Holocene (Rosen, 2007). The late Pleistocene (126000-11700 cal. yrs. B.P.) in the Eastern Mediterranean shows a synchronous climatic history to the rest of the Northern Hemisphere, in effect being driven by changes in radiation balance, greenhouse gases and land ice cover (Roberts, 2011). The Late Glacial Maximum (LGM) occurring between ca. 25000-18000 cal. yrs. B.P. represents the last maximum extent of ice cover before warming ensued soon after ca. 15000 cal. yrs. B.P., and before the cold climatic reversal known as the ‘Younger Dryas’ (ca. 12900-11700 cal. yrs. B.P.) The shift back to warmer and wetter conditions ushered in the Holocene (Rosen, 2007). The general picture of long-term climate trends driven by precessional forcings during the Holocene is relatively well-understood. A warmer and wetter first half of the Holocene is replaced around 6500 years ago with generally drier conditions in the EM (Roberts *et al.*, 2008). However, super-imposed on this long-term trend are smaller scale fluctuations in climatic variability that resulted in a rather complex climatic history for the Holocene (Finné *et al.*, 2011). Of importance are the rapid climate change events that repeatedly caused a short-lived deterioration in climate (Rohling *et al.*, 2002) and potentially constrained societal development (Weninger *et al.*, 2009). The Holocene also witnessed a significant switch from a relatively nature-dominated to a relatively human-dominated earth system that caused greater environmental instability and anthropogenic landscape changes (Messerli *et al.*, 2000).

Establishing reliable climatic records remains one of the challenges of Quaternary research in the Eastern Mediterranean (Eastwood *et al.*, 2007a). Nevertheless, a wide range of natural archives (e.g. lake sediment, cave speleothem and tree-ring) is available for analysing past climate. Palaeoclimatic data and reconstructions have been drawn from a number of different sources including pollen, diatoms, geomorphological evidence and historical data (e.g. Gvirtzman and Wieder, 2001; Leroy, 2010; Roberts *et al.*, 2004; Woodbridge and Roberts, 2011), but each of these proxy indicators has their limitations. The number of studies undertaken has provided a good understanding of EM climate variability at various spatial and temporal scales. An useful overview of climatic changes during the late Pleistocene and the beginning of the Holocene can be found in a paper by Robinson *et al.*, (2006), whilst changes in the latter Holocene are summarised by Roberts and others (Roberts *et al.*, 2011a; Roberts *et al.*, 2011b).

2.3.2. Eastern Mediterranean climate from lake sediment archives

As outline above in section 2.2, lake sediments offer a unique record of changes in hydrological and vegetation conditions through proxy studies such as geochemical scanning. Lakes and lake sediment archives are infrequently found in some parts of the Eastern Mediterranean due to low summer precipitation levels and high evaporation rates (Roberts and Wright, 1993). There are however a few lakes which offer a firm understanding of Late Glacial and Holocene climatic change for the region; key sites include Lake Hula (Huleh) (Baruch and Bottema, 1999), Lake Ghab (Meadows, 2005), Lake Kinneret (Sea of Galilee) (Baruch, 1986), Birkat Ram (Schwab *et al.*, 2004), the Dead Sea (palaeo-lake Lisan) (Migowski *et al.*, 2006), and Burdur, Tüz, Nar, Eski Acıgöl, Konya, Gölhisar, Tecer, Beyşehir and Van Lakes from Turkey (see Eastwood *et al.*, 2007a; Erol, 1978; Erol, 1997; Jones *et al.*, 2006; Kuzucuoğlu *et al.*, 2011; Roberts, 1983; Roberts *et al.*, 2008; Roberts *et al.*, 2001). Sites discussed in this, and the following sub-sections are mapped by location in figure 2.3.

Palaeoclimate records extracted from lake sediment archives from the EM region offer a history of climate change over the last ~25000 years (figures 2.4 & 2.5). A cold and dry Late Glacial Maximum (LGM) and warm and moist conditions centred around 15000 years ago are inferred from lake archives. Rainfall and temperature are documented to have steadily increased from ca. 17000-13000 cal. yrs. B.P, highlighting a long-term trend from cold, glacial conditions of the late Pleistocene to warm, interglacial conditions of the Holocene (Robinson *et al.*, 2006). The trend towards climatic amelioration from the LGM was punctuated by a short climatic event known as the Younger Dryas which saw a temporary reversal back to cold conditions (Robinson *et al.*, 2006). This pattern of climatic change is seen, for example, at Pleistocene Lake Lisan (precursor of Dead Sea) as sediment data (Bartov *et al.*, 2002) suggests high lake levels during the LGM linked into a cooler climate with less evaporation (figure 2.4). Lake Lisan water levels began to progressively decrease following this high lake stand as a result of increasing evaporation levels and higher temperatures.

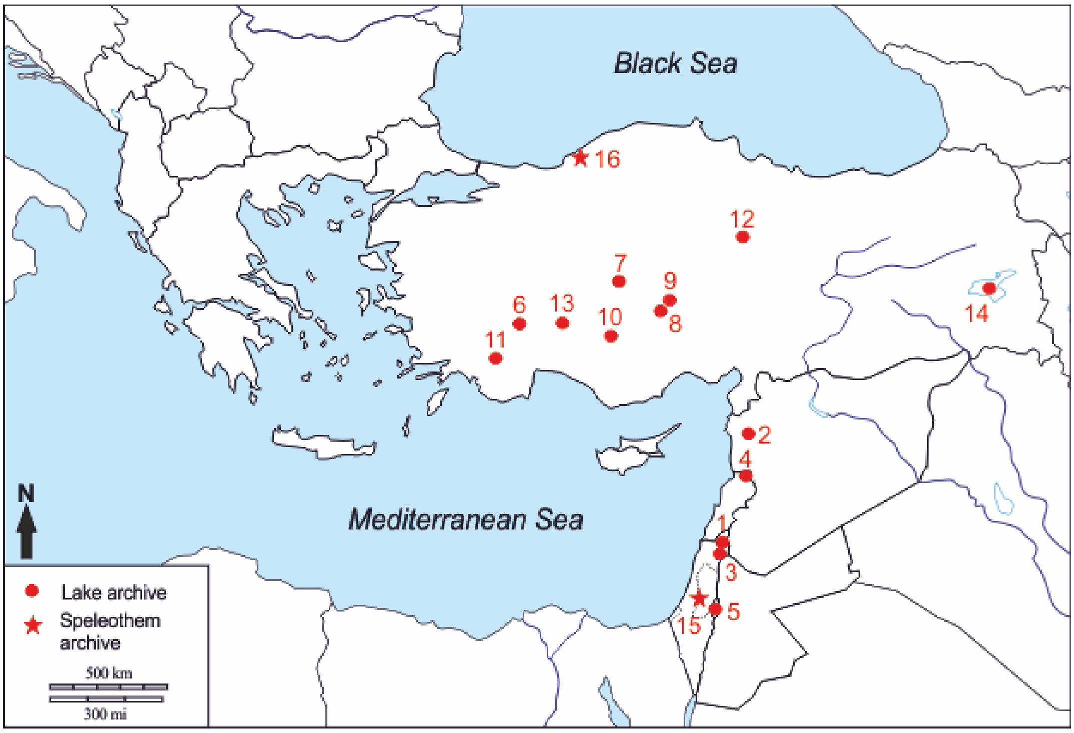


Figure 2.3: Location of sites discussed in section 2.3 of this chapter. 1) Hula (Huleh) Lake, 2) Lake Ghab, 3) Lake Kinneret (Sea of Galilee), 4) Birkat Ram Lake, 5) Dead Sea and associated sites, 6) Burdur Lake, 7) Tüz Lake, 8) Nar Lake, 9) Eski Acıgöl Lake, 10) Konya Lake, 11) Gölhisar Lake, 12) Tecer Lake, 13) Beyşehir Lake, 14) Van Lake, 15) Soreq Cave, 16) Sofular Cave.

Palaeo-lake Konya (Roberts, 1983) in central Turkey provides a record of lake level change throughout the Late Glacial phase. High lake levels represented by *Dreissena*–littoral sands and a dominance of chemical and minerogenic over organic sedimentation occur between ca. 22850-17610 ^{14}C. yrs. B.P. This period witnesses some fluctuations in lake level but the biggest shift towards lower lake stands occurs after 17.0 ka years ago. Lacustrine stands between 17000 and 12000 years ago suggest lake levels fell dramatically but the precise nature of the shallowing is unknown. This pattern of change is not too dissimilar from that seen at palaeo-lake Lisan and Akgöl Lake (Roberts *et al.*, 1999), and is suggested to relate to changes in both temperature and water availability. High lake levels at Konya Lake in this instance were reliant on temperature lowering to reduce evaporative losses, and increased moisture levels from snow and ice melt in the lake catchment during glacial conditions (Roberts *et al.*, 1999). Subsequent lake regression in comparison stemmed from a climatically arid phase and higher evaporation following the LGM (Roberts *et al.*, 1999). The Late Glacial/Interglacial climatic transition at Eski Acıgöl Lake in central Turkey (Roberts *et al.*, 2001) also shows a step-wide progression into the Holocene that is driven principally by cooling/warming events.

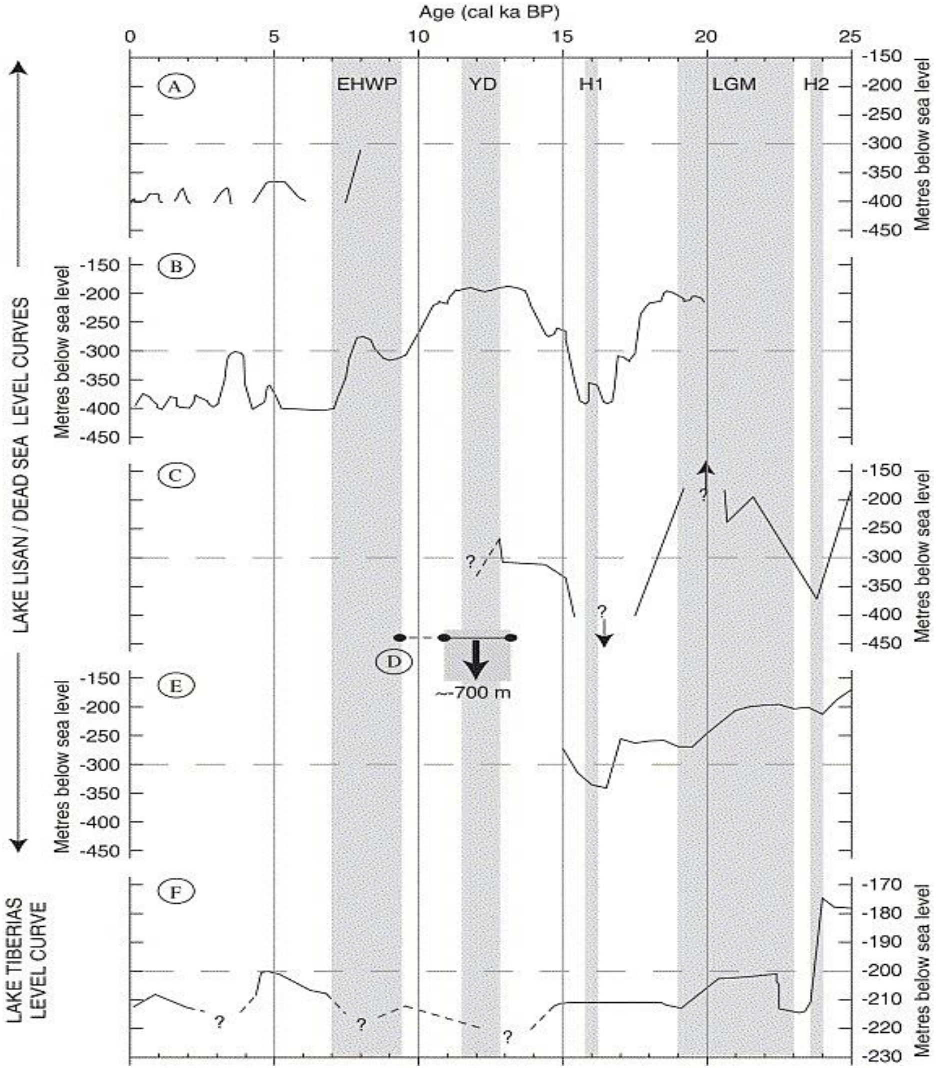


Figure 2.4: Compilation of lake sediment archives from Lake Lisan and Lake Tiberias for the late Pleistocene and Holocene showing shifts in lake level related to changes in EM palaeoclimate (Robinson *et al.*, 2006, pg. 1522). Permission to reproduce this image was granted by Elsevier.

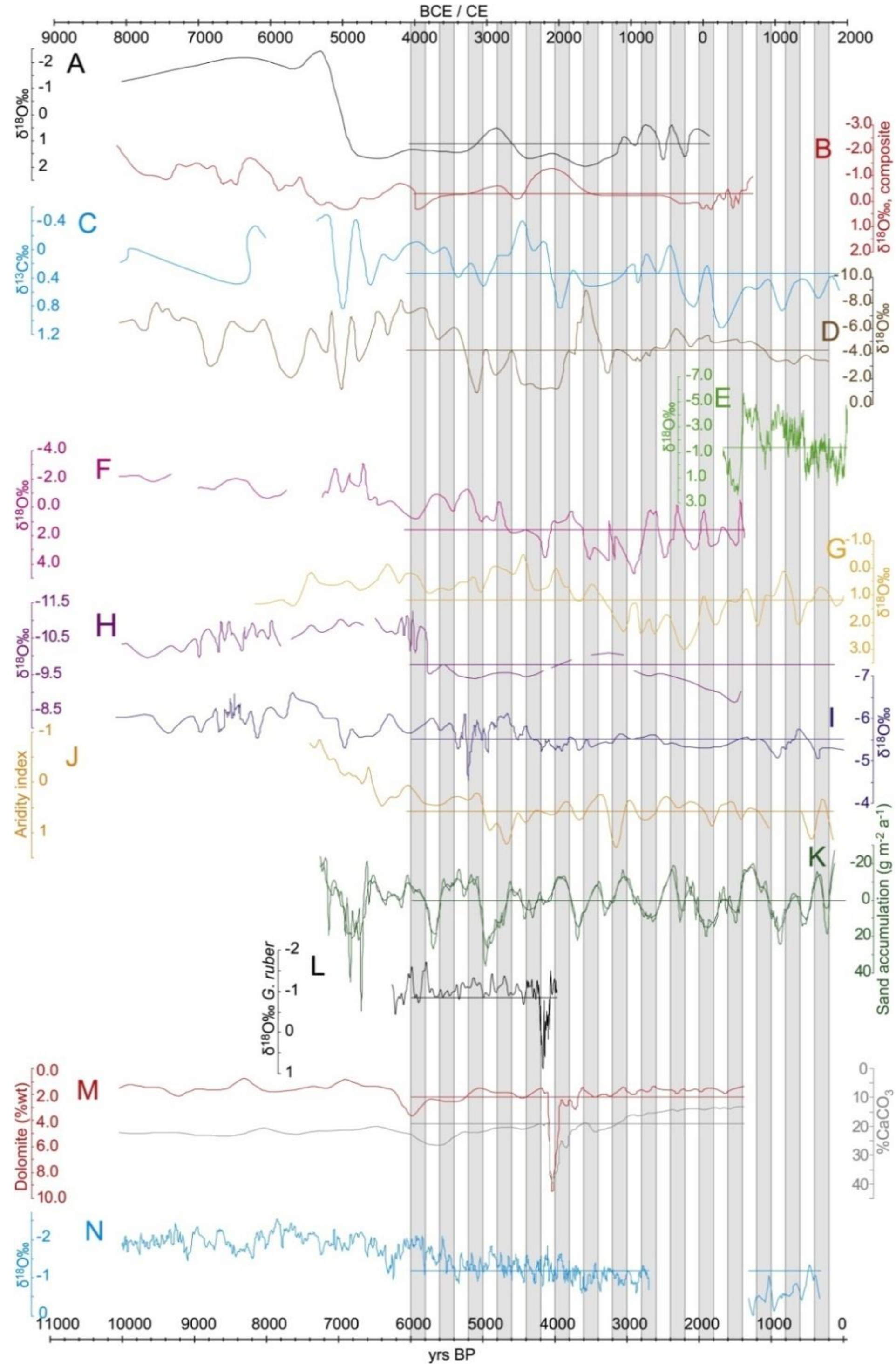


Figure 2.5: Collection of proxy based palaeoclimate data showing wetter (up) and drier (down) conditions for the Holocene. Records D (Gölhisar), E (Nar), F (Eski Acıgöl) and G (Van) highlight data from lakes in Turkey. Notice that all records show a long-term downward trend towards drier climate conditions and that there were repeated shifts between wet and dry (Finné *et al.*, 2011, pg. 3158). Permission to reproduce this image has been granted by Elsevier.

Two further lake settings which provide information on the late Pleistocene are Lake Ghab and Lake Hula (Rosen, 2007). The Ghab pollen sequence suggests that during the LGM (ca. 23500-17000 cal. yrs. B.P.) there was an expansion of Mediterranean forest into the Ghab basin until temperatures warmed after the LGM and the forests receded to their minimum extent between ca. 17000-13000 cal. yrs. B.P. Forest cover was also high around 13500-11450 years ago, corresponding to a Younger Dryas type cooling event (Niklewski and Van Zeist, 1970; Rosen, 2007). Rossignol-Strick (1995) suggests that adjustment of dating errors in the Lake Ghab core would put this sequence more in line with other pollen diagrams from the region which highlight major forest decline during drier and cooler conditions, and not during wetter and warmer phases. The Lake Hula pollen sequence (Baruch and Bottema, 1999) shows low tree pollen at the end of the LGM (here dated to ca. 20500 cal. yrs. B.P.) and a marked rise in arboreal pollen between ca. 18700-13550 cal. yrs. B.P. This pollen sequence shows a typical late Pleistocene climatic evolution with distinctive shifts between wet and dry, warm and cold associated with stadial and interstadial events.

A sharp shift in climatic conditions to warm and wet accompanies the change into the Early Holocene (ca.11700-7500 cal. yrs. B.P.). Lake records for this time period expand into previously desert type environments in Arabia and North Africa which supports a picture of moister climatic conditions (Street-Perrott and Perrott, 1993). The Lake Ghab and Hula records both show a significant rise in arboreal pollen types at the beginning of the Holocene, associated with warming and wetting (Rosen, 2007). The Lake Ghab record shows a growth in oak, pine and pistachio tree pollen (Yasuda *et al.*, 2000) suggesting forest expansion and points towards a clear shift to higher precipitation levels.

The transition at the beginning of the Holocene at Eski Lake showed a shift from herb- to grass-steppe at the same time as a negative shift in $\delta^{18}O$ values (Roberts *et al.*, 2001), with both proxies clearly responding to a more favourable water balance. Lake Van in Eastern Turkey (Lemcke and Sturm, 1997) records a similar palaeolimnological history which witnesses an abrupt isotopic depletion during the Early Holocene. In contrast to Eski Acıgöl, however, the isotopic results from Lake Van imply that maximum moisture levels were not reached until some 3000 years after the transition into the Holocene (Roberts *et al.*, 2001).

During the mid-Holocene (ca. 7500-4000 cal. yrs. B.P.) lacustrine evidence begins to characterise a new phase of climatic conditions, this time marking a period of drier episodes and the transition to late Holocene aridity. The Dead Sea record for this period (Frumkin, 1997; Frumkin *et al.*, 1994; Migowski *et al.*, 2006) shows frequent shifts between low and higher lake stands. Migowski *et al.,* (2006) records very dry conditions between 7500-5500 cal. yrs. B.P. and rising Dead Sea levels from 5400-3500 cal. yrs. B.P. This may support ideas of a wet phase around 5000 cal. yrs. B.P. as depicted in the Levant (Robinson *et al.*, 2006).

The initiation of a mid-Holocene drying trend is also depicted at other lake sites like Tecer (Kuzucuoğlu *et al.*, 2011), Gölhisar (Eastwood *et al.*, 2007a) and Van (Lemcke and Sturm, 1997; Wick *et al*., 2003). Numerous sites indicate that humidity levels were greatly reduced at this time, although the exact timing of the onset of drier conditions differs from place to place (Finné *et al.*, 2011). Generally, multi-centennial oscillations between wet and dry were superimposed on an overall drying trend as suggested by negative to positive shifts in δ^{18}O values from stacked lake sediment data (Roberts *et al.*, 2011b) .

Persisting wet conditions were followed by aridity around 4000 cal. yrs. B.P. at Lake Van (e.g. Wick *et al*., 2003), at roughly the same time (ca. 4500-3800 cal. yrs. B.P.) as a pronounced shallowing of Lake Zeribar in NW Iran as inferred from vegetation data (Wasylikowa *et al.*, 2006). At Eski, the disappearance of varved deposits around 6500 cal. yrs. B.P., and the establishment of salt-tolerant diatoms species indicate a clear fall in lake level (Roberts *et al.*, 2011b). Pollen data from this lake site also substantiate a decline in regional moisture levels as oak pollen percentages fall between ca. 5300-3800 cal. yrs. B.P., and steppic plant species begin to dominate the sequence suggesting lower soil moisture availability (Roberts *et al.*, 2011b). At Gölhisar, the vegetation record also highlights increased aridity between 4400-3900 cal. yrs. B.P., but the size of Lake Van prevents it being as responsive to climatic change as other Turkish sites (Roberts *et al.*, 2011b).

In the late Holocene (ca. 4000 cal. yrs. B.P. - present), lake data suggests a general aridification of climatic conditions and a move towards climatic conditions similar to today in the region. The best late Holocene climatic record for the Eastern Mediterranean comes from Nar Gölü (Lake) in central Turkey. The stable isotope record for this site during the last 1700 years (Jones *et al.*, 2006) indicates positive isotopic values prior to 1410 cal. yrs. B.P. and between 550 cal. yrs. B.P-present day, and generally more negative isotopic values in-between, suggesting that from AD 200-540 and AD 1400-1950 there was regional drying but between AD 540-750 and AD 1000-1350 conditions were relatively wetter.

Prior to 1700 cal. yrs. B.P., other Turkish lake sites (Roberts *et al.*, 2008; Roberts *et al.*, 2001; Wick *et al*., 2003) show that arid conditions were prevalent after 3000 cal. yrs. B.P., although a brief return to higher lake levels is evidenced around 2000 years ago. Rising lake levels of the Dead Sea, with a high-lake stand at 2050 cal. yrs. B.P. (Bookman *et al.*, 2004), also suggests that dry conditions were interrupted by a wetter phase. Lake Kinneret (Dubowski *et al.*, 2003) isotopic data details shifts between wet and dry for the late Holocene. The period from ca. 3250-2550 cal. yrs. B.P. was highlighted as being dry; this was followed by a shift to wetter conditions around 2550-1600 cal. yrs. B.P. A hiatus in the record disturbs the sequence until ca. 1250-900 cal. yrs. B.P. when dry conditions return. At 900 cal. yrs. B.P. there is a short lived wet phase and then another return to dry conditions following ca. 170 cal. yrs. B.P. (Rosen, 2007).

Most of the relevant pollen records for the late Holocene are from Lakes Hula, Ghab and Birkat Ram (Schwab *et al.*, 2004). Most of the pollen diagrams probably reflect a major influence of anthropogenic activity on landscape change for this period and therefore are only partially linked to palaeoclimatic changes. A decline in olive around ca. 1500 cal. yrs. B.P., and an accompanied increase in oak and *Pistacia*, a sign of forest re-growth could possibility be linked into a warmer and wetter phase during the Medieval period (Rosen, 2007). In Turkey, a decline in cultivated plant species and a rise in natural tree species are associated with a period of recurring Arab invasions (England *et al.*, 2008). Regardless of the influences of human activity of vegetation response, a lack of olive cultivation in Italy and higher levels of cultivation in eastern sites (like in Turkey) may suggest regional variations in relative humidity levels that favour olive growth in more eastern regions (Finné *et al.*, 2011).

2.3.3. Eastern Mediterranean climate from non-lake archives

As with varved lake sediment records tree-rings are frequently used as a proxy indicator of past rainfall because of their ability to record moisture change at high resolution. The temporal control is afforded by the annual (yet seasonally specific) formation of tree-rings. Whilst in their infancy, dendroclimatological studies in the Eastern Mediterranean (e.g. Akkemik & Dağdeviren, 2005; Akkemik and Aras, 2005; D'Arrigo and Cullen, 2001; Hughes *et al.*, 2001; Touchan and Hughes, 1999; Touchan *et al.*, 1999) probably offer the most detailed records of past climatic change, but mainly only for the last millennium. For example, studies by Touchan and others (e.g. Touchan *et al.*, 2007; Touchan *et al.*, 2005) reconstructed wetting and drying phases, and changes in precipitation levels during the last few centuries; a particularly humid episode was identified between 432 and 363 cal. yrs. B.P.. Sarris *et al*., (2007) suggest that the EM has become progressively drier, and that this pattern of aridity has become more pronounced since AD 2000 based on tree ring growth and precipitation data from southwest Turkey.

Cave speleothem records have also offered a detailed history of late Pleistocene and Holocene climatic change within the EM. Speleothem records can act as a proxy for changes in palaeo-precipitation as demonstrated by Bar-Matthews *et al*. (e.g. Bar-Matthews *et al.*, 1997; Bar-Matthews *et al.*, 2004; Bar-Matthews *et al.*, 1999). Probably the best tool for understanding climatic change has been the isotopic changes as depicted from speleothem records (e.g. Bar-Matthews *et al.*, 2003; Fleitmann *et al.*, 2009; Frumkin *et al.*, 1999; Jex *et al.*, 2010; Roberts *et al.*, 2010; Rowe *et al.*, 2012).

The Soreq Cave $\delta^{18}O$ and $\delta^{13}C$ isotopic records (see Bar-Matthews and Ayalon, 2011; Bar-Matthews *et al.*, 1997; Bar-Matthews *et al.*, 1998, 2004; Bar-Matthews *et al.*, 1999; Orland *et al.*, 2012) clearly record a LGM phase around 19000 years ago which indicates extremely cold climatic conditions. Following the LGM, isotopic values drop until minima are reached around 14000 cal. yrs. B.P. suggesting a warming and gradual increase in rainfall. A clear Younger Dryas type phase is also evidenced by higher oxygen isotope values from ca. 13200-11400 cal. yrs. B.P. and is associated with another period of regional climatic cooling (Rosen, 2007). The early Holocene record from Soreq shows a clear drop in $\delta^{18}O$ ca. 11000-9500 cal. yrs. B.P., with subsequent drops ca. 8400 and 7600, representing very warm and wet climatic conditions. A small reversal to drier conditions between these too wetter events gives evidence for an 8.2 ka cal. yrs. B.P. abrupt cooling event in the EM (Rosen, 2007). Isotopic evidence suggests that optimal warming and wetting was reached towards the end of the early Holocene around 7500 cal. yrs. B.P. where climatic conditions switch to distinct alternations between wet and dry. Rosen (2007) raises an interesting point in that the period was marked by high amplitudinal shifts in climate that became less pronounced throughout most of the latter Holocene. The Soreq Cave isotopic data detail a similar pattern for the late Holocene as is evidence elsewhere in the EM, that climate became much drier and was similar to modern day conditions. Rainfall levels were on the whole lowered but fluctuations between wet and dry were still more pronounced than they are today.

Another cave speleothem record from Sofular Cave, Turkey (Fleitmann *et al.*, 2009; Göktürk *et al.*, 2011) also offers an overview of the timing and type of climatic changes which occurred throughout the late Pleistocene and Holocene in the EM. A drop in $\delta^{18}O$ between ~16.5 and 14.8 ka years ago shows isotopically depleted values associated with wetter conditions and a subsequent increase in $\delta^{18}O$ until ~7 ka years ago suggests a shift to less moisture availability following 15000 cal. yrs. B.P. (Fleitmann *et al.*, 2009). Moisture availability in the EM though is more adequately expressed by the $\delta^{13}O$ record from Sofular Cave which highlights generally warmer and wetter conditions around 14000 cal. yrs. B.P. which gave way to drier climatic conditions by ca. 13000 cal. yrs. B.P. (Fleitmann *et al.*, 2009). Another substantial wetting is evidenced at the start of the Holocene (ca. 10500 cal. yrs. B.P.) following a period of greater aridity between ca. 13000-11300 cal. yrs. B.P. (Fleitmann *et al.*, 2009). From ~9.6 ka years ago until ~ 5.4 ka years ago, the $\delta^{13}O$ Sofular record indicates an increase in rainfall amount and intensity, in line with other EM studies (Göktürk *et al.*, 2011). On the whole, the mid-late Holocene (~ 5400 cal. yrs. B.P.-present) is dry and reflects modern day climatic conditions (Göktürk *et al.*, 2011).

Some of the geomorphological evidence for climatic and environmental change in the EM generally stems from geoarchaeological investigations in association with archaeological studies. Beach and Luzzadder-Beach (2008) have reported on increased aggradation as a partial result of climatic drying throughout the Hellenistic and Roman periods (ca. 2281-1555 cal. yrs. B.P.). Boyer *et al*., (2006) have used alluvial sediment sequences to document changing Holocene environments, and have related the geomorphological history to changing flood regimes and soil and water variability, that were likely affected by regional moisture conditions. Flood alluvial deposits during Neolithic times (ca. 10500-8000 cal. yrs. B.P.) highlighted significantly wet conditions but a shift around 4500-4200 cal. yrs. B.P. to a new alluvial regime and a cessation of flooding may relate to an oscillating trend towards drier climatic conditions after ~6500 cal. yrs. B.P.

Orbital forcing of the climate system, or more precisely precession, leads to the formation of sapropels (black, organic rich laminated sediments) in the Mediterranean Sea (Rohling and Hilgen, 1991). The formation of sapropel S1 from ~ 9300-5200 cal. yrs. B.P. coincided with enhanced levels of productivity, relating to increased seasonality and anoxic bottom water conditions (Rohling *et al.*, 1997). The formation of sapropels at this time are therefore thought to relate to warm and wet conditions (Myers and Rohling, 2000; and references therein). An interruption to sapropel S1 found in marine sediment cores around 8000 years ago was related to a climatic deterioration and disruption to deep-water ventilation which sub-divided the two sapropel units (Myers and Rohling, 2000; Rijk *et al.*, 1999; Rohling *et al.*, 1997). Although sapropel formation is driven principally by bottom water ventilation and increased productivity, the coincidence of S1 termination with dry conditions and reduced winter precipitation, and the growth of S1 during climatic ameliorations enables for climatic instabilities to be inferred from the study of sapropels (Rijk *et al.*, 1999). In this instance, EM climate during the early Holocene was moist but punctuated by a cooling trend which cooled surface waters and changed the balance of marine waters, resulting in an incursion in S1 formation.

2.3.4. Eastern Mediterranean rapid climate change events (RCC)

2.3.4.1. Rapid climate change events (RCC), an introduction

Rapid climate change events (RCC) or abrupt climatic downturns often form the backdrop for investigations into climate of the Eastern Mediterranean (e.g. Sahoğlu, 2005; Weiss, 1982; Weninger *et al.*, 2009). These climatic events are frequently believed to be involved in regional settlement abandonment, subsistence replacement, conversion to a lower hierarchical state and complete societal collapse (Weiss and Bradley, 2001). With the increased use of high-resolution, well dated palaeoclimatic data sets, each RCC has more regularly been correlated to a specific archaeologically defined redirected societal trajectory (e.g. Cullen *et al.*, 2000; DeMenocal, 2001; Weiss and Bradley, 2001). The suggested association between social change and RCC's warrants a summary of their timing and structure as they clearly represent phases of profound impact.

2.3.4.2. The 8.2 ka cal. yr. B.P. abrupt event

The 8200 cal. yr. B.P. event has been observed in a number of high-resolution proxy records in the Northern Hemisphere (Alley *et al.*, 1997; Daley *et al*., 2011). The event is clearly defined in both the oxygen isotope signals (Johnsen *et al.*, 2001) and accumulated records of three ice cores taken within Greenland (Thomas *et al.*, 2007). The climate anomaly is documented to have had a gradual onset but with a more abrupt end at 8140 years ago giving a rough duration of around 160±10 years (Rasmussen *et al.*, 2007). Oxygen isotope work on the GRIP ice core (Greenland) has suggested that overall there may have been a substantial drop in surface air temperatures by 3-6°C (Johnsen *et al.*, 2001).

In the EM, there are many uncertainties as to whether the 8200 cal. yr. B.P. climate anomaly documented in the Greenland ice cores played any role in climate variability across the region. Evidence from organic and carbon-rich marine sediments known as Sapropel 1 (S1) show a clear disruption to S1 formation around 7800 cal. yr. B.P. (Myers and Rohling, 2000). Figure 2.6 shows this break in S1 formation using oxygen isotope ratios from benthic foraminifera. Dating of this interruption puts it in close proximity to the 8200 cal. yr. B.P. Greenland climatic deterioration but not at the 8.2 ka boundary; this may confirm Rohling & Palike's (2005) ideas about a more general cooling event at this point in time in Southwest Asia.

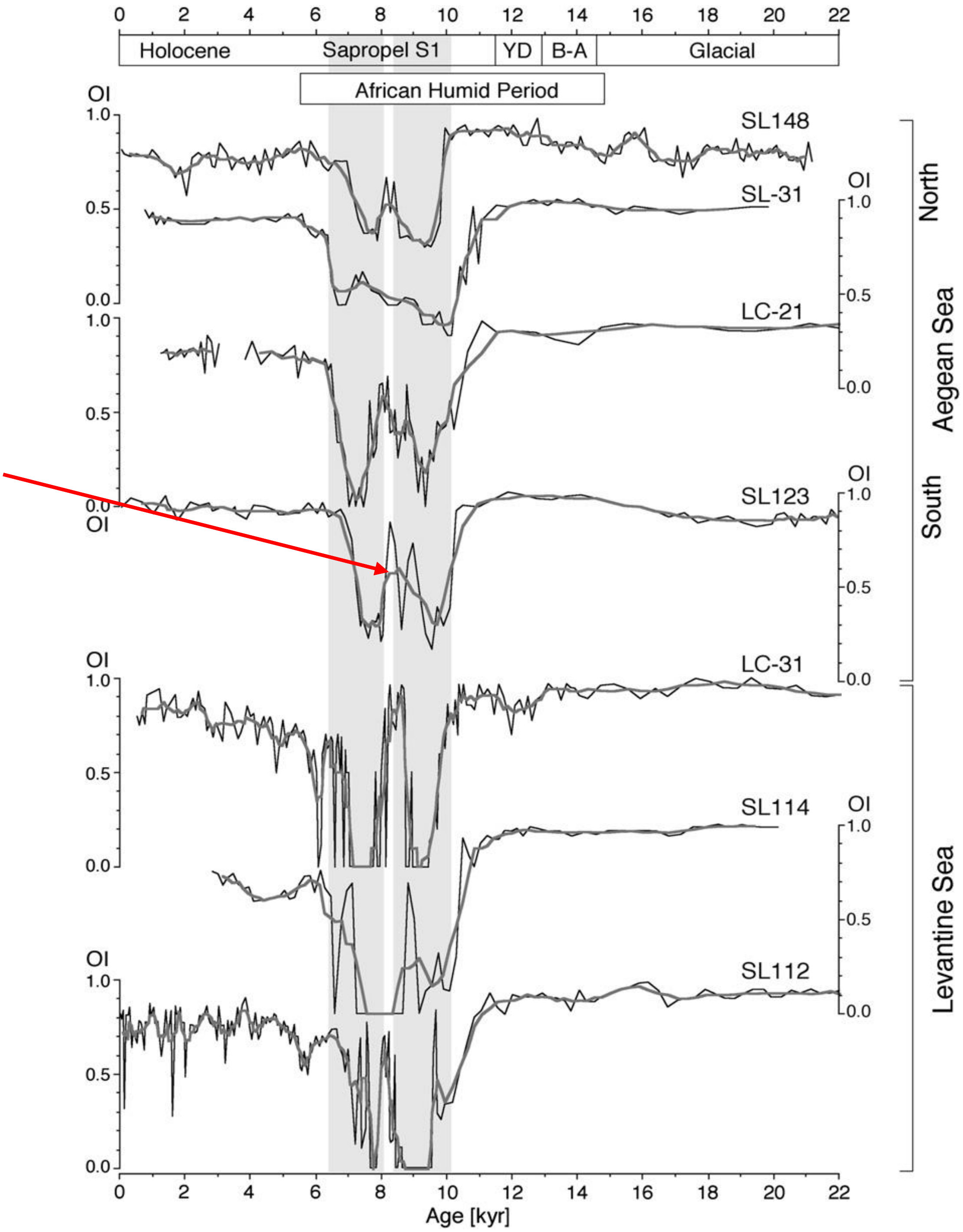


Figure 2.6: Benthic foraminiferal Oxygen Index (OI) for Eastern Mediterranean cores. Thin black line indicates fine resolution data and thick black line indicates data from 5-point running means. The grey bands represent sapropel S1 formation with the white band between indicating a short return to oxygenated conditions (Schmiedl *et al.*, 2010, pg. 6). Permission to reproduce this image has been granted by Elsevier.

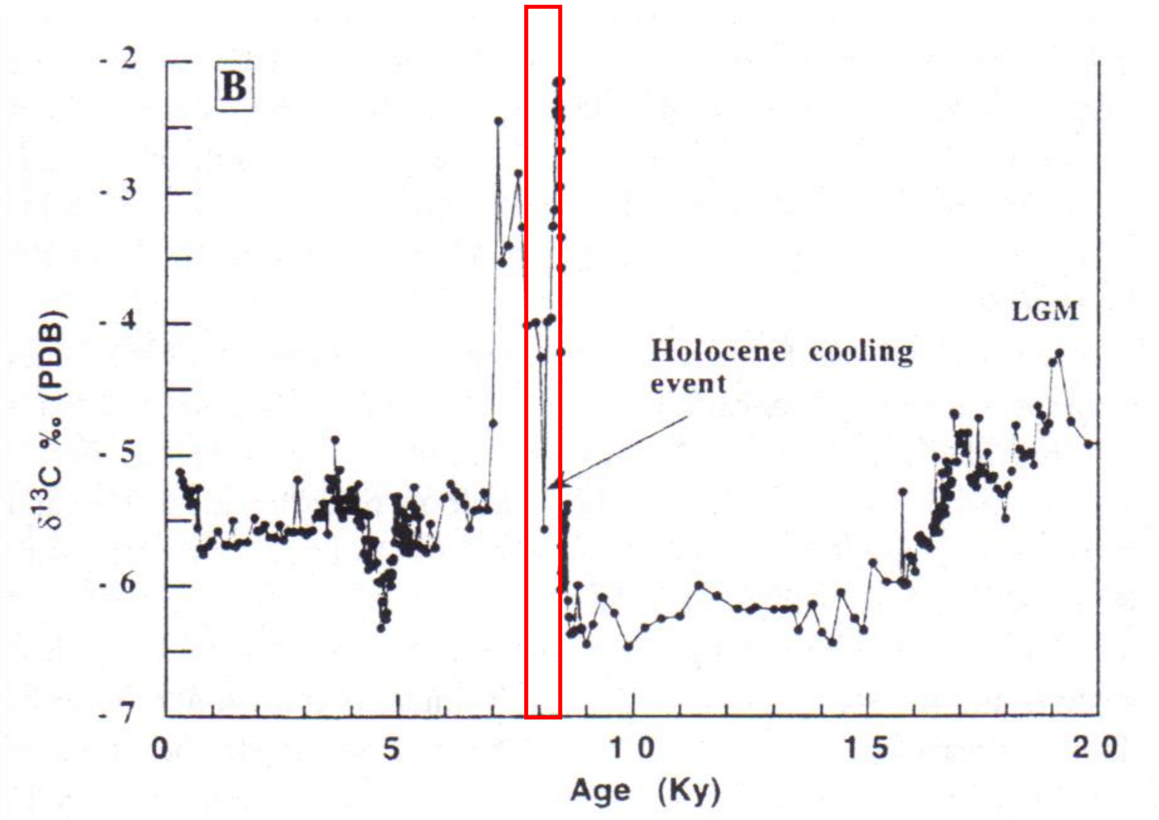


Figure 2.7: Carbon isotope curve from Soreq Cave documenting a marked low isotope reading around 8000 years ago (Bar-Matthews *et al.*, 1999, pg 90). Permission to reproduce this image has been granted by Elsevier.

Stronger evidence for an 8.2 ka event in the EM is developed by Bar-Matthews *et al* (1999) using $\delta^{13}C$ data to argue for a more precise timing of the climatic downturn (figure 2.7). Similarly, geomorphological evidence shows a strong colluvial element to stratigraphic units and the absence of sediment material at various sites during this time which could be attributed to a distinct arid phase (see Rosen, 2007). The short lived decrease in arboreal pollen types (*Quercus*, *Pistacia* etc.) documented by Rossignol-Strick (1999) around 8900-8400 cal. yrs. B.P. may also be the result of cooling and decreased regional moisture availability. The uncertainty here lies with sample resolution and dating accuracy which makes temporal resolutions between short-lived events from proxy records complicated (Alley *et al.*, 1997). Evidence points towards a dry phase and generally cold conditions around 8200 cal. yr. B.P. but it is hard to define a clear abrupt climatic anomaly in the EM which coincides with the evidence from the Greenland ice cores. A summary of the 8.2 ka cal. yr. B.P. event can be found in (Maher *et al.*, 2011).

2.3.4.3. The 4.2 ka cal. yr. B.P. abrupt event

The 4.2 ka cal. yr. B.P. abrupt event is a similar dramatic change event as the 8.2 ka cal. yr. B.P. cooling phase but is described as a switch to drier conditions, dating to ~ 4500-3500 cal. yrs. B.P. (the majority of proxy records suggesting a more precise date of 4200 cal. yr. B.P.) (see Booth *et al.*, 2005; Drysdale *et al.*, 2006; Staubwasser *et al.*, 2003; Weiss *et al.*, 1993). This event is particularly recognized in the Eastern Mediterranean where it is also associated with the abandonment of many settlement sites and the ‘collapse’ of complex societies e.g. the Akkadian empire (Cullen *et al.*, 2000).

Evidence for a rapid climate change event during the mid-Holocene is numerous. Investigations into wood remains found in alluvial flood deposits within the Mount Sodom caves, Israel reveal a series of Dead Sea lake level changes for the Holocene, of importance is a drop in lake level which is dated to around 4000 years ago (Bruins, 1994; Frumkin, 1997; Frumkin *et al.*, 1994). Other Dead Sea records also suggest a drier phase at the 4200 cal. yr. B.P. boundary. A shift from detritus clay to salt deposits recorded by Neev & Emery (1967) indicates a drop in moisture levels at this time and a higher rate of evaporation. Klinger *et al.,* (2003) also record lake terrace systems formed during low water levels, one dating to a similar time period as Frumkin’s (1997) low lake level suggesting some similarity between records in the region. The 4.2 ka discontinuity in mid-Holocene climate is additionally discussed in relation to down-cutting events and a decrease in fine clastic sediments found in sedimentary sequences of hydrological systems from the rest of the Levant region (Rosen, 2007). Rosen (1989, 1991, 1995) demonstrates that incision of streams and reduced flooding events are indicative of drier conditions as less plant cover due to aridity would cause more clastic material to enter the water system causing erosion and less over-bank alluvial deposition.

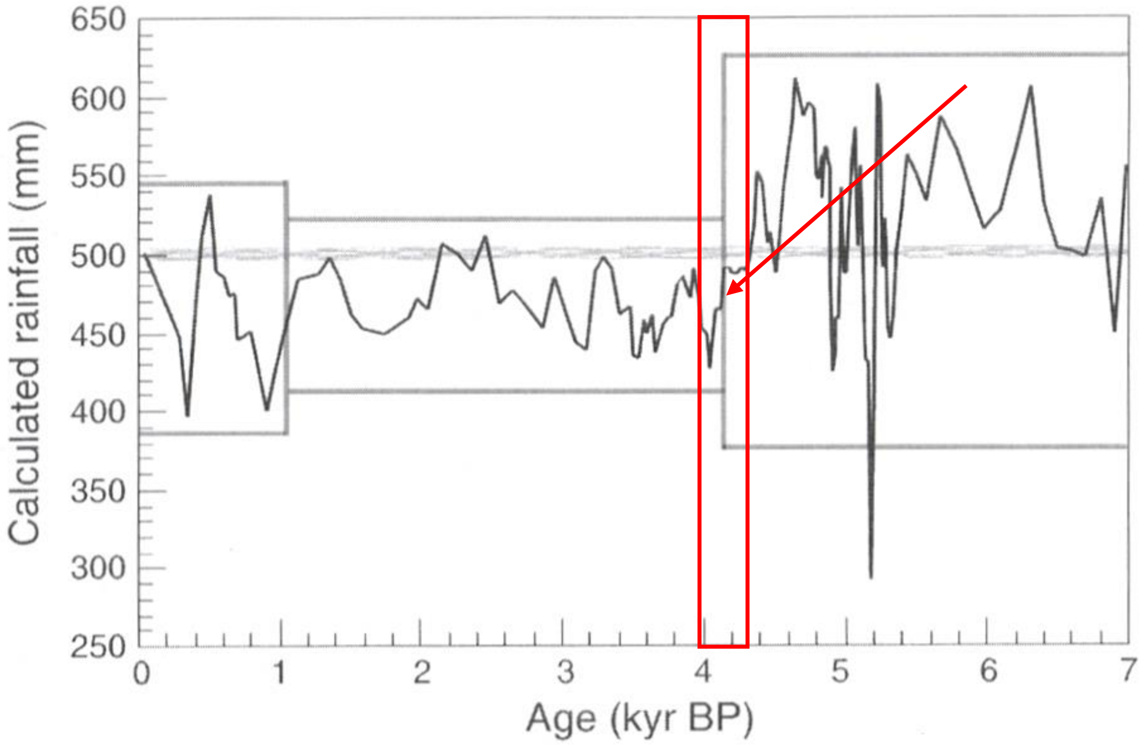


Figure 2.8: Record of palaeo-rainfall for the last 7000 years taken from isotopic values of Soreq cave speleothems. The values show a general drying trend initiated around 4000 years ago and a decrease in amplitude of the climate signal (Bar-Matthews *et al.*, 2004; Rosen, 2007, pg 82). Permission to reproduce this image has been granted by the authors.

In more recent times this evidence for a 4.2 ka cal. yr. B.P. climatic event in the EM has come under scrutiny. There are some signals from proxy records which suggest a climatic anomaly (Arz *et al.*, 2006; Cullen *et al.*, 2000; Lemcke and Sturm, 1997; Weiss *et al.*, 1993) but there are also many other records which point towards a more general long term trend towards drier climates; for example the Dead Sea records also show a continuation in low lake levels from the mid-Holocene onwards (Enzel *et al.*, 2003). Speleothem records from Soreq Cave, Israel similarly reveal a general drying trend after a typically humid mid-Holocene phase, within which a dated dry event at 4100 cal. yr. B.P. is present (Bar-Matthews *et al.*, 1999) (figure 2.8). Whilst large scale climatic shifts may be picked up by speleothem or terrace formation archives, smaller and subtle climate shifts are much more difficult to separate from other variants which could influence the climate signal (Fairchild *et al.*, 2006); as such, RCC events can be blurred and have different characteristics depending on which proxy is used to investigate the climate signal. This may explain why some scholars define the drying event as a general switch in conditions whilst others define it as more sudden.

2.3.5. Eastern Mediterranean climate and cultural change

The Eastern Mediterranean and its associated palaeoclimate are frequently discussed in relation to its long human history. Holocene climate variability, it has been argued (Rosen, 2007), played a pivotal role in the types of behaviour and changes in social systems that are recognized in the EM archaeological and historical records. Examinations of these relationships have primarily seen social groups as uniform entities who rise, adapt, or fall in response to past climate change (e.g. Neev and Emery, 1995; Weiss *et al.*, 1993). Climate change in this instance is seen as abrupt and severe; these events often tie into rapid climate shifts like those previously mentioned (Staubwasser and Weiss, 2006). Less commonly, interactions between past societies and climate/environment variability have been dealt with at the smaller socio-evolutionary level (e.g. Rosen and Rivera-Collazo, 2012) to fully understand the motivations and climatic drivers of cultural change, at a scale which might give a more accurate reflection of human response mechanisms.

Arguably, studies into the relationship between EM climatic/environmental change and regional cultural change are improving. Older assumptions that the Younger Dryas climatic event explained the development of agricultural lifestyles in the Levant region (e.g. Richerson *et al.*, 2001) no longer fit the data for pre-domestication cultivation and the ability of Naufian people to adjust to adverse climatic conditions (Rosen and Rivera-Collazo, 2012). A recent study by Rosen & Rivera-Collazo (2012) uses new theory to show the robust nature of foraging systems in the face of EM terminal Pleistocene changes. At no point does the study highlight a collapse of cultural traditions at times of shifting climates but it does suggest the climatic change played a particularly important role with regards to resource availability (Rosen and Rivera-Collazo, 2012). During cold and dry episodes in late Pleistocene EM climate, the plant resources exploited were broadened as a response to changing natural conditions (Rosen and Rivera-Collazo, 2012) which decreased the number of woodland based products which could be accessed. The model of climate and culture outlined using adaptive cyclic changes considers more than just simple cause and effect relationships but understands the complexity of social behaviours in the context of climatic variability.

The interaction between past people and changes in EM climate is also understood in terms of the abruptness, magnitude and duration of climatic changes. The globally observed events during 8200 and 4200 years ago were fast changing, high magnitude and short phases of climatic deterioration that coincided with phases of proposed societal disruption. The final Pre-pottery Neolithic B & C (PPNB/C) (8800-8200 cal. yrs. B.P.) farming communities of the southern Levant region were marked by the 8.2 ka cal. B.P. event which were probably reduced in size due to a reduction in water availability necessary for agriculture (Weninger *et al.*, 2006). Other Levantine sites like Jericho, Byblos and Ain Ghazal also have discontinuities in their occupational sequences during the final PPNB phase (Berger and Guilaine, 2009; Simmons, 2000) which corresponds to EM cooling. The problem with defining the true nature of climate and cultural interactions for this transition phase is that changes which are witnessed are not uniform across the EM; instead there are some sources of data which point towards a climatic stimulus for change and some which do not. Twiss (2007) strongly believes that social factors are to blame for the late PPNB/PPNC social discontinuities. Kuijt (2000) also offers non-climatic viewpoints as to why social groups may have disbanded at this time.

The 4.2 ka yr. B.P. climatic anomaly has also been considered as a reason for social disbandment. This argument stems from evidence that major settlement sites were abandoned during the Early Bronze Age (EBA) IV or EBA III/MBA I period (~4300-4000 cal. yrs. B.P.) and smaller or more ephemeral settlements with an emphasis on pastoral subsistence strategies were established (Richard, 1987) (figure 2.9). Characterisation and understanding of this final phase in Early Bronze Age culture indicates that instability in social systems was greatest in the central and southern parts of the EM where the effects of social ‘collapse’ are manifested within widespread settlement abandonment and economic decline (Tubb, 1998). Traditional representation of this shift in cultural development creates a picture of basic, nomadic lifestyles which were heavily influenced by climatic deterioration (Weiss *et al.*, 1993). This over simplified view of final EBA climate and culture does not account for other evidence that suggests a continuation in social systems and lifestyles. Continued occupation of EBIV sites is documented in Syria and at the southern Levantine sites of Iktanu and Iskander, East Jordan Valley (Richard, 1987; Roberts *et al.*, 2004).

New ideas like those by Rosen (2007) have gone further, suggesting more than a climatic stimuli to this cultural change event by emphasising data concerning crop yields, buffer systems, surplus, belief systems, trade with Egypt and elite control of resources as factors relevant to the linkages formulated between the 4.2 ka yr. B.P. RCC event and social abandonment. Rosen (2007) argues that climatic conditions appear bad at this time because of society’s ill-response to severe climatic stress. Esse (Esse, 1989, 1991) provides a counter argument suggesting purely social influences for the EBIV transition. An important note to draw from both Rosen’s and Esse’s ideas is that systems are integrated (Flannery, 1972); climate is rarely constraining to past communities on its own but is linked with other economic, political and social spheres to become influential in cultural change. The question remains though whether dating precision really allows us to compare climatic and cultural changes side by side.

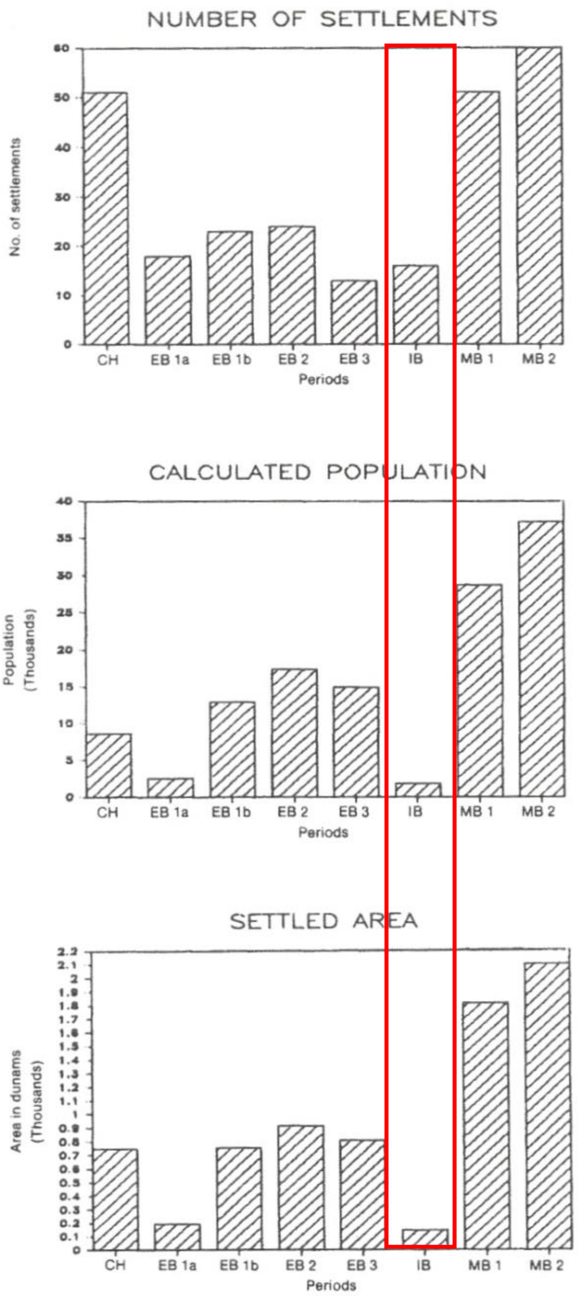


Figure 2.9: Population and settlement changes at the end of the Early Bronze Age (EBIV), in the Eastern Mediterranean, in relation to earlier and later periods (Rosen, 2007, pg 136), referencing (Gophna and Portugali, 1988). Permission to reproduce this image has been granted by the authors and ASOR publications.

One way to test synchronicity of relationships is by using climate reconstructions from the same stratigraphic sequence; for instance pollen data could be used to provide evidence for human land-use changes whilst stable isotope or geochemical evidence could be used as a proxy for past moisture level changes (Roberts, 2011). As records come from the same sequence, there is little chance of miscorrelation even if the dating accuracy is small. A study of this sort has drawn on EM climate data from Nar crater-lake in central Turkey (England *et al.*, 2008) for the last 2000 years. Stable isotope data from the lake site highlights a period of pronounced drought from 1500 to 1410 cal. yrs. B.P., with a variable age uncertainty this could be aligned with a phase of social abandonment towards the end of the Early Byzantine period (ca. 1550-1340 cal. yrs. B.P.) and it would be tempting to suggest a climatic cause for cultural change. Cultural pollen indicators from the Nar record however do not fully decline until ~1280 cal. yrs. B.P. based on precise varve count ages which are much later than the proposed arid phase. Dry climatic conditions could therefore not be a driver of cultural change at this time as the climatic stress clearly exists around two centuries earlier. Other mechanisms were therefore driving social change at this time (see Roberts, 2011).

2.4. Contextual background to climate and culture studies

2.4.1. General overview

A historically important question in academic research has been the links between climate and people and their development side by side across different temporal and spatial scales. During the Holocene, a period of connected climate and culture relations, humans have spread out across landscapes, domesticated nature, increased in number, built urban environments and dominated ecosystems (Kirch, 2005). These kinds of defining events have accelerated discussions into the role that changing climates played in past human trajectories and the intertwined nature of natural and social events during the last ~10,000 years. Given the increasing concern over human-climate-environment interactions (Rosen, 2007), it is important to evaluate, within a selected spatial and chronological framework, aspects of the archaeological record that may offer evidence of human choice and decision making processes that arise as a reaction to climatic and environmental change (Asouti, 2009).

The realms of nature and society have been studied in very diverse ways, and most research is conducted from either the anthropogenic or climate perspective, but this approach to research is slowly changing (Wylie, 2000). The role of climate in socio-climatic relations has dwindled and the emphasis given to human beings has increased, to the point that the responsibility of socio-natural dynamics lies principally with cultures (Leeuw and Redman, 2002). A climatic shift therefore is primarily a matter of the social realm and cannot become a factor in social development unless people allow it to. In this sense, climatically induced stress, for instance, is the result of adaptive failures rather than climate alone (McIntosh *et al.*, 2000). Scholarly work in recent years has focused heavily towards understanding these socio-natural interactions and recognising human perceptions of climatic change, assessed through uncertainties, risks and potentials (Leeuw and Redman, 2002). Societies, communities, individuals adjust their behaviour in light of climatic shifts and it is this adjustment in response that makes for interesting research focuses (Adger *et al.*, 2005). Past human adaptation and adjustment to climatic and environmental variability remains insufficiently studied in the Eastern Mediterranean. The question of socio-economical adaptation and adjustability, as identifiable in the archaeological record, therefore requires further study in the EM region.

2.4.2. Climate as the determining factor

Western cultures like to assume that relationships, particularly with climate, are generally external to us (McIntosh *et al.*, 2000). Relationships are therefore understood through rational and objective techniques that aim to analyse each element of the system and at specifically defined scales. This understanding of climate and culture is evidenced in the position termed ‘Climatic Determinism’; the defining statement of which is climate drives societal trajectories (Manley, 1958). Most climatic determinists seek to understand change by concerning themselves with the general laws and theories relating to the natural world and collecting and observing climatic data using ‘appropriate’ scientific methodologies (Bell and Walker, 1992). Researchers who take this position assume the world is regular, uniformitarian and predictable and that links with the human past are also recurring and expected.

The problem with ‘Climatic Determinism’ is that researchers in the field are primarily concerned with explaining/reconstructing climate or environmental changes without any connection to human agency or community response behaviours. If such attempts are made, they often refer to past people as organisms constrained by their external world (Manley, 1958). Deterministic ideas coming mainly from the natural sciences are also fundamentally lacking in an understanding of archaeology which is needed to develop and interpret concepts of human response mechanisms (Cooper and Peros, 2009). There is even less understanding of how to link archaeological and historical material to highly refined climate records; different datasets are often superimposed together to allegedly prove the impact of climate-induced stress on past people and their social development (Eddy, 1980).

Despite a long history of deterministic ideas being discredited, climate as the defining factor in anthropogenic change has become an accepted concept again (Stehr and Storch, 1998). For some current scholars (e.g. Cullen *et al.*, 2000; DeMenocal, 2001; Diamond, 2005) climate can be ultimately damaging, abrupt and constraining and inevitably detrimental to past cultures. Civilisations such as the Maya (Haug *et al*., 2003) and Akkadian Empire (Weiss *et al.*, 1993) are widely believed to have ‘collapsed’ due to climatic perturbations which appear to occur at a similar time to disruptions in the social realm. These comparisons treat past civilisations as passive bodies unable to foresee the damage that changes in climate may initiate within their social, economic and political systems. It acknowledges climate as the prime mover of human development, treating all communities as large entities without considering that cultural change may occur at various scales and for very different reasons within different communities.

Diamond’s (2005) work in particular has been criticised for not explicitly considering the role of people and their social systems in alleviating and dealing with climatic induced stresses, and the systemic disregard for past peoples problem solving abilities (Dasgupta, 2005; Good and Reuveny, 2009; McAnany and Yoffee, 2010). This may be an unfair representation of Diamond’s work however (Porritt, 2005) as there are some complex interactions considered by Diamond (2005), including the influence of hostile neighbours and trade systems.

The deterministic perception of climate/culture relationships has been fuelled in recent times by contemporary concerns over global climate change, increasingly putting climate back to the forefront of archaeological interpretations (Pillatt, 2012). Problems of dating reliability and correlating records have also left many scholars seeking more refined understandings of palaeoclimatology from the sciences to help with these dating inaccuracies (Pillatt, 2012). As a result, the emphasis placed on scientific reconstruction of past natural conditions (Anderson *et al.*, 2007) naturally leads to rather simplistic understandings of climate and people, seeking direct chronological links between evidence for climate change, archaeological change and associated aspects of societal behaviour (e.g. Bogaard and Whitehouse, 2010; Peiser *et al.*, 1998; Van Geel *et al.*, 2004). These simplistic narratives of change events are at odds with a number of scholars who have been vocal in resisting new forms of determinism (McIntosh *et al.*, 2000; Pillatt, 2012; Tipping, 2002).

2.4.3. Cultures create their own destinies

The nature/society dichotomy is a major influence on disciplinary study and is strengthened by social non-deterministic anthems also (Sluyter, 2003). At the opposite end of the scale, researchers dealing with social responses to past climate change from the humanities disciplines tend to take a rather non-climatic deterministic approach to human development and view it as primarily the result of social relationships at various scales (Renfrew, 1979). At a more extreme level, some argue that environments and climate have negligible impacts on past human societies (e.g. Aimers, 2007; Dean, 2000).

This critical reaction to climatic and environmental determinism developed from the 1950/60s onwards when concepts like cultural ecology and systems theory introduced new ideas about people and nature (Butzer, 1982; Flannery, 1972; Steward, 1955). Climate and culture relationships were for the first time considered as complex and were studied from a whole systems perspective, incorporating all aspects of the social realm. Climate change became a limiting factor to past occupations instead of being the only decisive cause. Past societies became the prime mover in social trajectories; physical parameters were therefore seen as secondary in controlling human action and development (see Coombes and Barber, 2005 for further information).

New considerations, particularly picked up within archaeology in the 1980s and 1990s also realized that the way people responded to climate change was ultimately tied up in how the natural world was perceived or the ‘meaning’ given to change events. Tsing (2001, page 6) summarises this well by arguing that ‘ the agency of nature in affecting human affairs develops in tandem with human abilities to know it and manage it in particular ways’. To put another way, the physical and mental worlds matter; sometimes these are inextricably linked and it can be difficult to fully conceptualize how past individuals, communities, societies understood their world and acted upon those notions.

Nevertheless, attempts have been made to look at all the interplaying social factors that may relate to climate change and in some way impact upon the way it is perceived, responded to and how this relates, if at all, to social action. Historical ecologies were the first move towards more balanced understandings of how social relations developed, and responded to natural change (Crumley, 1994). A people-centric perspective was established in a study by Hsu (2000) who investigated the impact of climate by trying to understand Chinese attitudes and traditions throughout time and across different spatial scales. He did this by showing that concerns regarding climate are distinctive depending on which region of China one is looking at. The Northern provinces for instance have developed legends concerning drought and the impact this has on food crops. They represent the sun as the devil and ask the dragon king to bring the rains. Hsu (2000) argued that this link between climate, ritual and folklore originated back in time when priests and divine kings exercised shamanistic rituals to influence the weather and looked towards the cosmos to correct adverse climatic conditions. Human responses in China therefore seemed to relate to social memory and the cosmology, and to distinctive ideas based on what is understood in the social world.

2.4.4. Possibilism and Incommensurability

Incommensurability is a useful concept to help explain the two different viewpoints of human/climate relations and the lack of coherency between the two (see Adger *et al.*, 2009). On the one hand there are relationships seen from the climatic deterministic perspective and on the other hand there are relations which virtually disregard any climatic input into socio-economic trajectories. The different aims, objectives and methods often confuse each field and neither is fully aware of what the other is discussing. Both concepts may be equally valid in climate and culture studies, but without working together, the types of questions being asked from both sides are not relevant to each other or comparable. This ultimately affects the way we can understand and interpret the data.

The middle ground is evident in ideas relating to ‘Possibilism’ or the concept that climate can be limiting or constraining to social systems but that culture and cultural change is predominately the creation of agency (Herzfeld, 2001). Most recently, theories such as complexity theory, non-linear change and feedback regimes (Byrne, 1998; McGlade and van der Leeuw, 1997; Schneider, 2004) have played a big impact in assessing the importance of viewing climate and anthropological change as the same process, on the same level playing field, i.e. that they are co-evolutionary and work off each other. For example, traditional ideas that the Akkadian empire collapsed (Cullen *et al.*, 2000) have been re-evaluated and argued from a feedback perspective rather than a climatic perspective. The heavy reliance of Bronze Age societies on irrigation as an adaptive measure to unstable arid climatic events was actually detrimental to their continued habitation as complete reliance on wet conditions actually made them even more sensitive to arid conditions; this is termed a positive feedback mechanism (Dearing, 2006) and is explicitly ‘agent-based’ (Wilkinson *et al.*, 2007), i.e. it is strongly control by human choice.

2.4.5. Better integration of social and climate narratives

Most recently, understanding climate and cultural change as one entity has attracted particular interest from the humanities and social science fields which widely acknowledge that traditional ideas of human-climate relationships are outdated (e.g. McIntosh *et al.*, 2000). Important arguments to draw from discussions coming out of these fields are those concerned with how we as human beings experience and understand change events. The development of ecological perspectives within archaeology has been highly influential in this instance (Kirch, 2005; Nelson *et al.*, 2007; Nelson *et al.*, 2006; Redman and Kinzig, 2003).

Adaptation to climate and climate change is one of the most discussed topics relating to climate/culture relations (e.g. Grothmann and Patt, 2005). Adaptation is often regarded as reactive in the sense that responses are triggered by past or current events (Adger *et al.*, 2005). Human behavioural change is therefore promoted by understanding the system initiating change and often takes the form of abrupt or rapid decisions (Hulme, 2003). Adaptation however can also be anticipatory, assessments are made based upon future impacts and outcomes of events which have yet to develop (Adger *et al.*, 2005). These two processes, it is argued (Adger *et al.*, 2005) must be understood before responses to change can be defined.

Adaptations are not isolated but are formulated and implemented through context (Adger *et al.*, 2005). Therefore, adaptation to change is intertwined with actions of other social, political and economic factors and can be transformed by the various elements that success of adaptation relies upon e.g. flows of capital or social affiliations (Adger *et al.*, 2005). This reiterates the idea that climate and culture cannot be dealt with as separate areas of research; that it is highly likely that one will impact upon the other at any given time, and that they co-exist. This inter-relatedness of climate and cultural aspects crucially demonstrates the need for current research to accommodate the dynamism of human agency and to understand the choices that past people would have faced.

Adger (2001) states that human response relates to all the relationships that exist in a given situation, he particularly draws on political ecology ideas to show how the political world can impact upon how societies handle risk. Whilst political ecology (Robbins, 2012) ideas may be beyond the scope of this project, Adger clearly demonstrates a way of achieving more sophisticated interpretations that account for culturally conditioned experiences of climate. Another method would be to employ modelling techniques to focus on the climate changes experienced, recognised and responded to by past people, and to focus on the self-organising and adaptation principles outlined here. Exploratory models have been most informative when demonstrating resilience to climate within social systems (Hudson *et al.*, 2012; McAnany and Yoffee, 2010; McGlade and van der Leeuw, 1997; Redman and Kinzig, 2003; Redman *et al.*, 2009). The shifting emphasis towards resilience and longer-term socio-natural dynamics does not disregard collapse events but asks why there may have been social change concurrent with climatic changes - questions such as adaptation abilities and the role of limiting factors for example (Hudson *et al.*, 2012).

2.4.6. Resilience theory in climate and culture studies

The concept of resilience theory is most adequately explained in Redman (2005). It is a concept that can be used to characterise, by periods, changing and stable relationships between humans and climate. It is defined as the amount of change a system can undergo yet remain stable before having to move into a new regime (Hudson *et al.*, 2012). It represents a means for archaeologists and natural scientists to approach the ideas of human adaption, societal perception and self-control without completely disregarding the potential impact of climatic stress or necessary climatically induced collapse. Collapse though is not thought of as the same as Diamond's (2005) collapse but a shift to a new resilience state, following Holling & Gunderson's (2002) idea of the adaptive cycle and panarchical transformations (Gunderson and Holling, 2002) (figure 2.10).

The adaptive cycle model (figure 2.10) is a way to understand change events. Change in the model can be both sudden and unexpected, created and needed, and is used to visualise and contextualise continuous transformations within systems (Weiberg, 2012). To understand the concept further the reader is directed towards Holling and Gunderson (2002). Associated with the adaptive cycle model is the idea of panarchy (Gunderson and Holling, 2002) which is a nested set of cycles within a sort of hierarchy to theoretically identify scales of adaptation. Over long-term periods of stress, for example caused by climatic or environmental variation, socio-economic systems can change position across these scales to combat stress (Vaneeckhout, 2012).

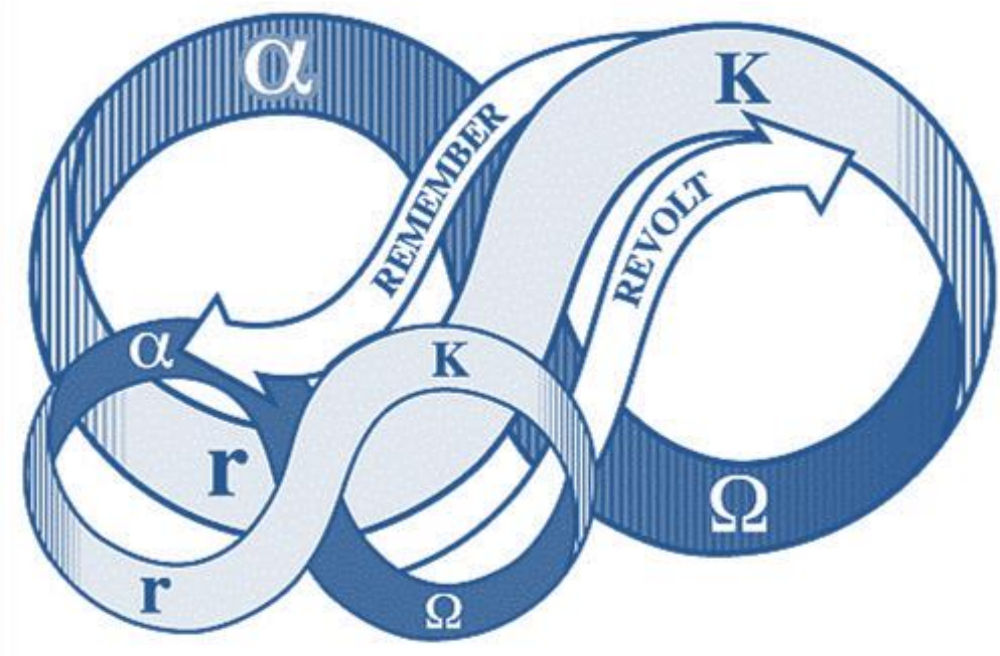


Figure 2.10: Illustration of panarchy model showing two adaptive cycles. From *Panarchy* edited by Lance Gunderson and C.S. Holling (Gunderson and Holling, 2002). Copyright © 2002 Island Press. Reproduced by permission of Island Press, Washington, DC.

Principally, the resilience model of change built around adaptive cycles highlights four dynamic phases of transformation per cycle to include: 1) a release phase (Ω), 2) a re-organisation phase (α), 3) a rapid growth phase (r) and 4) a conservation phase (K) (Zimmermann, 2012). The forward loop identifies periods of increasing exploitation and accumulation (r) which reach a saturation point of maximum conservation and connectedness (K) (Dearing, 2008). The backwards or negative loop witnesses a force of destabilisation (Ω) which culminates in the eventual stabilisation and re-organisation (α) of another cycle (Dearing, 2008). Higher resilience levels are defined between the (Ω) and (r) stages, and decline between (K) and (Ω). Social groups who are less resilient (or potentially it could be argued, more resilient) will collapse into a different cycle as a means of adaptation to tolerate a disturbance or stress factor. It is therefore possible to understand the potential causes of collapse and the emergent features that arise from evolution into a new state (e.g. simplification or increasing complexity) (Dearing, 2008).

Resilience theory, epitomised by the adaptive cycle concept includes two key features which makes it useful for understanding culture-climate relations. Firstly that change is inevitable and recurring (although change cycles may evolve in different ways) and secondly that there are only some scales of analysis that are applicable to any one particular system, which has repercussions for understanding the speed of change (Redman, 2005). There is also a third consideration, but this insight is really the reason why resilience theory is seen as useful in studies regarding human response to climate change events; it is that people can be self-organising and can move a system towards a more desirable state (Redman, 2005). Perceived in this way, climate is but one part of the system and has the potential to influence any part of it. Climatic uncertainties and stresses, and/or positive climatic influences, will be more influential in effecting a human response if the phenomenon is perceived by the people expecting them, and considering other system factors e.g. population expansion.

The generally longer-term, large scale viewpoint of the resilience model concept is seen by some to be too Processual in nature, drawing heavily on systematics and cultural evolutionism (Weiberg, 2012). On the other hand, using resilience theory within culture/climate studies has brought back aspects of large scale analysis and integrated ideas of complex systems theory that were lost to some degree under Post-Processual strands of archaeological investigation (Bentley and Maschner, 2003; McGlade and van der Leeuw, 1997). The benefit of this is that change processes can be dealt with in light of individual historical cases and archaeological data can be adequately contextualised.

2.4.7. Research needs

Research on natural environmental-change and how it interacts with documented human histories needs to be extended in new ways to include a humanist as well as scientific approach to relationships. Many examples already exist which try to add social issues into studies of past climate change but it is important to keep these contributions going to develop a deeper understanding of nature/climate dichotomies at spatial and temporal scales that have yet to be investigated. For scientists, the nature of past adaptive responses may be intriguing but for modern societies it may be even more necessary to look at how climate change altered lifestyles given the current shifting climate state.

Whilst many studies discuss connections between climate and cultures (Dalfes *et al.*, 1997; Roberts *et al.*, 2011a; Weninger *et al.*, 2009), the discourse on complex systems theory and resilience has been virtually overlooked. In cases where such studies do exist (see Weiberg, 2012), they generally focus on what has been lost rather than gained by each adaptive transition and most have been directed towards understanding typically 'collapse' style events (Weiberg, 2012). The challenge therefore is to expand scholarly debate by looking at transformations in new areas, and where research is not usually directed towards full scale collapse. Resilience theory as a contextual concept offers a positive outlook on cultural transformations taking into account human flexibility and thus is a promising model to use within future culture-climate studies.

2.5. Chapter summary

Palaeolimnological studies offer the potential to understand shifting climatic and environmental characteristics using a range of biological, sedimentological and chemical indicators. A current focus of palaeolimnological studies is on utilising higher-resolution data sets to refine our understanding of natural change at the shorter timescales and to ensure we retrieve material that can be accurately dated. Those with the highest precision are lake sediments which are annually banded. Varved lake deposits are generally dependent on both internal and external factors thus are good recorders of change happening within and outside the lake environment. There are numerous ways of extracting climatic and environmental data from these yearly deposited sequences but recent advances in XRF scanning techniques have resulted in the frequent use of this analytical technique.

The Eastern Mediterranean (EM) region is influenced by a number of climatic and environmental factors. The region has a complex climatic history that has been documented using multiple investigatory techniques including proxy studies on lake sediments. EM climate has principally been documented in terms of shifts between wet and dry conditions; the LGM and Younger Dryas being dry and cool whilst the early Holocene being moist and warm. Desiccation and more frequent aridity are documented from around 6000 years ago towards present day. These shifts in climate have been particularly important to human development in the EM throughout the Holocene and have been related to key changes in social systems.

Understanding of climate-environment-social relationships is a complex topic, and it is generally not agreed upon as to how best to tackle the issue of how past societies responded to noticeable shifts in climatic conditions. Traditional viewpoints took a rather deterministic stance, suggesting that climate was a key driver of societal change. More nuanced perspectives however suggest that climatic events may only play a role when humans cannot comprehend and/or adapt to climate and climate change. It has been deemed necessary to avoid implying that societies were passive hostages to climate and to use case by case situations to investigate the role of both natural and anthropogenic factors in cultural development. New research is required to address socio-evolutionary trajectories in relation to climatic fluctuations of different magnitudes, drawing on ideas of adaptability and societal resilience. A problem is that studies lack an understanding of the whole system, but at the same time it is important to remember that changes in natural conditions are fundamental components of that system.

3. Methods

3.1. Chapter Introduction

This chapter outlines the methods applied to analyse lake sediment samples from Nar Gölü. It introduces site selection procedures and describes the field and laboratory processes employed to investigate palaeoenvironmental and climatic histories of the lake site. Also included is a discussion of archaeological archival research and data collection for Cappadocia, central Turkey.

3.2. Site selection and overview

3.2.1. Justification of site selection

The aims and objectives of this project were to produce a well-dated, fine resolution record of Holocene climate/environmental variability, and to compare the palaeo-climate story with past socio-evolutionary trajectories as delineated from archaeological data. The site chosen for study therefore needed to incorporate material that was annually to decadally resolved, covered the Holocene time period, allowed for strict chronological control and be in close proximity to areas of past human habitation.

Investigations at Nar Gölü, a crater-lake site (figure 3.1), from 1999 onwards by Professor Neil Roberts and colleagues (various institutions) identified lake sediment material that was annually varved and therefore suitable for establishing a reliable chronology. A new coring programme in 2010 extended the varved sediment record back into the Late Glacial adding to existing datasets which cover the late Holocene. Multi-proxy work conducted on previously extracted lake sediment sequences from Nar Lake have characterized past climatic and environmental change well (England, 2006; England *et al.*, 2008; Jones, 2004; Jones *et al.*, 2006; Turner, 2007; Turner *et al.*, 2008;

Woodbridge, 2009; Woodbridge and Roberts, 2010, 2011; Woodbridge *et al.*, 2010), suggesting that material from this site is highly suitable for Holocene climate/environment variability studies. Nar Gölü is also conveniently located in the Cappadocia region of Turkey which has been extensively occupied by past people and where widespread archaeological investigations have taken place (Eastwood *et al.*, 2007b; England, 2006).

Figure 3.1: Study site – Nar Gölü (looking north-west).

3.2.2. Summary of study site - Nar Gölü

Nar Gölü (also known as Acı Göl/Acıgöl on Google Earth; Göl is lake in Turkish) (38°20’25’’ N, 34°27’24’’ E; elevation 1363 m.a.s.l) is located in Cappadocia, central Turkey (figure 3.2). Nar is a >20m deep oligosaline volcanic crater-lake, 0.5km in diameter, with a modern conductivity of 2.5-3.1 mS cm-1, and pH of 7.1-7.4. Its catchment is small (2,408,000 m^2) and does not reach far beyond the upper lake boundaries; human activity and disturbance are therefore relatively limited at the present day (Jones *et al.*, 2006). The main features of Nar Gölü (figure 3.3) include basalt intrusions to the north, steep walls to the east and west, volcanic ignimbrite features (‘fairy chimneys’) to the south and an alluvial delta fan on the southern side which extends deep into the lake waters (Jones *et al.*, 2005). Whilst there is a relatively simple hydrology with no permanent surface inflows or outflows, there are a number of springs in the south, as well as a hot spring which enters below lake level (figure 3.5) (Jones *et al.*, 2005). Investigations of the upper springs during 2010 and 2011 found them to be almost dry (personal observation).

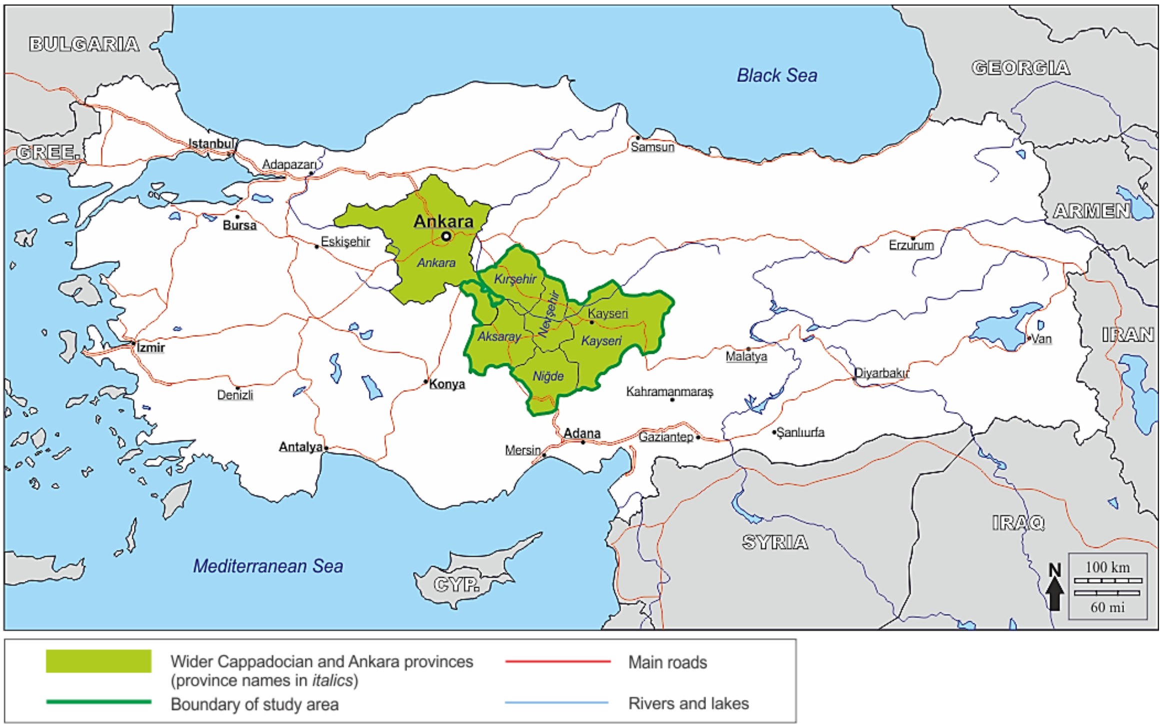


Figure 3.2: Map showing the wider geographical context of the study region Cappadocia.

The modern day climate of the area is semi-arid; in summer there is little rainfall and high temperatures (Türkeş, 2003). Average temperatures for July and August range between 20°C and 27°C, while those in winter fall to 3°C to -3°C reflecting the continentality and elevation of the area. Mean monthly and annual precipitation levels for two weather stations close to Nar Lake (Nevşehir and Niğde) from 2001-2010 can be seen in appendix 1. The data highlights that modern precipitation levels in Cappadocia during the summer are low, with some years recording 0mm for the months of July, August and September. Autumn and winter precipitation levels (appendix 1) in contrast are relatively high but can vary dramatically year on year. The climate at Nar Lake falls neatly within the Central Anatolia climatic zone (Unal *et al.*, 2003). Present day vegetation of Cappadocia is characterised by dry-steppe-forest but below ~1100 m.a.s.l vegetation becomes steppic, with *Festuca*, *Poa* and other grasses, along with *Artemisia* and chenopods. Above ~ 1400 m.a.s.l deciduous oak woodland dominates but is highly degraded. The area is agriculturally active today, with cultivation of cereals, pulses and some areas under vines, particularly below ~ 1100 m.a.s.l (Eastwood 2011, *pers. comm*).

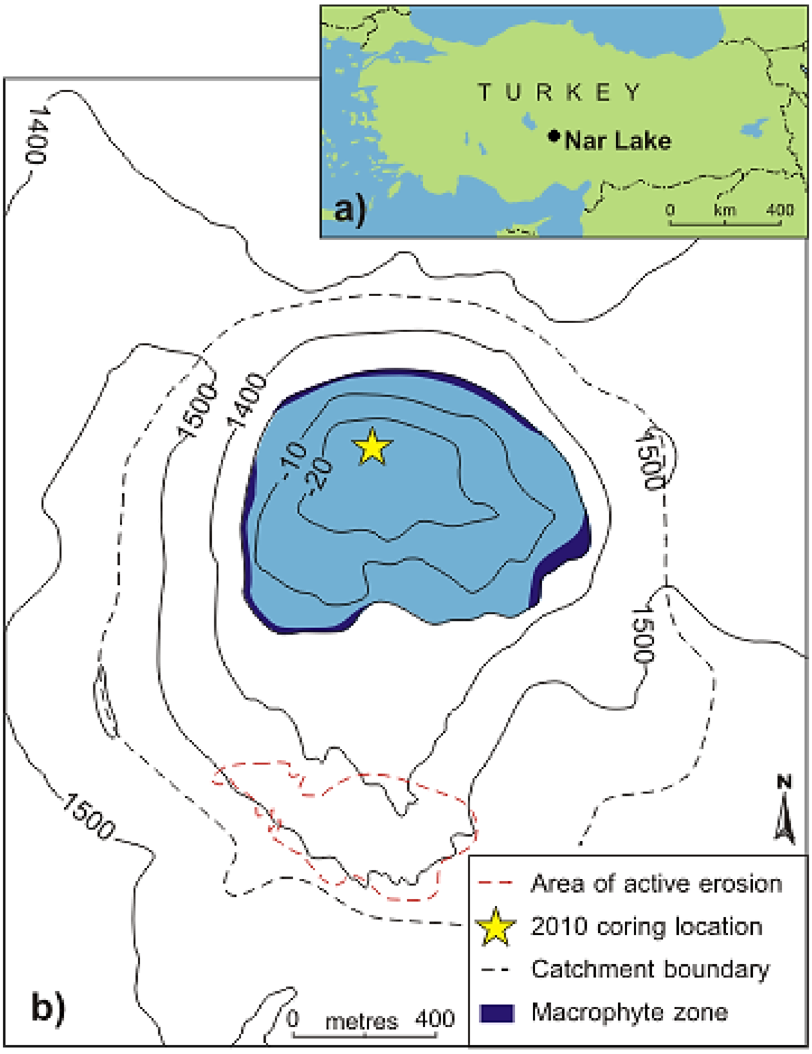


Figure 3.3: Location of Nar Lake within a) the wider region and b) its catchment.

3.2.3. Regional geology

Nar Gölü is situated within Cappadocia that forms part of the Central Anatolian High Plateau (CAHP) and the Cappadocian Anatolian Volcanic Province (CAVP) (Aydar *et al.*, unpublished), which have a long history of volcanic activity of Neogene-Quaternary age

(Druitt *et al*., 1995) (figure 3.4). The CVAP comprises several eruptive centres and extends across the modern day provinces of Nevşehir, Aksaray, Niğde and Kayseri. As a result of faulting and volcanism, numerous lake basins of Miocene-Pliocene and Quaternary age dot the landscape (Karabıyıkoğlu *et al*., 1999; Woodbridge, 2009). The crater-lake at Nar is believed to have been created by fault-controlled volcanic eruptions which left topographic depressions that resulted in the evolution of lake-basin (Gevrek and Kazanci, 2000). The region of Cappadocia has been subjected to at least nine major ignimbrite eruptions of tertiary age (Le Pennec *et al*., 1994) but the exact age of Nar Gölü is still unknown. The presence of basaltic and volcanic ash layers just south of Nar Lake, which have been dated by K/Ar and Ar/Ar dating techniques, give evidence that Nar is younger than the 1.6 Ma basalt deposit (Jones, 2004).

There are four key Cappadocian Quaternary volcanoes: Acigöl (Nevşehir) caldera, Göllü dağ, Hasan dağ and Erciyes dağ (Kuzucuoğlu *et al*., 1998). Nar Gölü is located within the Göllü dağ – Acigöl area of the CAVP. Volcanic tephra studies on lacustrine material from lake Eski Acigöl (25 km from Nar Lake), suggest that Cappadocia has been subjected to several volcanic eruptions during the Late Pleistocene and Holocene up until ~5000 years ago (Kuzucuoğlu *et al*., 1998; Woodbridge, 2004). Tephra horizons most certainly originate from the near-by volcanoes mentioned above, in particular the Hasan dağ and Acigöl complexes (Kuzucuoğlu *et al*., 1998). The ages of the ten tephra layers recorded in the Eski Acigöl sediment sequence give evidence for strong volcanism during a period of important climatic and societal changes (Kuzucuoğlu *et al*., 1998). The proximity of Eski Lake to Nar Gölü suggests that the Nar Lake basin likely experienced some of the same volcanic activity as Eski, and therefore could also record Cappadocian tephra horizons of Holocene age. There is also evidence of a major explosive volcanic eruption within Cappadocia at 8.6 ka B.P. from distal tephra found widely across the Eastern Mediterranean (Develle *et al*., 2009; Hamman *et al*., 2010).

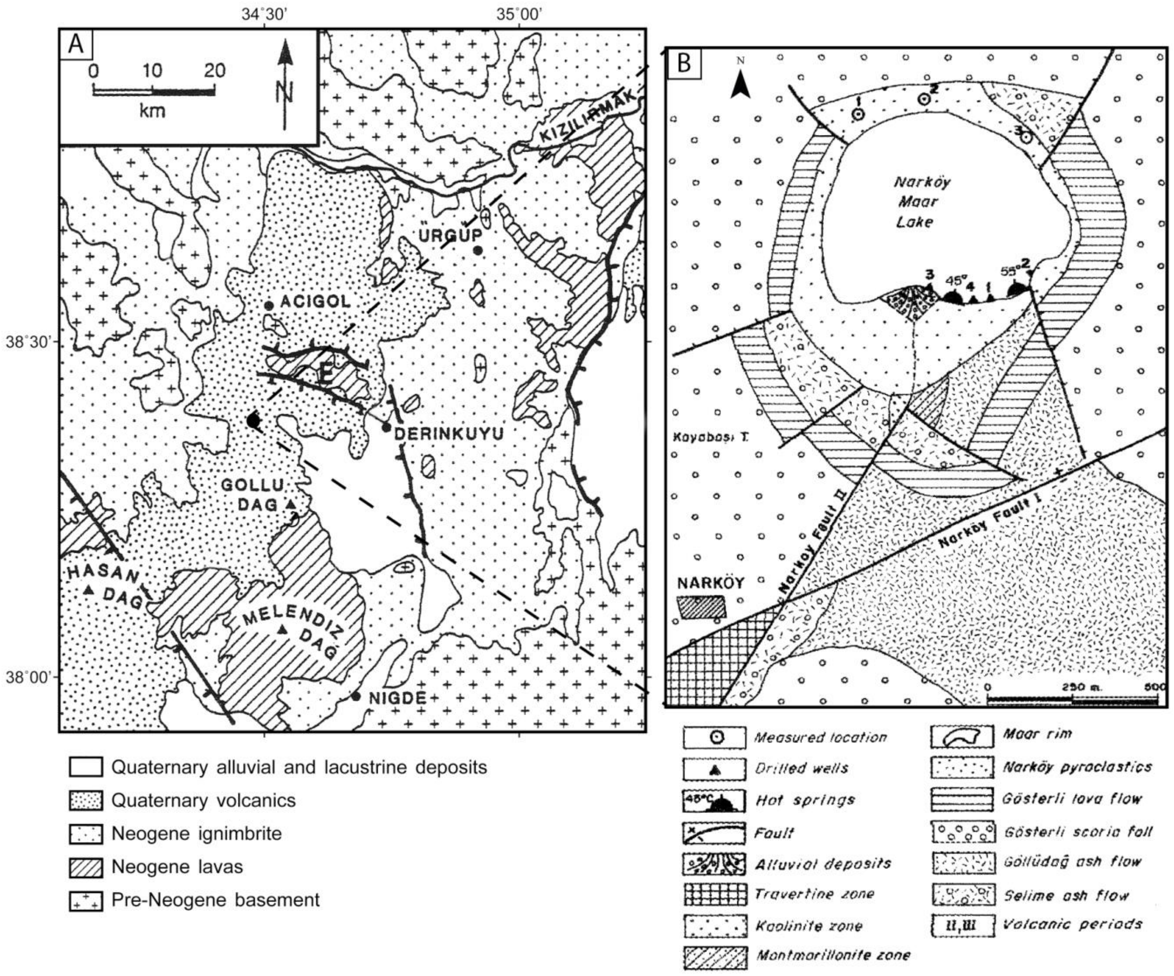


Figure 3.4: a) Regional geological map of Cappadocia (adapted from Druiit *et al*., 1995) and b) geological map of Nar Gölü (adapted from Gevrek *et al*., 2000).

3.2.4. Previously extracted core sequences from Nar Gölü

Previous coring programmes and preliminary investigation work was carried at Nar Gölü between 1999 and 2002, and in 2006 (table 3.1). Using lake bed morphology to identify the deepest part of the lake (25m water depth at time), a site was chosen for core extraction to obtain a long and undisturbed sediment record (Dean *et al*., 2012; England, 2006). In total, a 376cm composite core sequence (NAR01/02) was developed from cores extracted in 2001 and 2002 (figure 3.5) using three coring methods; consisting of Glew (Glew and Smol, 2001), Mackereth (Mackereth, 1969) and Livingstone (Livingstone, 1955) techniques. The Glew corer was used to extract the top most sediment from the lake bed and to ensure recovery of the sediment water interface (England, 2006). Mackereth and Livingstone cores allowed longer core sequences to be retrieved (1 & 3, and 5 meters respectively) and less disturbance of the sediment profile (Jones, 2004; Turner, 2007; Turner *et al.*, 2008; Woodbridge, 2009). In 2006, another short Glew (Glew and Smol, 2001) core of 36cm was collected from Nar Lake (NAR06) (figure 3.5) to correlate to the existing master core sequence from 2001/2002 (Woodbridge, 2009).

Table 3.1: Nar Lake 2001, 2002, and 2006 core information. The 2001 and 2002 individual core sections were combined to create one composite master core sequence (NAR01/02) (only the details of individual core sections used in the master sequence are listed).

Core	**Year of core extraction**	**Total core length (cm)**	**Length of core section used for analysis (cm)**	**Time period of sections used for analysis (vys)**
NAR01 GB	2001	27	27	0-21
NAR02 M2(1)	2002	97	89.5	39-261
NAR02 M2(2)	2002	79	76	279-701
NAR02 M2(3)	2002	87	70	719-1001
NAR02 M3(3)	2002	86	80.5	1019-1282
NAR01 LBIII	2001	96	5.5	1298-1342
NAR01 LCIII	2001	85	81.5	1359-1705
NAR06	2006	36	36	0-80

These core sequences were laminated throughout. ^{210}Pb and ^{137}Cs dating of the top 50cm of the master core sequence and sediment trap data confirmed the laminated couplets to be annual deposits (Jones *et al.*, 2005; Woodbridge and Roberts, 2010). Dating of the rest of the master core sequence from 50cm down was based upon laminae counts given in varve years before AD 2001 and converted to calendar years (see Jones *et al.*, 2006 for further details). The three core sequences from the 2001, 2002 and 2006 coring seasons were stratigraphically correlated through visual identification of varve couplets and matching sedimentary patterns between cores.

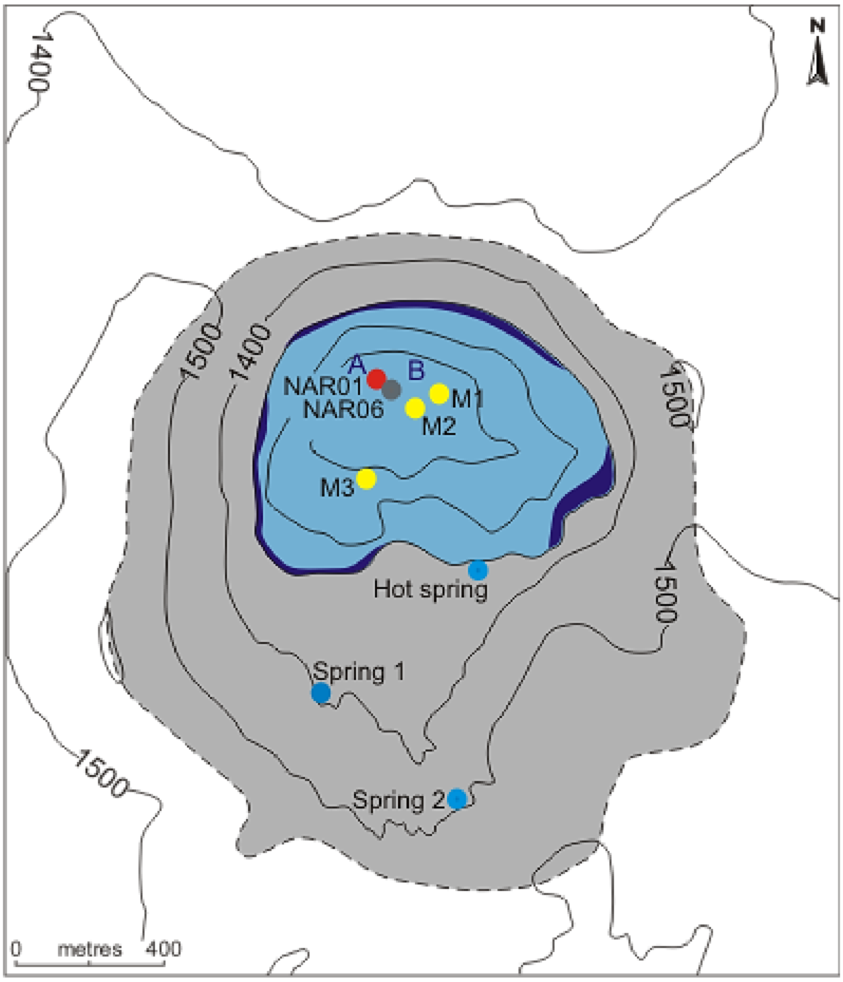


Figure 3.5: Previous Nar Lake sampling locations. NAR01 (red circle); NAR02 (M1, M2, M3; yellow circles) (Jones, 2004); NAR06 (dark grey circle) (Woodbridge, 2009). Also indicated are sediment traps installed in 2006 (A & B) and known spring locations. Grey shading indicates the boundaries of the Nar catchment (Imaged adapted from Woodbridge, 2009).

3.2.5. Previous work on the Nar 2001/2002 extracted core sequence

The Nar Gölü 2001/2002 (NAR01/02) composite sediment core sequence has been investigated using a number of different proxy indicators with the aim of studying past Eastern Mediterranean environmental and climatic change. Analysis of the NAR01/02 record highlights changes for the last two millennia related to a combination of natural and anthropogenic factors. For an in-depth understanding of previous work at Nar Gölü the reader is directed to the original publications which detail stable isotope (Jones *et al.*, 2006), diatom (Woodbridge, 2009), micro-charcoal (Turner, 2007) and pollen (England,

2006) work to date. Whilst these works provide the best overview of the late Holocene sediment record from Nar, variability in the different proxy records will be highlighted again here.

The sediment sequence was analysed at high-resolution for stable isotope analyses to record changes in δ^{18}O and to understand late Holocene variations in precipitation and evaporation (figure 3.6). A major change to more negative isotope values is dated ca. AD 530, while major shifts to more positive isotope values occur at ca. AD 800 and ca. AD 1400 (England *et al.*, 2008; Jones *et al.*, 2005; Jones *et al*., 2007; Jones *et al.*, 2006). The stable isotope data therefore show drier periods (AD 300-500 and 1400-1960) and wetter intervals (AD 560-750, 1000-1400 and post-1960) that were related to the intensity in summer drought and changes in the amount of spring and winter precipitation (Jones *et al.*, 2006).

Diatom-inferred (DI) conductivity (excluding bloom taxa) and δ^{18}O show very good correspondence for the first half of the NAR01/02 record and demonstrate that the Eastern Mediterranean region experienced repeated drought prior to AD 540, with a subsequent rapid and simultaneous shift to fresher lake conditions and wetter climate (figure 3.7) (Woodbridge and Roberts, 2011). Diatom data suggests that following AD 540 there was another dry phase during AD 800-950 before the onset of a wet medieval phase from AD 950 to AD 1400. During the subsequent Little Ice Age (LIA) (~AD 1700-1900), DI-conductivity and δ^{18}O become decoupled. The presence and growth of distinct diatom bloom events at this time may suggest that the diatom community had a different relationship with lake water conductivity for the latter part of the record. It is postulated that increasing human influences on the lake environment as identified in the Nar Lake pollen record (figure 3.6) could be a contributing factor to the difference responses between the isotope and diatom proxies.

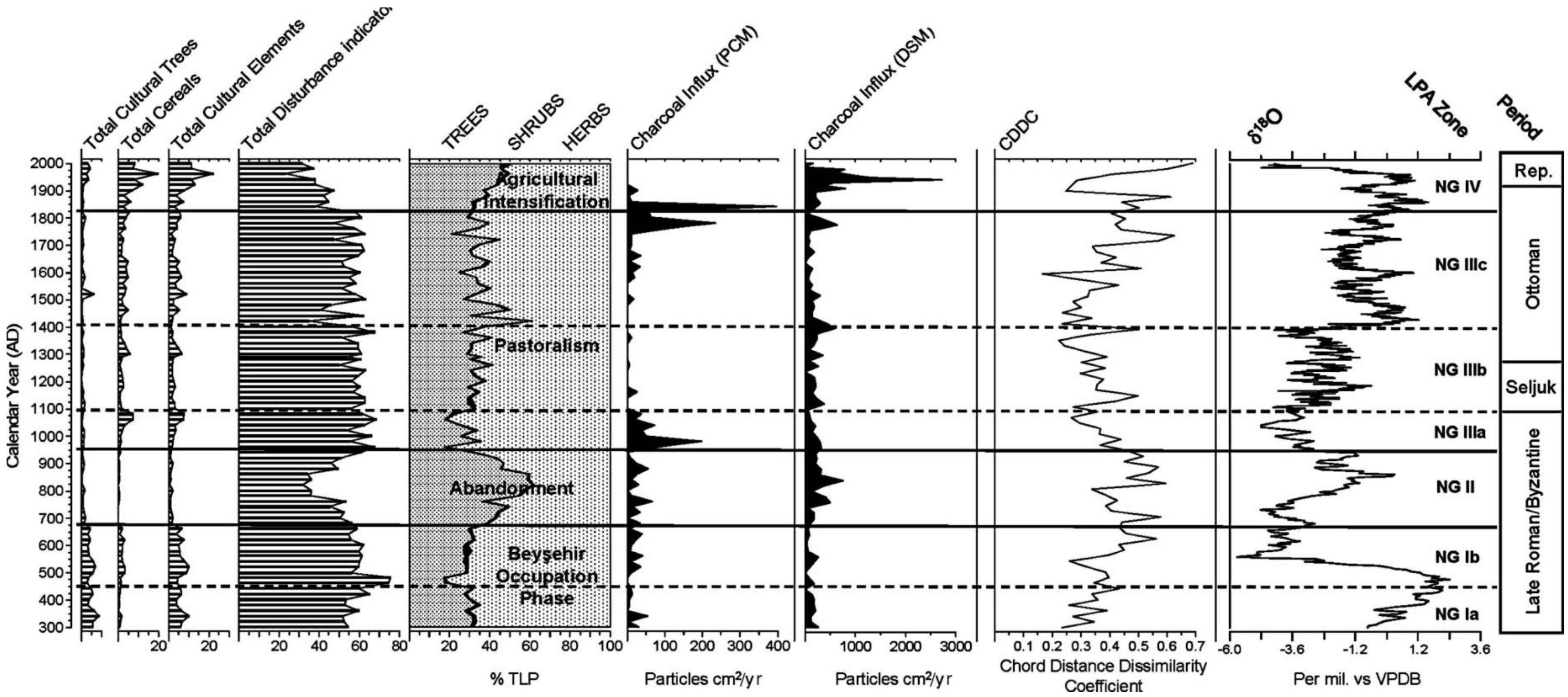


Figure 3.6: Synthetic diagram showing late Holocene environmental changes as inferred from Nar Gölü lake sediments. Shown are the results from pollen analysis, charcoal analysis using palynological (PCM) and density separation methods (DSM), and stable isotope analysis. Records are plotted alongside calendar ages and archaeological time periods for interpretational purposes (image taken from England et al., 2008, pg. 1239). Permission to reproduce this image has been granted by SAGE publishing.

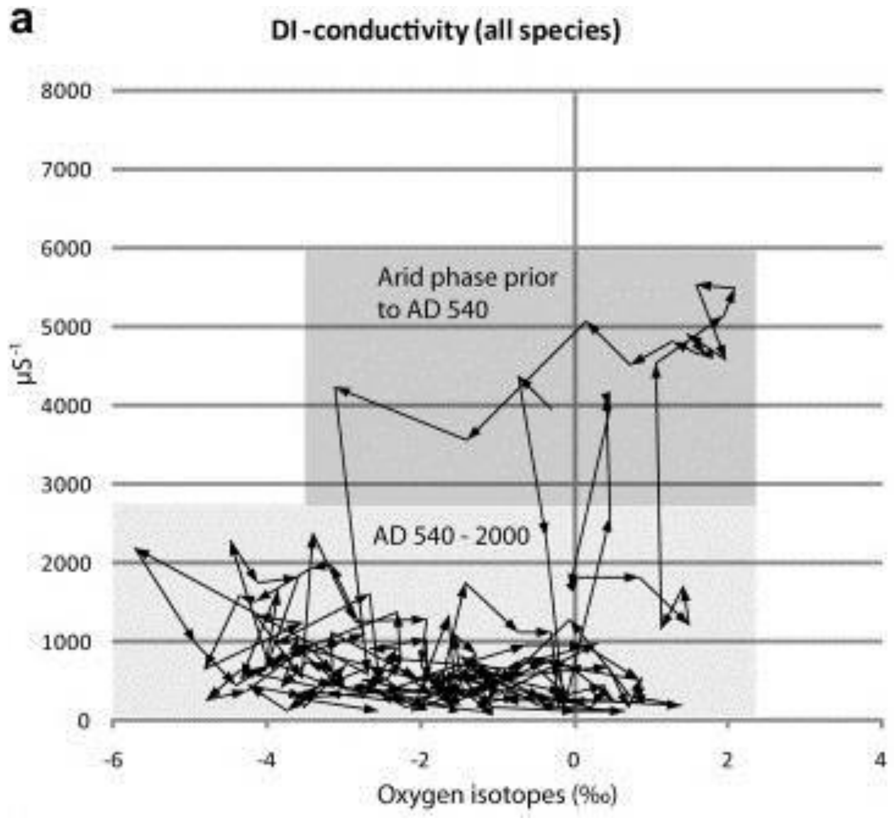


Figure 3.7: NAR01/02 δ^{18}O plotted against NAR01/02 diatom-inferred conductivity for the last 1720 years (arrows indicate direction of time and shaded areas represent different time periods). Highlighted is a distinctive climatic shift to relatively wetter conditions after AD 540 (Woodbridge and Roberts, 2011, pg. 3389). Permission to reproduce this image has been granted by the authors.

3.3. Fieldwork

A new field season was carried out at Nar Gölü during July 2010 by a multi-collaborative team to core and extensively study the lake in order to understand its past and present characteristics. A variety of field work was conducted for palaeo-environmental and palaeoclimatic reconstructions, and to study the lake's contemporary conditions. Bulk sampling of catchment sediments was undertaken to characterise the different sediment types and to map elemental erosion indicators.

3.3.1. Lake coring

Collection of lake sediment cores that are of sufficient length and resolution can be achieved through a variety of well-tested sampling devices (Glew, 2001). The type of core extractor used during fieldwork was constrained by the need to obtain a long and continuous sediment stratigraphy dating back to the start of the Holocene, and by the delicate nature of the varved lake deposits. It was also important to recover the sediment water interface, to be confident that the most recently deposited sediments were retrieved.

With these issues in mind, cores were retrieved using an UWITEC (Schultze and Niederreiter, 1990) hammer-based piston coring device operated from a raft platform; this coring system from the CNRS EDYTEM relies on gravity to hammer plastic tubing into the lake sediment to collect samples (figure 3.8). Whilst such an operation was expensive and bulky, the rig gave the support needed to successfully core the lake over deep waters and could hold the large aluminium frame to retrieve cores over considerable depths. Determination of the coring site was based upon lake-bathymetry and previous coring locations (figure 3.5). A suitable position was selected in the deepest part of the lake and far from the eroding fan delta to obtain a sequence which was as long as possible and not disturbed by processes such as bioturbation. Sediment was recovered from three parallel holes in the profundal zone of the lake and from one location close to the lake edge and active delta at intermediate water depth (table 3.2). A depth overlap of 50cm was maintained for the second and third holes to attempt to create a continuous and comparable sequence. It was found that 60mm and 90mm (external diameter) PVC down-piping regularly recovered a continuous sediment sequence, including undisturbed material from the sediment water interface. Due to the soft and often unconsolidated nature of the lake sediment, it was possible to carry out sampling in 2 and 3 meter drives. At times, more consolidated sections required more effort and hammering from the rig system to penetrate the plastic tubing through hard layers. A shorter, 44cm core was also collected in 2010 using a Glew corer (Dean *et al*., 2012; Glew, 1991) to retrieve material for samples covering the 20th and 21st centuries.

Figure 3.8: UWITEC coring device in operation (extracting the core tubing).

Due to the presence of annual laminations, it was vital that deposits were not disturbed during transportation so that fine-detail work could be carried out back in the U.K., without any loss of information. After each drive, the plastic tubing and sediment samples were covered at each end (after removal of water) by oasis and a plastic cap, taped and then packaged ready for transportation to Plymouth University. In some cases, there were signs of drying and shrinking of the sediment which had resulted in much shorter samples or in some cases larger samples due to expansion from trapped air. In these instances, the cores were cut down using a hand saw or were pierced using a hand held drill along the core length to release trapped gas. No stratigraphic integrity was lost through these processes. Samples were stored upright in a dry, cool and dark room until they could be exported.

Table 3.2: Nar Lake 2010 core locations and information.

Core	Latitude and longitude	Water depth (m)	Core start depth (m)	Core end depth (m)	Total core length (m)
NAR10 Core 1	34° 27.424'E 38° 20.498'N	21.32	0	21.56	21.5
NAR10 Core 2	34° 27.421'E 38° 20.497'N	21.32	1.0	22.45	21.45
NAR10 Core 4	No data	21.32	0.5	15.37	14.87
NAR10 Core 5	No data	11.6	0.25	7.25	7.0

3.3.2. Archiving of lake cores

It is important to store samples in a way that reduces the possibility of chemical alteration of the sample and which minimizes its chances of becoming distorted (Jones, 2004). All samples recovered from Nar Gölü during the 2010 field season were transported back to the U.K. by road. Core material was stored within the dark cold store (refrigerator at 4°C) at the Physical Geography laboratories at Plymouth University to chill the samples and prevent any further damage to the structure of the sequence.

3.3.3. Bulk sediment catchment sampling

Catchment sampling was conducted at Nar Gölü alongside the 2010 coring project to help comprehend the lake history and the attributes which relate to catchment inflows and sediment characterization. Catchment sampling is particularly important for understanding the geochemistry which has been conducted on the lake sediments recovered during coring. Catchment geochemical identifications will help detail human disturbances around the lake as well as where inorganic and organic material may have derived from the surrounding landscape (Boyle, 2001; Lottermoser *et al.*, 1997; Meyers and Teranes, 2001).

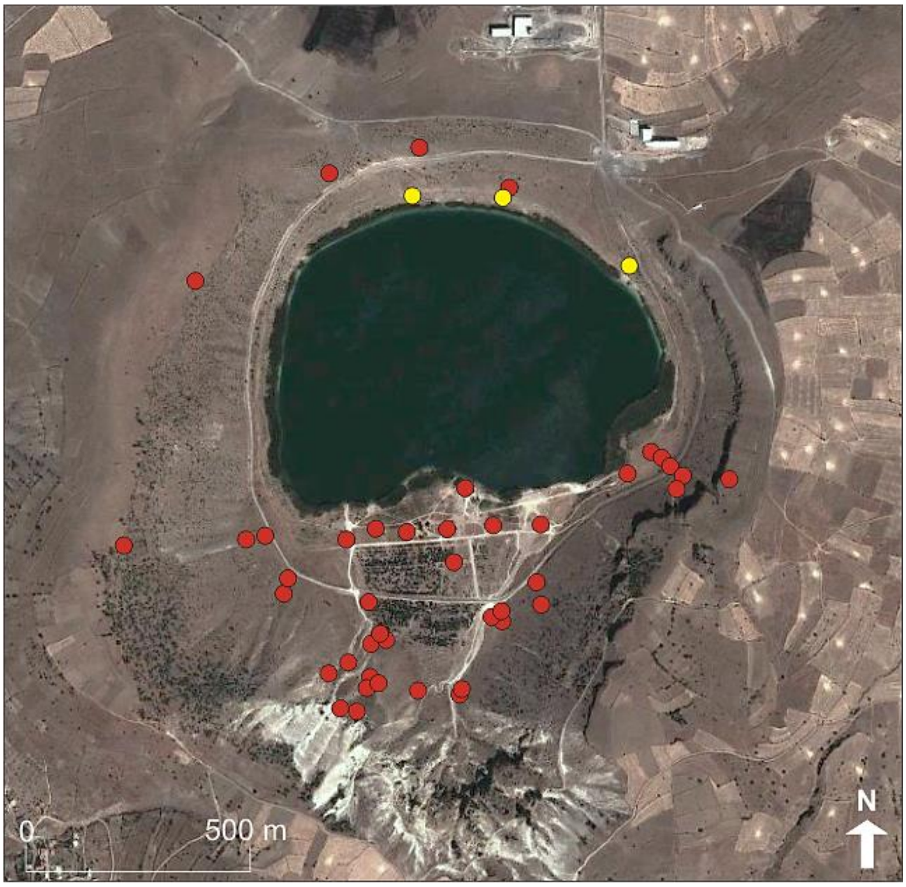


Figure 3.9: Points detailing the location of bulk catchment samples (red points) and higher lake stands (yellow points), referenced to the Universal Transverse Mercator (UTM) co-ordinate system for Turkey.

The short distances from the lake edge to its catchment boundaries allowed many samples to be collected over very short timescales. The samples were selected from exposed surfaces and eroding gullies (figure 3.9). Most of these feature types are situated to the south of the lake which meant that work focused heavily here. At sample sites, both the topsoil and sub-soil were collected as bulk samples of around 40g. Bulk sediment samples were collected using a trowel and placed into plastic polythene bags for storage and transportation. Once back in the U.K, samples were stored within the plastic bags in a cool and dry cupboard until analysis.

Alongside catchment sampling, a high lake stand noticeable by white carbonate-rich water marks on basalt rocks to the west and north (figure 3.9) was mapped using a hand-held GPS and a clinometer.

3.3.4. Further research at Nar Gölü

Aside from coring programmes, Nar Lake has been investigated using a number of techniques to look at modern and palaeolimnological conditions. A picture of lake bed morphology has been achieved through lake-bathymetry work (figure 3.10) conducted in 2001 (Jones, 2004; Woodbridge, 2009) and 2010 (Smith, 2010), mainly to support the lake coring operations. A survey of the underlying sediments in 2010 was achieved using an Applied Acoustic CSP-L and AA201 boomer type sub-bottom profiler, coupled with a high precision GPS system. In total, 53 transect lines across the lake with an interval spacing of 30m east-west and north-south was achieved, producing continuous trace layers for the upper ~20m of lake sediment deposits (Smith, 2010). Bathymetry investigations were used to locate the deepest parts of the lake to aid recovery of long sediment sequences.

In addition to lake-bathymetry work, systematic water sampling has been carried out since 2001 at different water depths. Lake surface waters are sampled for pH, conductivity, temperature, water chemistry and stable isotopes. For water sampling methods pre-2007 the reader is directed to Jones (2004). Temperature, pH and conductivity in 2010 were measured with a Myron ultrameter II, calibrated using standard solutions. A Glew corer (Glew, 1991) was used to extract water samples at specific depths along the water column. Water samples were also gathered from three spring locations (figure 3.5), for technique see Jones (2004). Both lake and spring water samples were subjected to the same analysis as surface samples. Lake monitoring by data loggers was also conducted alongside water collection. This was achieved using

Bara Troll pressure sensors at 1m lake depth and temperature '*Tinytag*' data loggers at different lake depths.

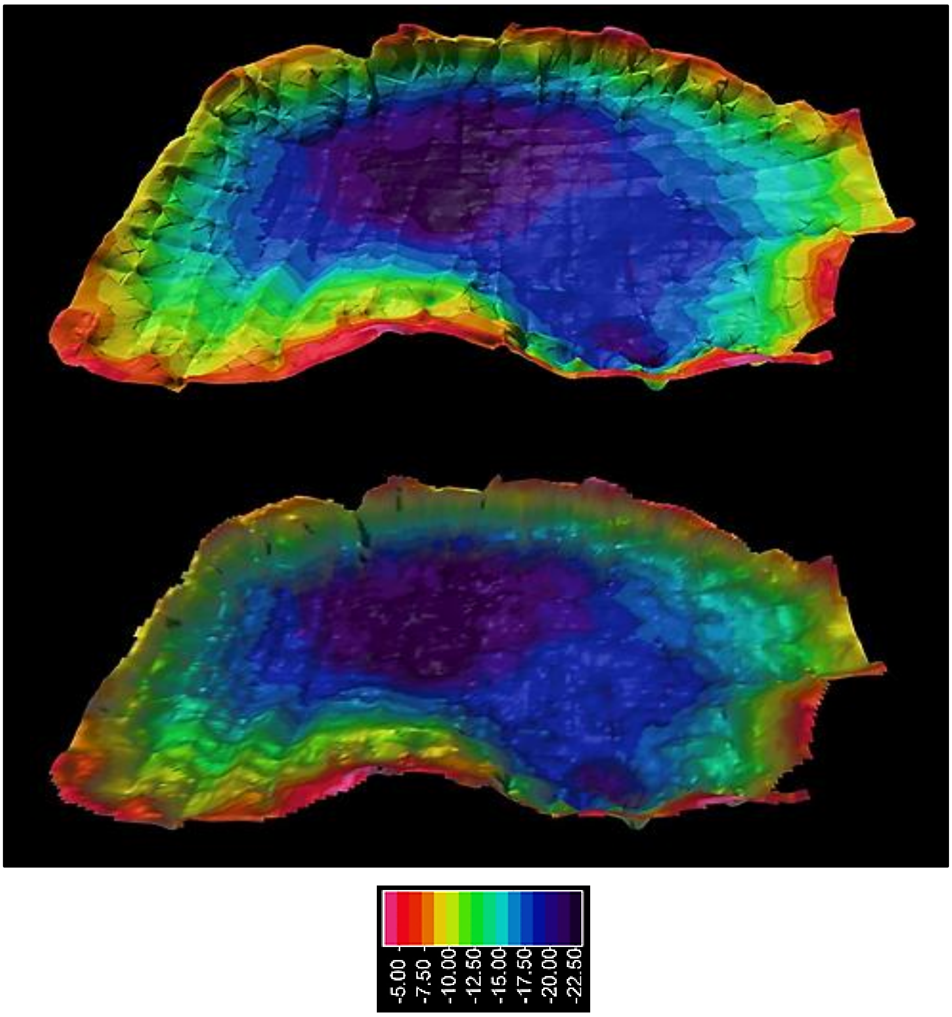


Figure 3.10: 1 m gridded lake bathymetry data (top) and 5 m gridded lake bathymetry data (bottom), as displayed in Fledermaus, showing lake depth across the site. Dark blue indicates deep waters and the preferred area for core extraction (Smith, 2010, pg. 37). Key indicates meters below water surface.

Seston sediment traps, similar to those used by Davis (1967) have also been installed to examine modern lake deposition and to help interpret palaeo-records. Two sediment traps were secured at two depths and planted in two different locations in the deepest part of the lake (as sedimentation is more secure here); these were emptied and replaced yearly between 2001-2011 (England, 2006; Jones, 2004; Woodbridge, 2009).

Sediment trap data have been used to investigate sediment falling through the water column, sediment accumulation over a year, sediment isotope chemistry, pollen concentrations, diatom communities and seasonality.

Trapping of modern pollen samples has also been conducted to see what types of pollen are being deposited within the Nar catchment. Pollen traps consisting of a plastic tub and glycerol were unsystematically left at locations around Nar Gölü in 2010 and recovered one year later. Recovery of these traps was minimal as most had been disturbed or stolen. Reinstallations of traps left in 2011 and recovered in 2012 proved more successful.

A daily record of lake-colour was kept March-June 2012 and regular photos have been taken by the nearby Nar Thermal Hotel to record changes within the lake on a regular basis. Ultimately, this was intended to delineate times of ‘whiting’ in the lake, linked to algal bloom events. Whilst daily diaries and regular photo archives have not documented such an episode, a scheduled field visit in July 2012 witnessed such an event, which lasted for three days.

3.4. Laboratory methods

Core sequences extracted from Nar Lake underwent a number of laboratory analyses. Analyses were conducted to record changing climatic and environmental histories for the Holocene (aim 1). High resolution sub-samples were extruded from the non-archived NAR10 core half sections to document changing sediment properties. The same half sections were scanned using XRF techniques to detail down-core geochemical variations.

3.4.1. Lithology and chronology

3.4.1.1. Core opening and preparation

A unique system for cutting the core tubing open was devised to deal with the 2-3m core samples (figure 3.11). A vibrating hand-held saw was attached to a laboratory bench and the sediment filled core tubing was moved along the work bench, against a ‘wood guide’ to cut a slit into the side of the plastic tube (figure 3.11). Once cut, cores were then opened length ways into two half sections using cheese wire and gently pulled apart and separated using a palette knife as outlined in Lamoureux (2001). One core half was wrapped in clean non-PVC cling film and a labelled plastic sleeve and placed back into the refrigerator for storage and archiving. The other half was left open for cleaning, recording and cross-correlating with other core sections.

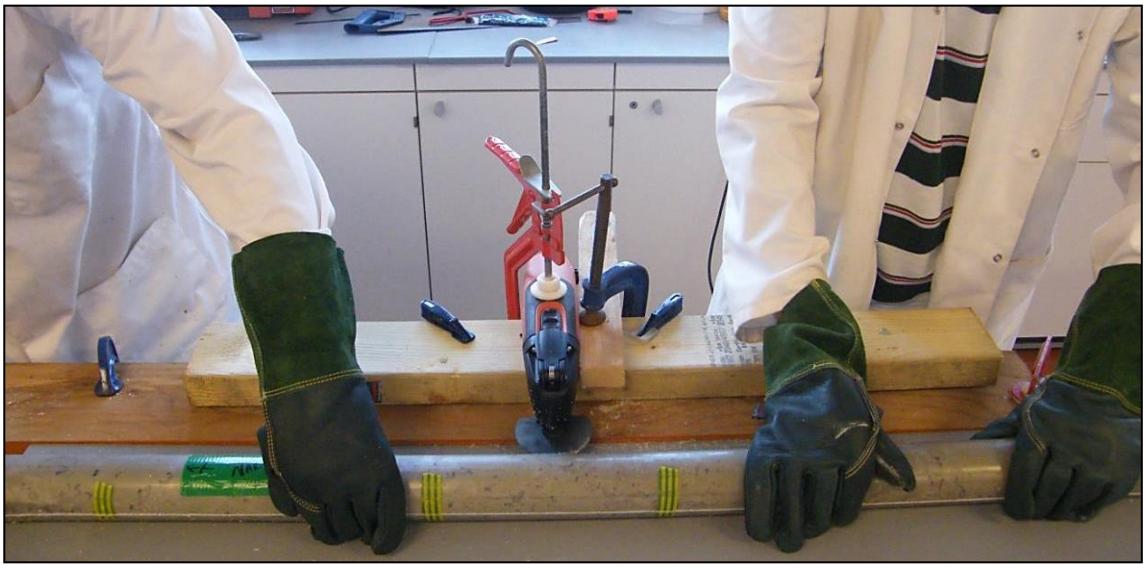


Figure 3.11: Photo of self-designed core cutting equipment and core opening procedure.

Non-archived core sections were cleaned to ensure that the sedimentary sequence was clearly visible and that layers were not smudged or blurred. Cleaning involved scraping off a few millimetres of sediment from the core surface using the straight edge of a spatula, following the direction of the varve structure as described in Renberg (1981). Core sections were then described and recorded. As photographs of the core face are a good way of accessing further detail concerning sediment characteristics (Renberg, 1981) and an effective means of storing information for the future (Francus, 1998), professional photographic equipment was set up to systematically photograph the core sections.

3.4.1.2. Sediment characterisation

The core sections were divided into major lithostratigraphic units and smaller sub-units depending on changes in sediment type and colour. Primarily this was achieved through visual examinations of the open core halves. Variations in sediment colour can be a significant indicator of change and a valuable aid in stratigraphic descriptions (Cornwall, 1958). A Munsell chart, as described by Shackley (1975), was used to describe the colour attributes of the sediment and to help highlight down core variation.

3.4.1.3. Master sequence formation

A composite master sequence for the Nar Lake sediment was determined by laying out all the core sections and identifying prominent marker points at fairly regular intervals of where core sections correlated (figure 3.12). Correlation between the cores was quick and simple because of the highly variable stratigraphy and changes in laminated sections. Over-lapping core sequences in this way provides a much more reliable and accurate master chronology as it can help identify inconsistencies and localised changes that might be inherent within one core sample (Lamoureux, 2001).

Although many over-lapping core sequences were obtained from Nar Gölü, unfortunately the sediment record is not 100% complete. There are some non-laminated sections and additionally there are a few gaps in the composite sequence, and it is unclear as to how much material has not been recovered. Ultimately, the estimated gap is small and should not affect any of the main inferences made as other dating and cross-correlation techniques have been applied.

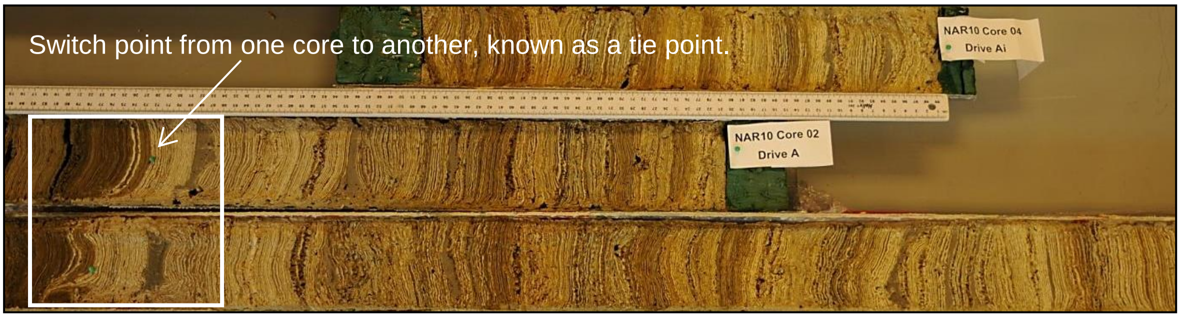


Figure 3.12: Cross-correlations of core sequences from three different core drives.

3.4.1.4. Nar Gölü laminae counting

From the composite master sequence, varve counting was conducted. Each varve couplet comprised a light lamina and a dark lamina to the naked eye. Once varve identification criteria were determined, an initial chronology was completed by visually counting individual varve sections and assuming a constant sedimentation rate for non-varved sections. Where major gaps in the sequence occurred, the length of the gap was determined from coring depths and counts were based upon those estimates. Cores were counted in 20 varve year intervals, and pinned at the end of each section. These sections were then independently counted by two further counters; if there was a difference in the counts then the corresponding section was recounted by all counters until agreement was reached. To enlarge the view of very fine laminations (<1mm), a magnifying lamp was used. Counts were also checked and marked on high-resolution digital photographic imagery. For confirmatory purposes, varve counts for the top 376cm were compared to existing varve counts for the NAR01/02 and NAR06 core sequences and found to match within <10 varve years.

3.4.1.5. Nar Gölü core chronology

A chronology for the Nar Gölü composite master sequence was achieved principally through new varve counts and correlation to previous varve counts and radiometric dates (^{210}Pb and ^{137}Cs) (Jones, 2004). For parts of the 2010 composite sequence which do not overlap with previously extracted core sequences, further radiometric dating is being conducted to help interpret non-varved sections and to tie in ‘floating’ varve counts to ‘non-floating’ sections towards the top and bottom of the core sequence. An attempt at identifying tephra horizons was also made to help date the Nar sequence but even though distinct layers were visually and chemically recognised, these horizons were found to not be diagnostic volcanic air fall deposits. ^{14}C cannot be used here either as there is a 15000 year old carbon effect that is related to on-going geothermal activity.

^{226} Radium (Ra-226) dating

Radium isotopes are useful chronometers for the determination of time series of environmental processes (Schmidt and Cochran, 2010). Radium dating is applicable to Nar Lake due to the deposition of inorganic carbonate precipitates and spring activity (Schmidt and Cochran, 2010). Bulk lake sediment samples of ~2cm thickness were removed from the cores, taking care to avoid contamination by potentially disturbed material from the edges of the plastic tubing, for ^{226}Radium dating. These were collected from mainly the top half of the core sequence (0-8 kyr B.P.) because whilst the series is appropriate for dating systems with millennial ages, the isotope only has a half-life of ~1602 years. Samples were packaged in a 3cm diameter plastic tube and sent to Pierre Sabatier at the EDYTEM facility in Savoie, France. Unfortunately, due to delays in the dating procedure, there are no ^{226}Radium derived dates at present.

Uranium-Thorium (U-Th) dating

U-series (uranium-thorium) dating can provide accurate and reasonably precise ages for Quaternary carbonates (Haase-Schramm *et al*., 2004). Nar Lake sediments are high in precipitated carbonates and are thus suitable for the application of this dating technique. Bulk sediment samples of ~1cm thickness were removed from the cores, taking care to avoid contamination again, for U-Th dating. U-series dating was carried out on authigenic lake carbonates at BGS (British Geological Survey) using a Neptune Plus MC-ICP-MS analyser. U-Th dating on the Nar Lake sediments has been difficult, particularly because of high detrital thorium, coupled with low levels of uranium. This has led for the need of an Isochron approach as used in Roberts *et al.*, (2001). Isochron techniques allow for different parts of the sediment sequence to be correlated and combined, giving an age estimate for a larger sediment sample (Bischoff and Fitzpatrick, 1991; Luo and Ku, 1991). This requires several coeval samples and will thus increase the statistical error on the dating results for Nar (± several hundred years). This dating procedure is still in progress with dates yet to be accurately obtained.

3.4.2. Sediment analysis

3.4.2.1. Sub-sampling of master core sequence

Sub-samples for geochemistry and total carbon (both analysed as part of this PhD project), along with pollen, diatoms, stable isotopes, pigments and other sedimentary investigations were obtained by cutting out sediment samples from the Nar Gölü half core sections using a scalpel and spatula. Three or five varve year (vy) samples were extracted every 20 varve years or at an interval of 4cm depending upon core condition; some non-laminated sections required sampling by depth. Also highly compacted or distorted sediments made it difficult to select individual lamina, making sampling by depth simpler. It is possible that some contamination may occur where lamina were thin or slanted. A bi-decadal resolution was selected to ensure coverage of the entire core sequence at intervals that did not result in too many samples and for practical reasons involving very narrow laminations. Individual lamina sub-samples were taken for the top 25vys to produce a much finer temporal resolution for comparison to meteorological data and existing multi-proxy palaeo-histories.

3.4.2.2. Total carbon content

A common way to generate a record of total carbon is to use a total carbon analyser. This determines total carbon automatically to help describe the abundance of organic and inorganic carbon in sediments (Veres, 2002). Determining sedimentological properties in this fashion from lacustrine sediments can provide valuable data on the nature of past depositional environments, and be useful indicators of climatic and/or environmental change (Lowe and Walker, 1997).

The organic and inorganic carbon content of the selected samples was determined by temperature controlled combustion of homogenous and dried samples using a Skalar Primacs Series Total Carbon Analyser in the Physical Geography laboratories, Plymouth University. Total carbon (TC) was determined by catalytic oxidation of the sediment sample at just over 1000 ^{0}C, converting the carbon present to CO_2 which is recorded by detectors when released. The inorganic carbon fraction (IC) was determined by acidification of the sediment sample in the IC compartment which converts the inorganic carbon to CO_2 and removes the organic carbon component. Windows software collects the data and uses this to calculate a reading for the organic carbon component (TOC) using the equation TC-TIC=TOC.

In total, 512 samples were analysed. Samples were weighed to 105 mg (TC) and 65 mg (TIC) before analysis. No sample preparation beyond drying was conducted because of issues concerning small sediment weights; due to this, the results strongly over-estimate the total inorganic carbon fraction and occasionally under-estimate the total amount of organic carbon presence. Samples remained in the furnace for 300 seconds to obtain the best reading possible for the sediment type.

3.4.2.3. Itrax high-resolution XRF core scanning and documentation of physical properties

Traditional elemental geochemistry methods such as single sample X-ray fluorescence (XRF) can be time consuming (Croudace *et al.*, 2006) which can make data collection a slow process if dealing with long sediment sequences. A much faster and non-destructive analysis can be achieved through the use of Itrax XRF core scanning instead. Itrax core scanning (Francus *et al*., 2009; Rothwell *et al.*, 2006; Rothwell and Rack, 2006; Thomson *et al.*, 2006), whilst a relatively expensive option, is a very good technique to use on long, continuous and annually deposited core sequences (Croudace *et al.*, 2006). The Itrax micro X-ray beam irradiates the sediment sample to collect positive X-ray images and to detect the energy of fluorescent radiation to provide a relative concentration level for various elemental components. The scanning machine will also produce X-ray radiographs and optical images (Guyard *et al*., 2007; Marshall, 2010). Standard procedures for Itrax scanning were followed as outlined in Croudace *et al.*, (2006) & Francus *et al.*, (2009).

Whole sections of cores covering the 2010 Nar master sequence were transported to Aberystwyth University and scanned using the Itrax scanner at 200 µm resolution (400 µm for concreted sections) under the guidance of Prof. Henry Lamb and Dr. Mike Marshall. This corresponds to around 5-20 data points for individual varves which measure between 1-4mm, thus attaining sub-seasonal resolution. Spilt sediment cores (between 24cm-183cm in length) were loaded onto the horizontal cradle with the core top positioned to the right (figure 3.13). Various programme settings were made and adjusted using the Core Scanner Navigator (CSN) program to ensure a successful scan. Step size and dwell time were selected with consideration to the quality of the acquired data, the nature of the annual layers, as well as time and money constraints. Prior to scanning, core surfaces were covered with a thin polypropylene film (4μm thick), which is pure and chemically resistant, to protect the scanning device from the wet muds (Berger *et al*., 2009). For a more detailed overview of how to use the core scanner, see Croudace *et al.*, (2006) & Marshall (2010).

Scanning was conducted using a molybdenum (Mo) tube, 10-s count time, 200-ms exposure time, 30 kV X-ray voltage and an X-ray current of 50 mA to detect 28 elements, including Iron (Fe), Calcium (Ca), Titanium (Ti), Strontium (Sr), Manganese (Mn) and Potassium (K). X-ray radiographs were also obtained with the same Itrax scanner using 60 kV X-ray voltage and 50 mA of current intensity. The density contrasts shown by the radiograph image indicate the presence of organic-rich layers (light bands) and carbonate-rich facies (darker bands). After scanning, data were explored and plotted using the Itrax-Plot software package which produced PowerPoint images of core section images alongside elemental profiles to help aid interpretation.

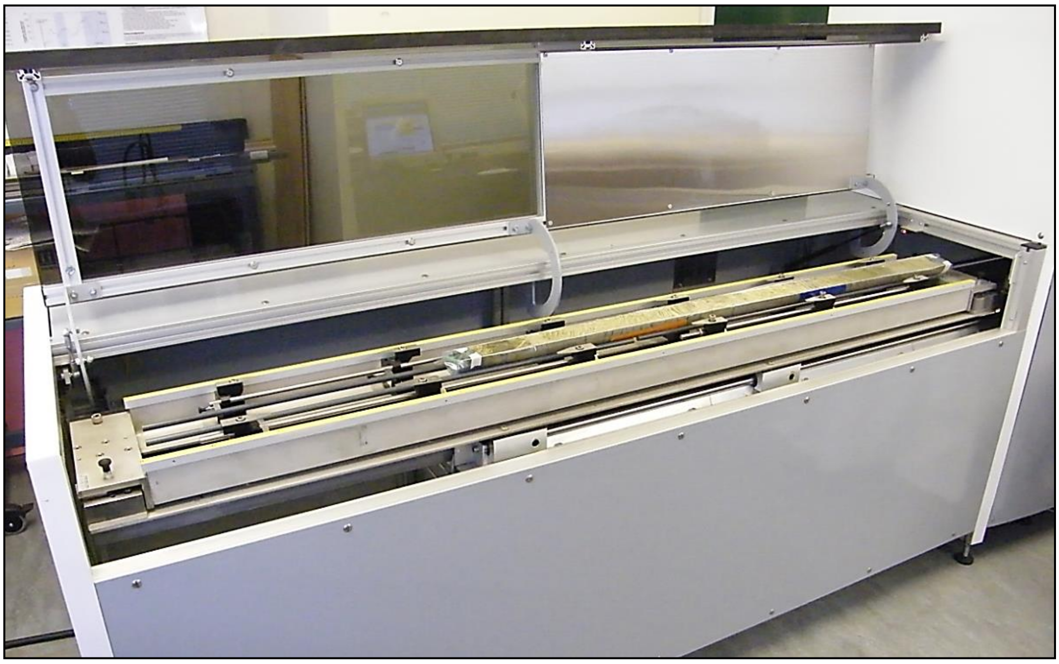


Figure 3.13: Photo of Nar core section in Itrax scanning machine.

3.4.2.4. Portable XRF core scanning of whole core sections

X-ray fluorescence (XRF) handheld core scanning is a relatively new analytical technique which allows for non-destructive, in situ XRF analysis of sediment cores and samples (Kylander *et al*., 2011a). The difference between this technique and Itrax procedures is that Itrax scanning produces one single dispersive energy spectrum for each sampling point along the core surface, resulting in data being expressed as peak area integrals rather than counts per second (CPS). Spectral readings from Itrax are correlated to theoretical spectra to help determine elemental compositions; problems can occur with this method if sediments vary significantly down core (Kylander *et al*., 2011a). Similar to XRF, if there is variability in sediment composition, texture, porosity and water content then the measured element concentrations in CPS have no quantitative representation (Rothwell *et al.*, 2006). One particular draw-back of Itrax scanning compared to traditional XRF is that the machine finds it hard to detect lighter elements at the top of the periodic table and cannot detect Sodium (Na) or Magnesium (Mg). Those lighter elements however can be detected by conventional portable XRF (if used with helium purging and used on mining mode) making the record of elements such as Si collected through this method substantially better than that collected by Itrax. By using the two techniques together, a broader elemental composition for the sediment core sequence can be determined and cross-correlations can be made to ensure that the elemental readings are an accurate reflection of geochemical alterations in the lake sequence.

The complete 21m core sequence from Nar Lake was analysed using the Thermo Scientific Niton XL3t GOLDD series XRF portable scanner housed at Plymouth University. The GOLDD standard machine allowed for faster measurement times and detection of light elements. The machine features a 50 kV miniaturised x-ray tube, internal camera for visual identification purposes and user-selectable 3mm small spot that collimates the x-ray beam onto small zones. A sampling resolution of every 8cm was used to account for time constraints and the length of the core sequence. By scanning a collimated 3mm spot every 8cm instead of one specific spot every 200 μm, an averaged and broader picture of elemental change was determined.

At 8cm intervals, the Niton XRF handheld gun was fired for 225 seconds (60 secs for heavy elements, 60 secs for medium elements and 105 secs for lighter elements); the unit was set to employ helium purging to allow the analysis of elements lighter than Potassium (K) and the 3mm toggle spot was switched on. 40 elements from Magnesium (Mg) to Uranium (U) were determined and error limits expressed. In recognition of the 'weak' penetration of X-rays involved in the analysis of lighter elements, half core sections were prepared with a thin, clear polypropylene cover instead of the standard Mylar cover recommended. The role of the film being to protect the source and detector from the wet and muddy sediment samples (Berger *et al*., 2009).

The in-house computer program (Niton Data Transfer (NDT) software suite) was used to analyse the spectra produced by the Niton gun in order to calibrate the results by comparison to known reference samples. The program is designed for downloading and managing data, and was used to produce excel print-outs of the results obtained for use in other statistical packages.

3.4.2.5. XRF scanning of bulk sediment catchment samples

In contrast to the scanning of core surfaces using portable XRF techniques, bulk catchment samples were analysed using more conventional XRF measurement techniques on single samples. Firstly, material gathered from the field was sub-divided to a small workable amount using the quartering technique, as outlined in (Shackley, 1975), chosen for ease and speed. For the XRF scan, these catchment sub-samples were then dried and homogenised to provide a flat and smooth surface for analysis (Rothwell and Rack, 2006). Samples were processed to powder pills using a Fritsch P5 Planetary Mill (PULVERISETTE 5 classic line with 4 bowl fasteners). A small amount of sediment sample, equating to around half a bowl full, was added to a metal grinding bowl and four agate grinding balls were added to each bowl. The bowls were clamped into the machine and spun at high speed for 30 seconds or until the milled particles reached a size of approximately 60 µm. This fine fraction was then used to fill 5cm^3 plastic pots ready for scanning.

Samples were scanned using the Niton XL3t GOLDD series XRF portable scanner which was held within its desktop base. Helium purging was selected for again to make sure that the lighter elements were detected. Each individual sample was scanned for 270 seconds as this seemed to be the optimal duration time for the potted samples. Mining mode was selected and the toggle spot was not use this time around. The Niton Data Transfer software was used again to output the results into a useful format.

3.5. Data presentation and analysis

Once results had been gathered, a number of numerical techniques were used to explore patterns within the datasets. Computer software programs were used to display and graphically represent key findings.

3.5.1. Visualisation of data

Changes in total carbon and geochemical parameters were graphically displayed as stratigraphic profiles using C2 data analysis software (Juggins, 2003) to present temporal changes in the elemental compositions and sedimentary variables. Where use of C2 was not available, the computer software program ‘R’ ('http://www.r-project.org/,'; Ihaka & Gentleman, 1996; R-core-team, 2001) was used to plot the data as line charts. The variables selected for graphical representation were selected based on their applicability to the study and on their potential as a climate/environmental change reflector, i.e. Argon (Ar) was not chosen for presentation because it was a bi-product of the scanning procedure and of no use to the interpretation process.

Relationships between variables, running averages, running correlation coefficients, PCA's and other statistical tests were graphically represented to help with the interpretation process and to highlight to the reader significant changes in the NAR10 profiles. Numerical analyses were visually displayed using C2 (Juggins, 2003) and R ('http://www.r-project.org/,') graphical functions.

3.5.2. Numerical analysis

3.5.2.1. Data transformations

3.5.2.1.1. Standardisation

Multivariate data can be highly variable and more often than not, unevenly distributed. This becomes a problem if two data sets are to be compared alongside one another. It was therefore desirable to convert the original scores to some standard scale so that two or more variables could be plotted together. Variables were transformed with the object of normalising the scores and reducing the distribution to the normal, or as close as possible; this process is known as 'standardisation' (Kendall & Buckland, 1976). Data were normalised so that they co-varied ($r^2=1$) by subtracting the parent mean of the full dataset from each individual sample, and dividing by the parent standard deviation, resulting in a dataset with mean of 0 and standard deviation of 1.

3.5.2.1.2. Correction of Itrax derived data

The usefulness of data extracted using XRF core scanning techniques is limited by the fact that elemental variations are not measured as concentrations and that sedimentary factors such as water content, organic content, surface undulation and porosity can all influence the measurements obtained (Böning *et al.*, 2007; Kylander *et al*., 2011b; Tjallingii *et al.*, 2007; Weltje and Tjallingii, 2008). Additionally, the aging of the X-ray tube can influence the measured count, unless two core sections were scanned close in time

(Lowemark *et al.*, 2011). The strength of XRF though is that it can provide geochemical variations directly from the core surface at much higher spatial resolutions, allowing for a near-continuous record of diverse elemental intensities. In order to understand relative variation in comparison to other elements it is therefore necessary to correct for problems relating to the sediment matrix to extract the XRF's full potential.

To adjust for variations cause by core properties and scanning procedures, all data are usually normalised to another parameter. Commonly, data are normalised to the incoherent and coherent scattering (inc+coh) (Kylander *et al*., 2011b) / (inc/coh) (Melles *et al*., 2012), as fluctuations in the sediment will influence this absorption measure, as seen in Thomson *et al.*, (2006). Incoherent fluctuations can be closely tied to the organic component of the lake sediment deposit, therefore kilo-counts per second (kcps) are often used as a normalising parameter, instead of incoherent and coherent values, to account for the complete changing nature of the sediment matrix (Bouchard *et al*., 2011). Normalising elemental data by a conservative element like Aluminium (Al) is also common practice (Lowemark *et al.*, 2011), particularly when assessing changes in lithophile elements (Bertrand *et al*., 2010). This helps detect supplementary elemental inputs different from the background concentrations (Rothwell and Rack, 2006). Other detrital elements, such as Rubidium (Rb), have also been used to standardise peak area integrals (Guyard *et al*., 2007). With these methods in mind, the Nar Lake Itrax XRF derived results were corrected for using the Inc/Coh ratio and kcps scores (figure 3.14), which yielded differing results; because kcps corrections can account for multiple core problems, this parameter was selected for over the incoherent scatter. Corrections using Al could not be made as the peak area integrals for this variable were too low to be of use. Other detrital elements (Ti and Rb) have however been used to correct for the lithogenic component.

Ratios have been used (figure 3.14) to minimise the effect of physical properties and closed sum-dilution effects present in the analysed spectrum (Tjallingii *et al.*, 2010). This is a useful way of correcting for some of the ‘disruptions’ in the sedimentary sequence caused by individual components. Whilst limited to just two variables, this is the best way to represent variability inherent in groups of elements.

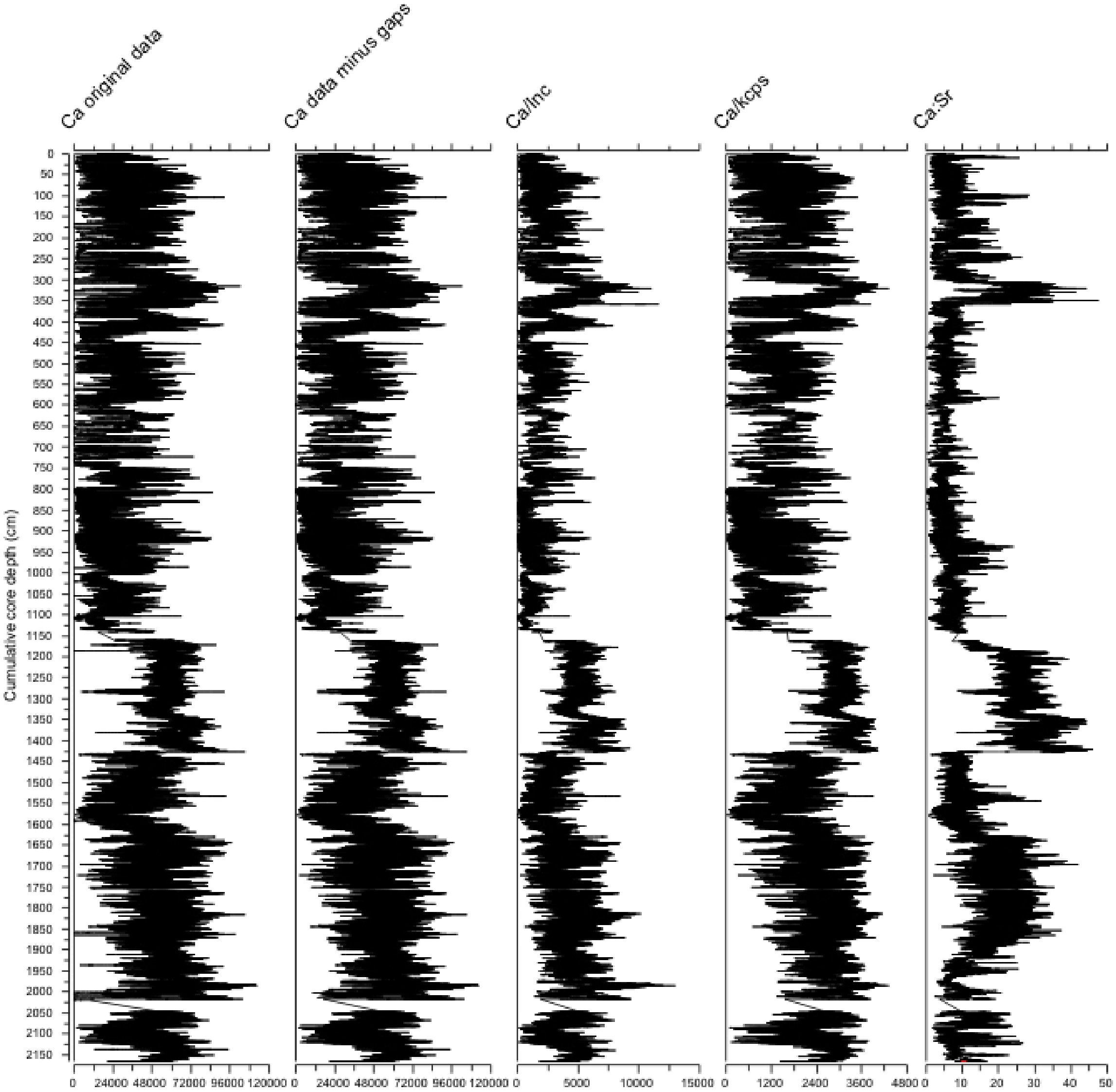


Figure 3.14: Stratigraphic diagram showing the stages taken to adjust and correct the Itrax derived geochemical data. The four different stages of correction are indicated using Calcium (Ca) data. The original data (measured in peak area) was corrected by removing gaps and cracks, and then were subjected to various alterations by using the incoherent (Inc) and kilo counts per second (kcps) profiles (both unitless). Ratios with other elemental records (e.g. Ca/Sr) (unitless) also provided a means of adjusting for individual elemental variation.

The quality of data obtained from Itrax XRF can also be affected by gaps and cracks in the sediment sequence. To account for this, sharp drops in elemental peak area integrals were detected from the stratigraphic profiles, mean standard error readings and x-ray radiographs, and removed from the measurement sequence before down core variations were graphically presented (figure 3.14). Inspection of the parameters for other erroneous peaks was also conducted, and these artefacts were ignored.

3.5.2.1.3. Data reductions

To look at longer terms trends and non-random fluctuations in the very highly resolved Itrax dataset, it has been necessary to use data reduction techniques to slim down the data. Running averages (also known as moving averages) (Matthews, 1981) (have been used to smooth the Itrax data to generally average out or mask very high and low values that make the signal noisy. This was achieved using Excel functions to calculate the mean of overlapping sections. 500 sample and 2000 sample running means were conducted as these would hopefully show fluctuations greater than 10-40 years in length. A comparable averaging process was used for correlation statistics (see section 3.5.2.2.1). Loess smoothing curves (Cleveland, 1979, 1981) were also plotted on stratigraphic diagrams displaying the Itrax derived data in a similar attempt to reduce the number of data points and to look at longer term trends. Loess smoothing, with a 0.2 span, was applied using the R statistical computer package ('http://www.r-project.org/,') to draw a smooth curve through a basic line plot.

To slim down the Itrax data and bin the samples into selected groupings a computer program called ‘File.format.conversion.for.LRA.12Oct09.exe’ initially designed for use with pollen count data by S. Sugita (Tallinn University, Estonia) in October 2009 was used. This allowed the 0.2mm Itrax data points to be averaged in bins of 3cm at every 8cm interval. The binned data was used to compare alongside portable handheld XRF data which was only scanned at 8cm resolution using a 3mm toggle spot. The 3cm bin width was selected for to account for any inaccuracies there may have been with the reading of depths during handheld scanning and the 8cm resolution ensured readings from the two techniques were comparable.

3.5.2.2. Statistical analysis

3.5.2.2.1. Correlation analysis

Correlation analysis was used to assess how two variables co-vary down core, particularly on those parameters established through Itrax core scanning to explore similarities between elemental components. To measure how two continuous variants (with a true zero) are related, Pearson’s Product Correlation Coefficient was used, which is a measure of the degree of correlation (Clarke and Cooke, 1998) and has been recognised as a power technique in correlation analysis (Wheeler *et al*., 2004). Analysis was conducted using Excel functions. The strength of the relationship was measured using the r value. Strong positive relationships will show an r value of 1 and strong negative relationships will have an r value of -1, very weak relationships will take a value close to 0. The strength and significance of r values was determined in Excel also using t and p values. A p value below 0.05 was seen as significant.

To look at relationships over a longer time-span, running correlation coefficients were produced using the same Excel functions for selected elemental profiles. This was achieved using 500 and 2000 sample bins to reflect change over ~ 10-40 varve year timescales. A Pearson’s Product Correlation Coefficient was computed for each overlapping bin interval in a similar fashion to how running averages were computed.

3.5.2.2.2. Principal components analysis

Principal Components Analysis (PCA) is an indirect (or unconstrained) ordination technique used to reduce the number of variables that need to be considered in a study to a small number of significant indices that are linear combinations of the original variables (Manly, 2004). Basically, PCA analysis is a data reduction technique; groups of variables can be positively and negatively correlated, or uncorrelated. This technique has been used to reduce the Itrax elemental variables to a number of significant dimensions that represent the underlying structure of the data. Analysis helped make the large Itrax dataset more manageable and to explain the largest variance in the dataset. PCA analysis was performed in C2 (Juggins, 2003) on standardised and centred species scores and results were displayed as ordination bi-plots using the same software package and as stratigraphic profiles using R ('http://www.r-project.org/,'). PCA-ordination diagrams show species scores represented by arrows and samples scores represented by dots.

The number of PCA ordination axes to be retained for interpretation was determined by assessment of the eigenvalues (total amount of variance witnessed by that axis). Assessment was made using the broken stick method and plotted using a scree plot to confirm the importance of axes (Frontier, 1976; Legendre and Legendre, 1998). The scree method followed that outlined by (Jackson, 1993).

3.6. Archaeological data collection

Research of primary and secondary archaeological sources was conducted as part of the PhD project; a study grant provided by the British Institute in Ankara, Turkey (BIAA) supported independent desk and archival research into long-term cultural change. Archival research enabled the capture of a sense of change over time which would not have been accessible through fieldwork or modern observational techniques. Retrieval and analysis of data extended over a one month period, starting September 2nd 2011. Work consisted of using archived archaeological and historical records to create a database of sites, chronologies and cultural change strategies for the Cappadocia region in Turkey. More in-depth work was possible for individual excavated sites to document artefact variability and human occupation sequences. This work has led to periods of societal change to be delineated, which may have been influenced by shifts in Holocene climate. The study provided a multi-period account of change from the Neolithic to modern times.

Initially, work involved engaging with the library collection and identifying key resources (books, journals, monographs etc.) of use. A preliminary assessment of the library resources made in 2010 as part of a BIAA supported study tour of Turkey had revealed that the resources available were suitable for the proposed research. Of the resources consulted in September 2011, access to Turkish journals and electronic access to Anatolian Studies proved to be very useful, as these are not readily available for use within the U.K. The labyrinth of individual site reports and monographs were also of benefit.

Archival and background research conducted in association with the BIAA study grant progressed in two stages. The first stage of work involved looking at archaeological survey data to obtain settlement numbers and sizes, along with mobility patterns through time for Cappadocia. In fact, this was a BIAA led project, managed by Institute Director Dr. Lutgarde Vandeput and Dr. Geoffrey Summers (previously of Middle Eastern Technical University). The project aimed to collate data from Ian Todd’s 1960’s survey of Cappadocia and to establish an accessible database for the sites mentioned in this survey. By summer 2011, BIAA research scholar Michele Massa (University College London) had already documented settlement pattern changes and shifts in site size for the three main provinces that form Cappadocia, the focus of which was on early Holocene occupational periods.

In light of this information, archival research became orientated towards expanding the dataset already produced in association within the British Institute and checking work for errors and inconsistencies. Work focused on collating data from the more recent archaeological surveys which have been conducted since the 1960’s, particularly those conducted in the Kırşehir, Kayseri and Nevşehir provinces. Dr. S. Omura and his Japanese team have so far produced the most comprehensive map of archaeological sites, following the lines of I. Todd and including key mining sites as well as occupational mound sites. Priority was given to those sources which included site numbers for later occupation periods. Whilst the Neolithic period may have been well documented, later ceramic cultures were often more complex and difficult to date, consequently leading to under-representation in site surveys. These problems of course apply to all survey investigations, particularly with smaller and more ephemeral sites or large flat exposures. Nevertheless, a broad picture of occupation for central Anatolia was developed using the available published data. Evidence has been collated into a master spread sheet document.

Second stage work involved far more intensive used of the library resources and detailed investigation into the excavated sequences of individual archaeological sites in the Central Anatolian Plateau. Key sites, as delineated by the survey data and by fellow researchers were chosen for detailed analysis. These include sites like Aşıklı Höyük, Çatalhöyük, Kültepe, Kaman-Kalehöyük and Can Hasan for which there are preliminary reports. Some sites outside the main focus region of Cappadocia were also looked at as they include information regarding the major chronological sequencing for certain time periods and include artefactual details (e.g. about storage remains) that are vital to the understanding of cultural change mechanisms. Such sites include Erbaba and Kerkenes Dağ. It is noteworthy that no reliable excavated sequence exists for certain cross-over period’s e.g. late Chalcolithic-EBA transition. Later levels, from Hellenistic times onwards, whilst apparent at sites like Topakli and Hacıbektaş, were not considered in this research. This was mainly due to time constraints and to the difficulties with sequencing of earlier phases which made interpretations difficult. An Excel spread sheet database was set up to record and document certain aspects of each site’s history including occupation levels, dating, structural changes and shifts in storage type/use.

3.7. Chapter summary

The methods applied and discussed here were selected according to the aims and objectives of the project; geochemical and sedimentary analyses helped to address aim 1 and archaeological data collection helped to address aims 2 and 3. Nar Lake site was chosen because of its usefulness for extracting suitable climate proxies, its potential for high-resolution sampling and its varved nature which helped to create a firm chronology, at least in part. Fieldwork allowed for the collection of relevant samples for geochemical analysis and to assess modern day conditions at the lake. Laboratory procedures were adequately developed to extract data suitable for addressing relationships between people and climate/environment change. Datasets underwent statistical analyses following standard methods to explore the patterns and information stored within values.

4. Sedimentology and elemental geochemistry

Nar Gölü results

4.1. Chapter introduction

In summer 2010, coring of Nar Gölü (Nar Lake) in Cappadocia, central Turkey produced a 21.6m continuous and mainly annually laminated sediment core sequence, hereby known as NAR10. The core sequence was sub-sampled for multi-proxy investigations every 20 varve years (vys) or every 4cm depending on the core lithology. At each sample point, three or five varve couplets were collectively sampled, depending on varve thickness, and divided into 8 sub-samples ready for further analysis. The sediment sequence is being evaluated using a range of methods, including analysis of various stable isotopes, pollen, pigments, X-ray diffraction (XRD) and diatoms. In this chapter, results are presented of X-ray fluorescence (XRF) core scanning and total organic and inorganic carbon, and a description of the sedimentary facies.

4.2. NAR10 sediment lithology

The NAR10 sedimentary record is composed primarily of 0.5-5mm thick, clearly discernible to faint laminations, varying in colour and in calcium carbonate and organic content. Around 90% of the 21.6m master core sequence is laminated, with most appearing to be annually varved (figure 4.1). There are several important stratigraphic changes along the sequence, which include a mainly non-laminated unit with calcium carbonate concretions at 5.9-7.5m (unit 2), thick multi-coloured banding centred around 8m (unit 3) and a non-laminated grey marl at 19.7-20.1m (unit 6), the top of which appears to mark the start of the Holocene. Grey clastic layers are also present, particularly in the top 2m, some of which are visually graded when thick; these layers are interpreted as ‘turbidites’. Annual varve couplets are composed of a light (usually dull white) lamina containing mostly summer-precipitated carbonate and a dark (usually dark brown or olive green) lamina consisting of diatoms, organic material and clastics which is deposited in the autumn/winter (Jones, 2004). In some cases, distinct diatom bloom layers are present (Woodbridge, 2009). ^{210}Pb and ^{137}Cs dating of the top 50cm of the NAR01/02 core sequence, together with modern data from seston sediment traps, provides evidence that these couplets are annually deposited, with each dark and light band representing one year of sediment accumulation (England, 2006; Jones *et al.*, 2005). There are changes in the composition of the carbonate laminae throughout the core sequence between aragonite, calcite and dolomite (Dean, in prep; Jones, 2004).

The NAR10 core sequence has been tied in with previous core sequences extracted from the same lake based on sedimentological descriptions, visual comparisons and microscopic observations; these are NAR06 (AD 1927-2006) and NAR01/02 (AD 276-2001). Correlation of Nar Lake cores for the uppermost units of NAR10 and NAR01/02 provides a means of checking the dating of the upper part of the new (NAR10) core sequence. Across the three Nar sequences, clastic event layers and varve types appear consistent which may imply that there is little variation in sediment accumulation and lithology across the central lake bottom. However, there are some variations, mainly the result of variations in the thickness of slump deposits. There are also several small sections in the NAR10 sequence which have been disturbed through the coring process, where the laminations have become folded and misshapen. Generally, cross-correlation between parallel cores has helped to avoid using these disturbed sections, yielding a relatively complete master sequence. There is however, one break in the composite stratigraphy below 11.3m depth because there was no core recovery for this interval; this stratigraphic gap is estimated to be ~22.5cm thick.

The composite sediment sequence was created using all three lake centre NAR10 cores with correlations based on 29 tie points (Tp) (figure 4.1). The master core sequence has been divided into seven key lithostratigraphic units based upon changes in visual appearance and composition (table 4.1, figures 4.1 & 4.2).

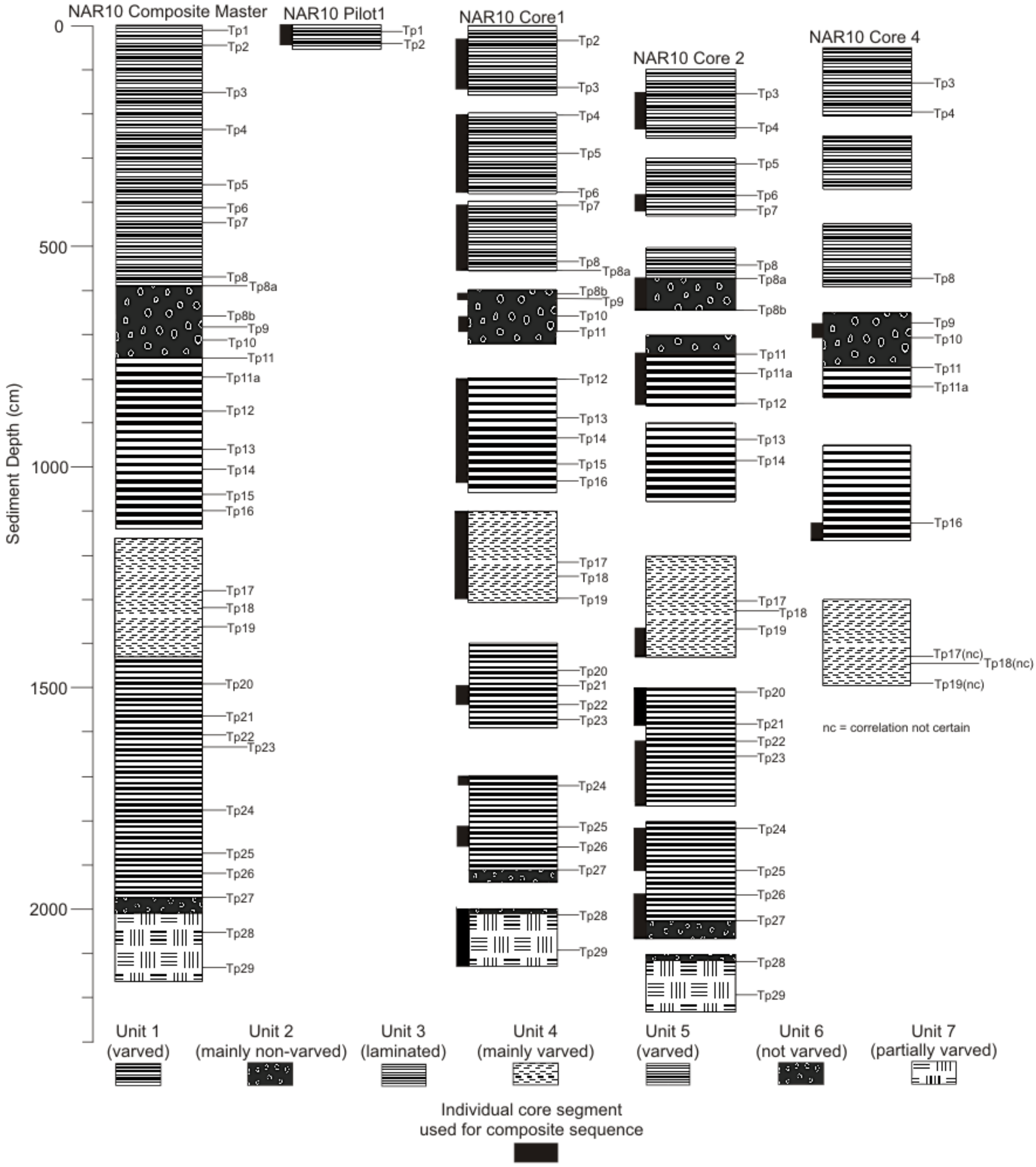


Figure 4.1: NAR10 composite master lithology and individual core sections. The sequence has been visually split into 7 key lithostratigraphic units with varved and non-varved deposits identified. ‘Tp(n)’ indicates the location of tie points used for cross-correlating individual core sequences.

Table 4.1: Descriptive summary of the key lithostratigraphic units and sub-units identified for the NAR10 sediment sequence.

Master sequence depth (cm)	**General description of unit**	**Master sequence depth (cm)**	**Detailed description (Tp = tie point)**
0-592.7	**Unit 1:** Mm thick laminated silts, black, brown, grey, olive, beige in colour; with distinctive, mid- grey turbidite events which occur frequently.	0-41	**Sub-unit 1a:** Mm thick laminated silt, brown, grey, olive, beige colour; with 2-3mm thick turbidite layers.
		41-152.7(Tp3)	**Sub-unit 1b:** Light brown, olive, beige laminated silt; with thin mm thick turbidite events.
		152.7(Tp3)-391.7	**Sub-unit 1c:** Dark brown, dark olive, beige laminated silt; thick and thin grey turbidite events.
		391.7-412.7(Tp6)	**Sub-unit 1d:** Light olive, beige, yellow laminated silt similar to above. Some thick grey turbidite layers towards top.
		412.7(Tp6)-592.7(just above Tp8a)	**Sub-unit 1e:** Darker colours. Black, brown, grey, olive, beige laminated silt; occasional turbidite events.
592.7-753.7	**Unit 2:** Mostly non-laminated and hard with rare thin, soft, interspersed laminations. Frequent nodular layers, some formerly laminated.	592.7(just above Tp8a)-599.7	**Sub unit 2a:** Dark laminations, hardened for top 5cm.
		599.7-622.7	**Sub unit 2b:** Dark grey hard carbonated silt. Finely laminated but highly disturbed by calcareous nodules.
		622.7-682.7(Tp9)	**Sub unit 2c:** Hard, homogenous light grey carbonated silt; Large nodules. Last 10cm cut by black organic rich band running left to right, 1cm thick (Tp8b).
		682.7(Tp9)-693.7	**Sub unit 2d:** Olive, white mm thick laminated soft, silt. Some oxidation to top due to orange colour.
		693.7-713.7(Tp10)	**Sub unit 2e:** Light grey, beige hard silt. Some linear carbonates at top which

			appear to be formerly laminated.
		713.7(Tp10)-719.7	**Sub unit 2f**: Soft, olive, grey, beige mm thick laminated silt. Thick grey lamina at top.
		719.7-753.7(Tp11)	**Sub unit 2g:** Light grey, olive hard silt. Frequent nodular carbonates with no laminations.
753.7-1138.7	**Unit 3:** Silty, brown, grey, olive, red, tan, cream, white 1-5mm thick laminations. Occasional non-laminated section.	753.7(Tp11)-798.7(Tp11a)	**Sub unit 3a:** Brown, olive-tan laminated silt. Thin, regular laminations with bowing to structure towards base. Some thick brown banding; lighter at bottom.
		798.7(Tp11a)-1006.2(just below Tp14)	**Sub unit 3b:** Brown, olive, beige, red laminated silt. 1-5mm thick, horizontal laminations. Occasional disturbance, distorted individual laminae structure.
		1006.2(just below Tp14)-1022.2	**Sub unit 3c:** Brown, dark olive silt. Laminated.
		1022.2-1099.7(Tp16)	**Sub unit 3d:** Thick, olive, cream laminated silt. Highly distorted with some non-laminated sections between Tp14 & Tp15 (984.2-1045.2cm).
	.	1099.7(Tp16)-1138.7(end of E drives)	**Sub unit 3e:** Brown, deep red, beige laminated silt. Finely laminated.
1138.7-1161.2	**Break in sediment sequence:** Core depths suggest no core recovery for this section.	1138.7-1161.2 (between E and F drives)	**No sub units**
1161.2-1428.2	**Unit 4:** Mostly laminated, very pale beige & white silt. Very fine laminations. Interrupted by carbonate tufa with plant stem inclusions and mm sandy bands.	1161.2(start of F drives)-1279.2(Tp17)	**Sub unit 4a:** Very finely laminated beige, white silt with banded sand inclusions. Some distorted laminations.
		1279.2(Tp17)-1299.2	**Sub unit 4b:** Homogenous grey/brown crumbly, calcareous deposit. Contains many tufa-encrusted plant stems, ~5mm long.
		1299.2-1428.2(end of F	**Sub unit 4c:** Weakly laminated silt, thin olive-beige alternations with very few

		drives)	breaks in the laminae. Includes similar but thinner calcareous, tufa encrusted plant deposit at 1291.2cm and thick black organic band at 1341.2cm.
1428.2-1974	**Unit 5:** Mm thick laminations of mainly olive-beige alternations but also black, grey, red, cream and white laminae.	1428.2(start of G drives)-1606.2(Tp22)	**Sub unit 5a:** Dark olive, grey, dark beige coarse laminated silt. Occasional 2-3mm thick turbidite and banded sand events; black organic band at 1470.2cm.
		1606.2(Tp22)-1921(Tp26)	**Sub unit 5b:** Fine, 1-2mm thick, distinctive laminated olive, beige, cream silt. Most laminae are uniform but few have been distorted; Very few clastics and banded sands. Following is a homogenous, light olive silt which is likely slop from coring.
		1921(Tp26)-1953	**Sub unit 5c:** Cream, white finely laminated soft silt. Broken by laminated brown banding, 0.5-2.5cm thick.
		1953-1974(just above Tp27)	**Sub unit 5d:** Dark brown, olive laminated silt. Various colour changes but predominately brown.
1974-2013	**Unit 6:** Homogenous mostly non-laminated grey, beige marl. Hard and calcareous; some large concreted nodules. Some dark laminations present between hard layers.	1974(just above Tp27)-2013	**Sub unit 6a:** Light grey marl. Softer towards top and more calcareous towards bottom. No laminations and some carbonate nodules.
2013-2169	**Unit 7:** Coarse and finely laminated olive, beige silt; occasional distortions. Frequent non-laminated sections; olive in colour, some soft nodular laminations. Abrupt colour changes at bottom between homogenous beige and olive silts.	2013-2128(just above Tp29)	**Sub unit 7a:** Light grey, beige laminations 1-3 mm thick. Some distortion to laminae from nodules above. Below 2033 cm, 1-3mm thick, distinctively laminated brown, olive, beige soft silt. Some laminae are coarse, nodular and distorted.
		2128(just above Tp29)-2165.2	**Sub unit 7b:** Weakly laminated beige, cream soft, silt. Interrupted at 2133-2137.5cm & bottom of core sequence by dark brown, weakly laminated silts.

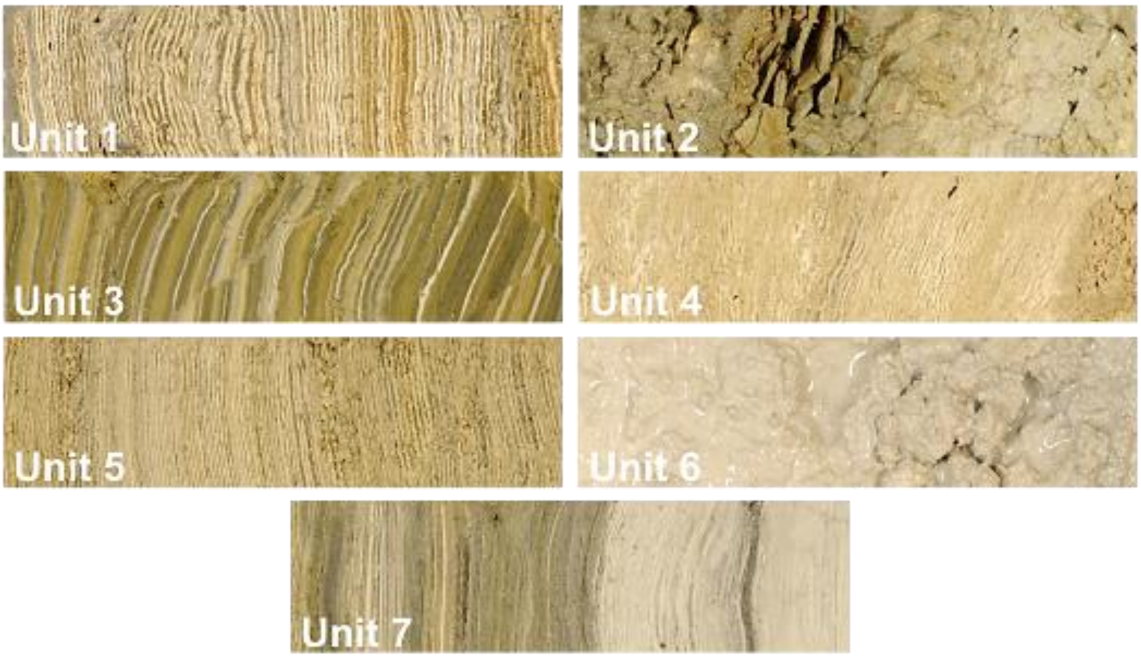


Figure 4.2: Overview images of the 7 key lithostratigraphic units identified for NAR10. Each image is a 15cm representative sample of the whole unit. To note are the changes in varve thickness and visibility, and changes in sediment colour and composition between each unit.

4.3. NAR10 dating and chronology

4.3.1. Chronology overview

Accurate dating of the NAR10 sequence has been problematic. The lack of terrestrial carbon and the remobilisation of old carbon stores from volcanic degasing have prevented the use of ^{14}C as a dating tool. Due to the annual nature of varved deposits at Nar Lake, it has been possible to establish a chronology from laminae deposits. The master chronology established for NAR10, to date, has been assembled using previously determined chronologies for the NAR01/02 core sequence and from varve chronological counting techniques (Lamoureux, 2001). Varve interpretation and the counting of varves was performed in 2011 by Nar Lake team members at Plymouth University, and a partially complete varve time series was constructed from these data. The assembled varve chronology is shown in figure 4.3. Other radiometric dating techniques are also currently being used but are not sufficiently complete to discuss in more detail here.

4.3.2. Varve chronology

A varve chronology (partially floating) has been established by visual varve counting of the NAR10 master composite core sequence, covering a time interval from the Late Glacial until present day (2010). Most of the chronological record was obtained from zones of clearly delineated varves, particularly in the top and lower sections of the composite sequence (figure 4.3). There were some zones of disturbed and concreted sediment that made varve counting impossible and for these areas varve counts have been extrapolated. Extrapolation for distorted sections and areas of problematic sedimentation was conducted using averaged varve thickness measurements from adjacent varves, measuring the associated depth interval and dividing the two. No single laminae type was seen throughout the core making components hard to define in places, and the presence of thick laminations, that can appear annual in nature, further complicated the counting procedure. Three estimates for the number of years represented by the thicker laminations have been devised to account for the possible annual/non-annual nature of these sections. The chronology was further complicated by 'turbidite' type layers that interrupted varve couplets. The regular pattern of clastic input during carbonate laminae formation made identification of these bands easy and the clear contact with material below and above in most cases confirmed minimal erosion. The proposed varve chronology should therefore be minimally affected by clastic sedimentary events.

A robust varve chronology has been established for the top 592.7cm as the stratigraphy is continually varved from there to the present day. Besides some disruption to the top 10 varves (discussed in section 4.3.3), there are no obvious hiatuses or sedimentological distortions in this section, resulting in a firm varve count of 0-2589vys equivalent to calendar ages of AD 2010-BC 579. The varve chronology for the top 1719vys was developed alongside previous core chronologies (NAR01/02); NAR10 varve counting commenced from the end of the NAR01/02 sequence until the top of unit 2 (592.7cm) where hard carbonate concretions prevented further counting.

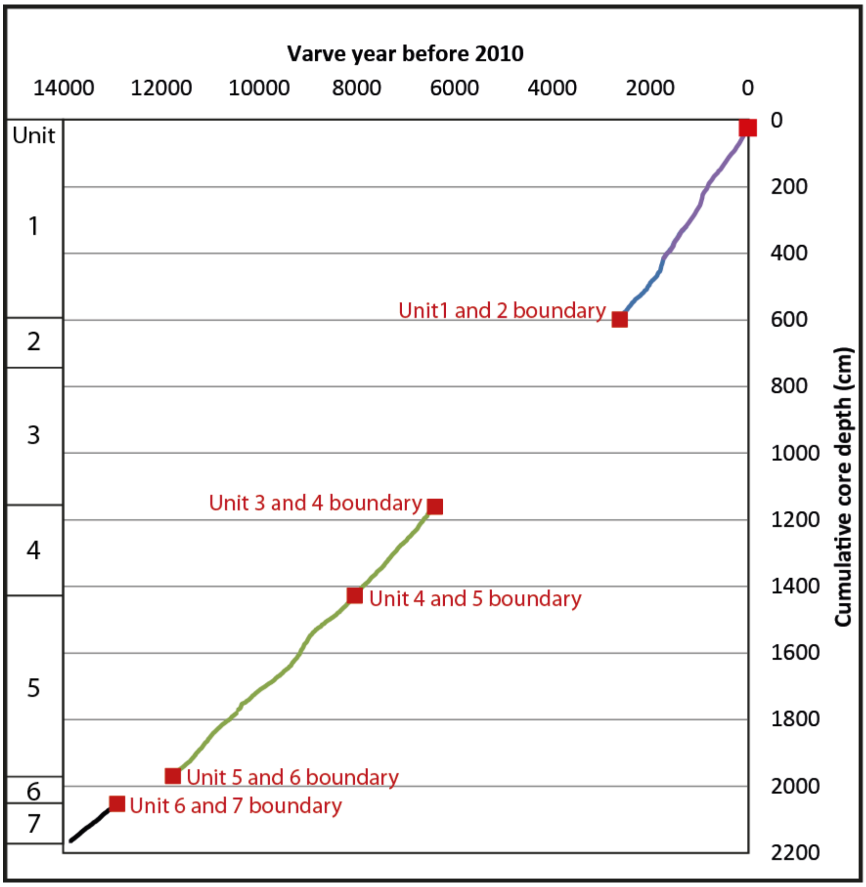


Figure 4.3: Age-depth model based on varve chronologies for NAR10. The purple line shows counts from the NAR01/02 sequence and the blue line shows counts for the NAR10 sequence (with some overlap). The green line shows varve counts established from 11700 years ago towards present. The black line shows counts for unit 7 which pre-dates the Younger Dryas (here delineated as starting at 12900 cal. yrs. B.P). Chronologies finish where varve formations stop or where sections are problematic.

A reasonably firm varve chronology has also been established from 11700 cal. yrs. B.P. until 6398vys as varves for this time section (units 4 and 5) are also clear and easy to count. The start date of 11700 cal. yrs. B.P. (end of unit 6) is an estimated date for this part of the core sequence as isotope studies (Dean, in prep), geochemical data and changing sediment characteristics (both this thesis) indicate that this boundary represents the termination of the Younger Dryas climatic anomaly, the end of which is commonly agreed as 11700 cal. yr. B.P. (e.g. Grootes *et al.*, 1993; Holliday *et al.*, 2011; Rasmussen *et al.*, 2006) and provides a suitable tie point for this varve sequence. Similarly, it is possible to delineate the start point of the Younger Dryas event through isotopic, geochemical and visual analysis of the sediment sequence. Varve counts from the start of this climatic event (dated here to 12900 cal. yrs. B.P. (Bakke *et al.*, 2009)) back in time have resulted in an annual count of 958vys, ending at 13858 cal. yrs. B.P. for the base of the varved core sequence (figure 4.3).

4.3.3. Comparison with NAR01/02 chronology

To assess the reliability of the varve chronology for the top 400cm of the NAR10 sequence, dates were correlated to the chronology established for the NAR01/02 composite sequence (figure 4.4) where the two records overlap. The benefit of comparing to the NAR01/02 sequence (figure 4.5) is that this record has been radiometrically dated, providing confirmatory evidence of the estimated varve years (Jones, 2004). ^{210}Pb and ^{137}CS dates revealed that the original NAR01/02 varve chronology needed to be shifted by 5 varve years to younger values to correct for the mismatch in the age-depth model (England, 2006). It is assumed that the same issue is of relevance to the NAR10 chronology due to an off-set in isotope samples for the two sequences of around 5 varve years, and has therefore also been adjusted accordingly (Dean, in prep). This has resulted in missing varve years for the top most 10 years of the NAR10 sequence and has led to laminae being assigned a two varve year interval in parts. There are a number of postulated causes for the missing varves, none of which are certain, but range from the presence of large ‘turbidites’ in the core sequence to the construction of a geothermal exploratory bore hole in the vicinity of the lake during the early 1990’s, both of which could have affected varve deposition.

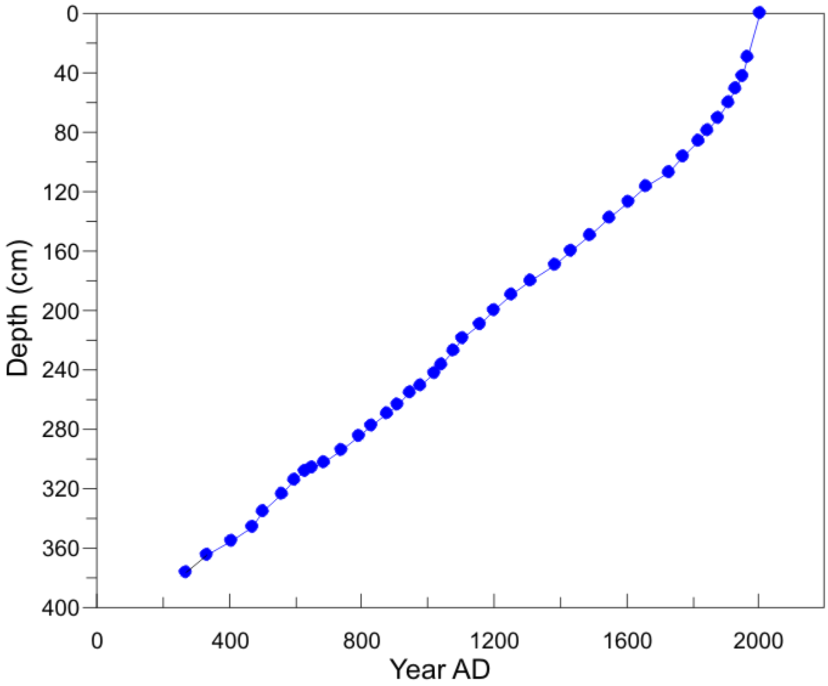


Figure 4.4: Age-depth relationship for NAR01/02 varve chronology (Jones, 2004)

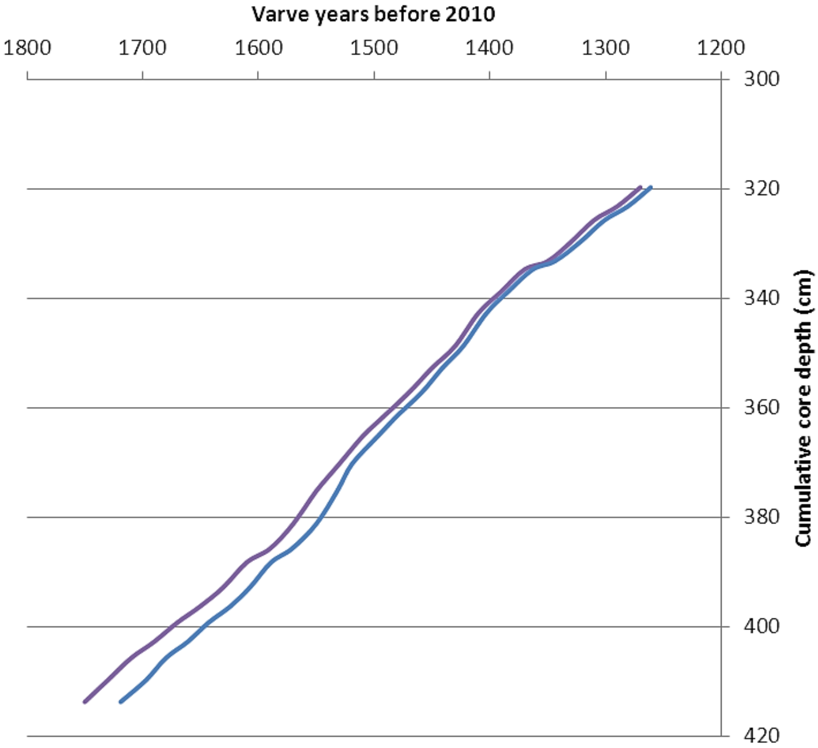


Figure 4.5: Comparison of the NAR01/02 (purple line) and NAR10 (blue line) varve counts against cumulative depth.

Table 4.2: Comparison of the NAR01/02 varve count with the NAR10 varve count for a 480 year overlap period.

NAR01/02 varve year	Date (AD)	NAR10 varve year	Date (AD)	Difference (vy)	Difference between NAR01/02 and NAR10 (%)
1270	731	1261	740	9	0.7
1290	711	1281	720	9	0.7
1310	691	1301	700	9	0.7
1330	671	1322	679	8	0.6
1350	651	1344	657	6	0.4
1370	631	1363	638	7	0.5
1390	611	1384	617	6	0.4
1410	591	1403	598	7	0.5
1430	571	1423	578	7	0.5
1450	551	1441	560	9	0.6
1470	531	1459	542	11	0.7
1490	511	1479	522	11	0.7
1510	491	1497	504	13	0.9
1530	471	1519	482	11	0.7
1550	451	1532	469	18	1.2
1570	431	1550	451	20	1.3
1590	411	1571	430	19	1.2
1610	391	1589	412	21	1.3
1630	371	1607	394	23	1.4
1650	351	1624	377	26	1.6
1670	331	1643	358	27	1.6
1690	311	1661	340	29	1.7
1710	291	1680	321	30	1.8
1730	271	1697	304	33	1.9
1750	251	1719	282	31	1.8

Table 4.2 shows the cumulative laminae counts for NAR01/02 against the cumulative laminae counts for NAR10 to help identify parts of the core sequence where varve

numbers may be under or over-represented. Comparing the two records in this fashion suggests that the counts for both sequences are not too dissimilar with an estimated maximum counting difference of around 1.9% for this part of the core sequence. The error estimates suggest that on average, the NAR10 laminae counts are up to 1% younger than the NAR01/02 laminae counts. It is reasonable to put forward that for the parts of the NAR10 sequence which overlap with the NAR01/02 sequence, there is minimal error in the NAR10 varve chronology. The counting error for NAR10 will have little influence on the climatic and environmental reconstructions made for the last 2589vys (unit 1) because the different between NAR10 and NAR01/02 is small. Further counting checks for the rest of the NAR10 sequence are planned once radiometric dates are made available.

4.4. NAR10 total organic and total inorganic carbon analysis results

Total carbon analysis is a method which measures the total inorganic (TIC) and total organic carbon (TOC) component of sediments (Dean, 1974). Total organic carbon concentration varies through the sedimentary sequence, indicating changes in organic deposition and preservation under different sedimentary conditions (Meyers and Lallier-Vergés, 1999). The NAR10 TOC and TIC results are presented in figure 4.6 and described according to depth and lithostratigraphic unit. With 512 sample depths and a mean sampling interval of 4.09cm, results show considerable down core variability, correlating with sediment lithology and clearly reflecting the diverse nature of the lithostratigraphic units. Total inorganic carbon concentrations are significantly higher than total organic carbon concentrations. The mean TOC content of the NAR10 sediments is about 1.1% although it ranges from 0 to 5.9%. TIC percentages are generally much higher, reaching levels of 14.1% (but also low levels of 4.0%). On average, TIC is 9.5%, indicating that the NAR10 sediments are relatively carbonate-rich. Visually, total carbon (TC) percentages for the top half of the NAR10 sequence are more highly variable than the lower section. Values range between 4.71-13.52% for the top and 5.3-13.15% for the bottom, with higher amplitudinal changes more commonly associated with the top 10m.

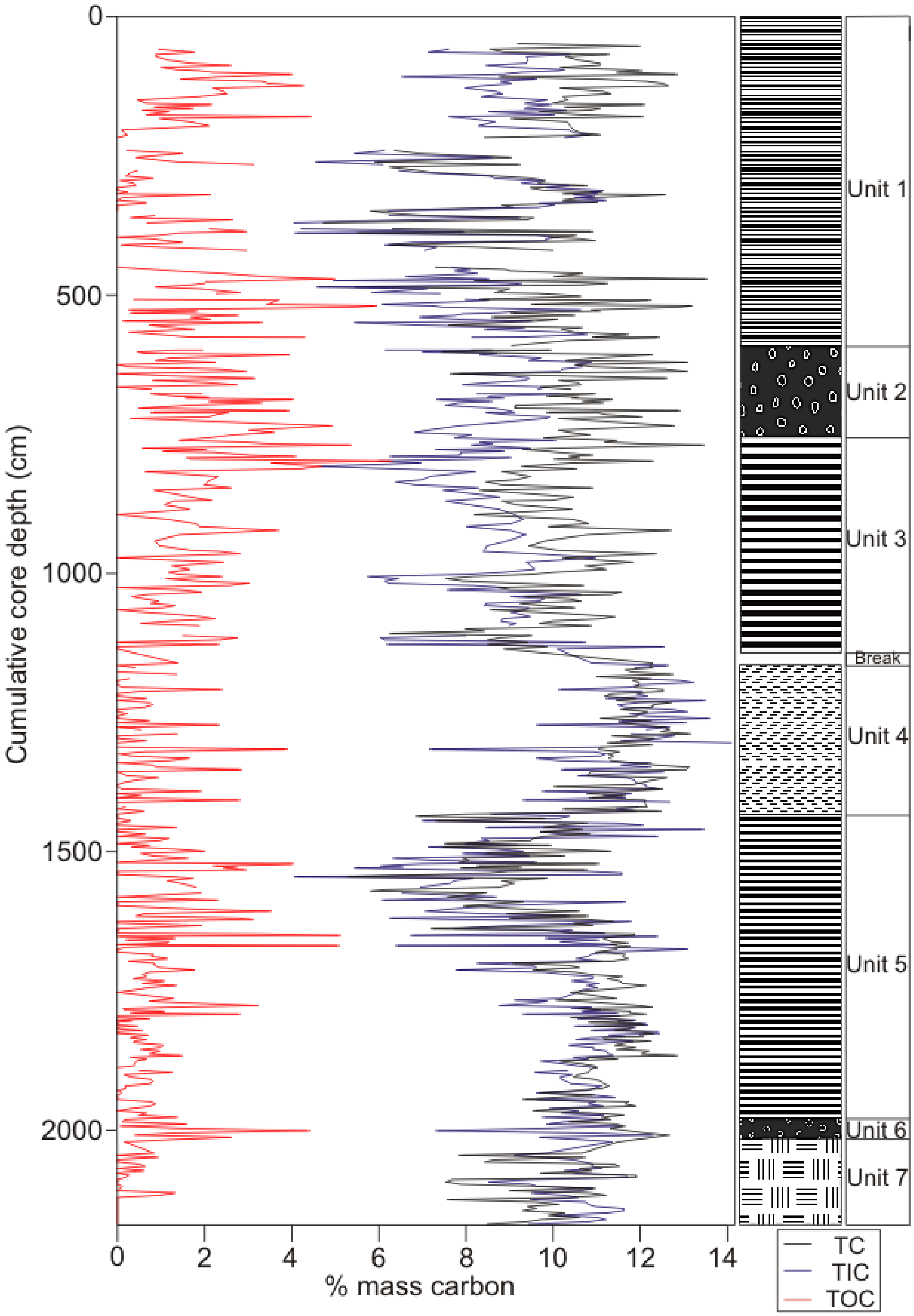


Figure 4.6: Total carbon (TC), total inorganic carbon (TIC) and total organic carbon (TOC) results for NAR10 plotted as carbon mass percentage. Total carbon percentages are shown against core depth, lithology and lithostratigraphic units.

Caution must be given to samples where inorganic carbon values exceed total carbon values as this indicates that during total carbon analysis, not all carbon was combusted and therefore will underestimate organic carbon values. Similarly, where high TIC values exist, organic levels may be swamped by high inorganic readings and also underrepresent the amount of organic carbon presence. Samples with low TOC readings must therefore be interpreted with some care.

Lithostratigraphic unit 7 shows the lowest average values of TOC for the whole core sequence (0.2%) with TOC values of zero recorded for the bottom 0.5m of the core sequence. High TIC levels, which fluctuate only moderately, and decreased levels of organic carbon typically characterise the bottom 165cm of the sediment sequence dating to the Late Glacial period. From unit 7 through to sub-unit 5c, values of TIC remain constantly high at this sampling resolution. TOC values are likewise consistently low, apart from a sharp increase at 20m to 4.4%. Towards the top of unit 5, TIC levels begin to decrease, ultimately resulting in relatively low TIC values (down to 4.08%) by sub-unit 5a. In sub-units 5a & (end of) 5b, carbon values vary quite significantly, with TIC percentages ranging between 4.08-13.4% and TOC percentages ranging between 0.5-5.15%. Unit 4 in comparison is characterised by very high levels of TIC and the occasional peak in TOC (0.8% average). The TIC record here is also relatively stable with values generally fluctuating between 10 and 13 %, and only dropping when organic levels increase beyond 2%. Unit 3 shows a different pattern to that witnessed in unit 4, with moderate levels of TIC (12.53% max) and greater fluctuations in concentration. The base of unit 3, the transition from unit 3 to unit 2, and unit 2 reveal increased levels of TOC, and slight decreases in TIC, making this section very distinctive in terms of organic carbon deposition. Average mass percentage values for TOC of 1.86% for unit 2 and 1.79% for unit 3 suggest fairly similar conditions across the two units. The transition to unit 1 is evidenced by a slight increase in TIC and a slight decrease in TOC concentrations. Unit 1 shows fairly high levels of TIC (8.4% average) with only three noticeable decreases in concentration at around 2.6, 3.7 and 4.8m. Variability and amplitudinal change is greatest here, but not too dissimilar from the variability witnessed in units 3 and 2 also.

4.5. NAR10 Itrax XRF core scanning results

4.5.1. Itrax core scanning results overview

Itrax XRF core scanning provided a high-resolution record (every 200 or 400 µm) of geochemical variations for the full NAR10 sediment sequence. The following Itrax XRF summary plots show the key results from core scanning that will be used to determine palaeoclimatic and palaeoenvironmental change for Nar Lake from the Late Glacial through the Holocene, and up until present day. The nature of Nar Lake's evolution will be discussed in relation to changes over time, with coverage of in-lake (autochthonous) and out of lake (allochthonous) processes. Down-core profiles of both heavy and light elements noticeably delineate the different sedimentological units and physical properties already described in this chapter (section 4.2). Broadly, data shows opposite trends between Ca and Fe peaks, while Ti, K, Rb and Si behaviour is variable. Some data obtained recorded very low peak area integral values and some individual elements were generally at the limits of detection; these have no significant meaning with regards to climatic/environmental change and have thus only been presented in appendix 2. Due to issues with dating accuracy in parts of the core sequence, elemental data have been plotted against core depth only here.

The fact that geochemical results tie in nicely with sedimentological units has highlighted an important issue concerning possible gaps in the NAR10 sediment sequence. Whilst it has been suggested that there is a gap between units 3 and 4 of around 22.5cm, the element profile for this part of the core sequence actually shows a clear gradual transition in sample values across the break suggesting that the coring gap is certainly not any larger than the proposed estimated depth. On the other hand, an abrupt change in sample values between units 4 and 5 is very marked, with change occurring over a very short time interval and may suggest that sediment material may be missing from this section also. Whilst core depths suggest no break in the sediment sequence at this point in time, elemental variations may imply a possible break in the core sequence following unit 5. It is likely however, given core depth estimates, that this stratigraphic gap prior to unit 4 would be small.

4.5.2. Itrax core scanning results for selected elements

The following figures (figures 4.7 & 4.8) are plots outlining the Itrax core scanning results for elements related to authigenic carbonate deposition within Nar Lake. Note that Magnesium (Mg) was not detected by the Itrax XRF scanning procedure. Moving averages have also been plotted to smooth out the short-term fluctuations in the data and to highlight longer-term trends.

Based upon the corrected Itrax data profiles of Calcium (Ca) and Strontium (Sr) (figure 4.7), elemental variation clearly parallels lithostratigraphy, with unit 4 being particularly distinctive. Starting from the bottom of the core sequence, unit 7 shows generally elevated levels of Ca and Sr, which can be relatively variable in nature. The change to unit 6 is subtle, and characterised mainly by higher levels of Ca and a small drop in Sr. The end of unit 6 reveals heightened Sr levels (600 max) and slight decreases in Ca (above 4000) (all values in peak area integrals). The beginning of unit 5 is not too dissimilar to unit 6 in terms of Ca (average 2500), but levels of Sr in contrast decrease significantly here (below 200). Unit 5 witnesses a decrease in Ca values from the base to the top, with a slight increase in the levels of Sr. A dramatic change is evident during the transition into unit 4 where Ca increases by 60% and Sr values decrease by 50%, revealing a major switch in climatic and environmental conditions here. Raised levels of Ca (above 3000) in relation to Sr (below 2000) characterises unit 4. This unit also shows pronounced stability in the geochemical record compared to other periods; particularly evident is the stability of Sr values at this time.

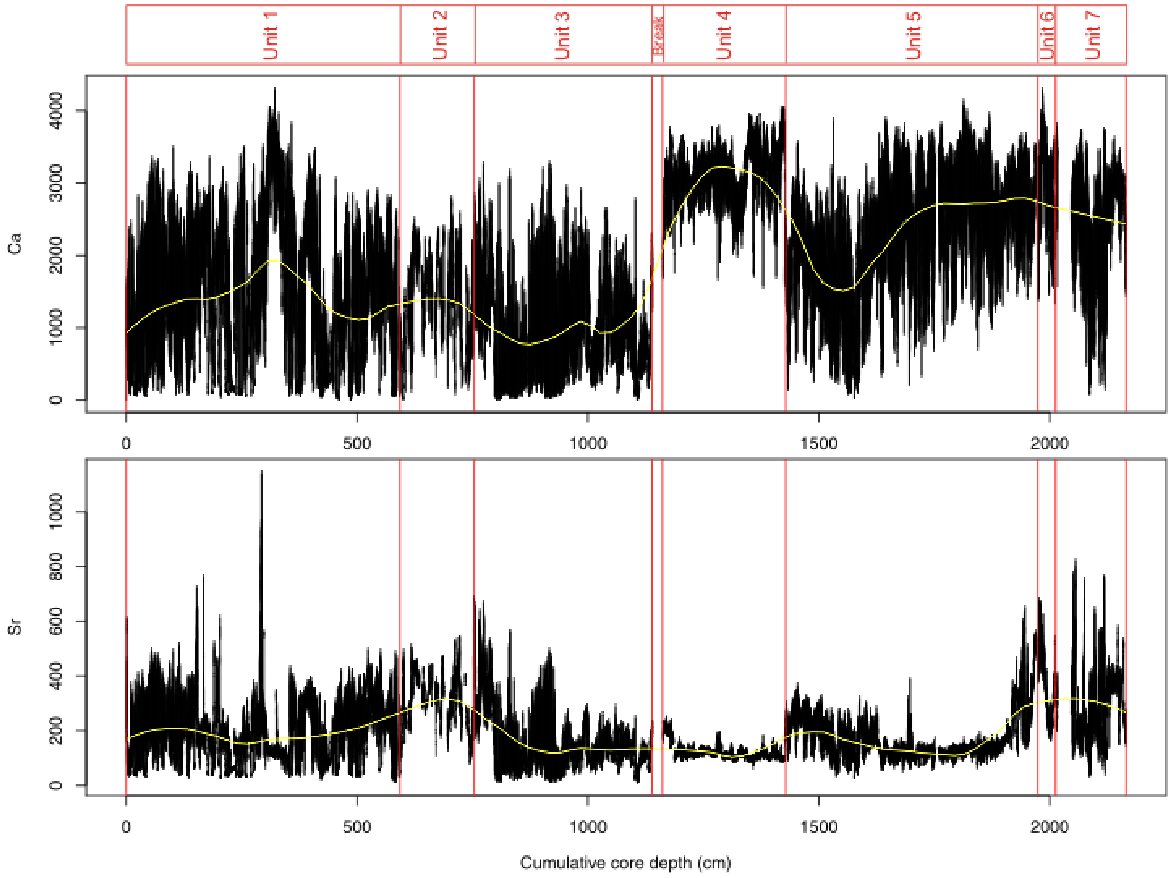


Figure 4.7: Stratigraphic diagrams of Calcium (Ca) and Strontium (Sr) (corrected peak area integrals) showing the Itrax derived values for these elemental components of NAR10. Lithological units are indicated by red lines. A 0.2 span loess smoother (yellow line) has been applied to the datasets to show longer-term change.

The biggest drop in Ca values is seen during the transition to unit 3. Unit 3 consists of low Ca; in fact the lowest average Ca values (~1000) for the entire core sequence are seen here. Sr and Ca both increase between unit 3 and 2, with peak area integral values increasing on average by 49% for Sr and 72% for Ca. Unit 2 shows elevated levels of Ca and Sr in relation to the end of unit 3 and start of unit 1. The top of unit 1 shows slightly reduced levels of Ca and Sr; Sr levels in unit 1 decrease by an average of 62%.

Fluctuations of Ca and Sr are typically higher in unit 1, resulting in a noticeable extreme event occurring during sub-unit 1c where Ca reaches values up to 4000. At the end of this event, a massive increase in Sr is also witnessed at ~293cm (the largest peak in the whole data set). In the most recent deposits towards the top of unit 1, Ca and Sr values decrease again.

Moving average window plots (figure 4.8) confirm many of the patterns seen within the corrected Itrax elemental profiles of Ca and Sr. Running averages reveal three key changes along the NAR10 sequence in the Ca record, at sub-units 1c and 5a, and unit 4 respectively. Unit 4 is the most distinctive, with significantly elevated values of Ca. Unit 4 is also characterised by very low Sr, a pattern also evident in sub-units 5b, 5c and 5d. The averaged Sr record reveals a slightly different pattern to Ca with units 3 and 6 being the most distinct; unit 6 indicating the most dramatic rise in Sr deposition for the entire core sequence.

Figures 4.9 & 4.10 for the Iron (Fe) and Manganese (Mn) elemental component of the NAR10 sediment sequence represent the distribution of these two elements which is controlled a) by influx of detrital iron compounds from the catchment, and b) the deposition of hydrous oxides down core and of reduction/oxidation (redox) reaction conditions at the lake bed. Moving averages have been plotted to smooth out the short-term fluctuations in the data and highlight longer-term trends.

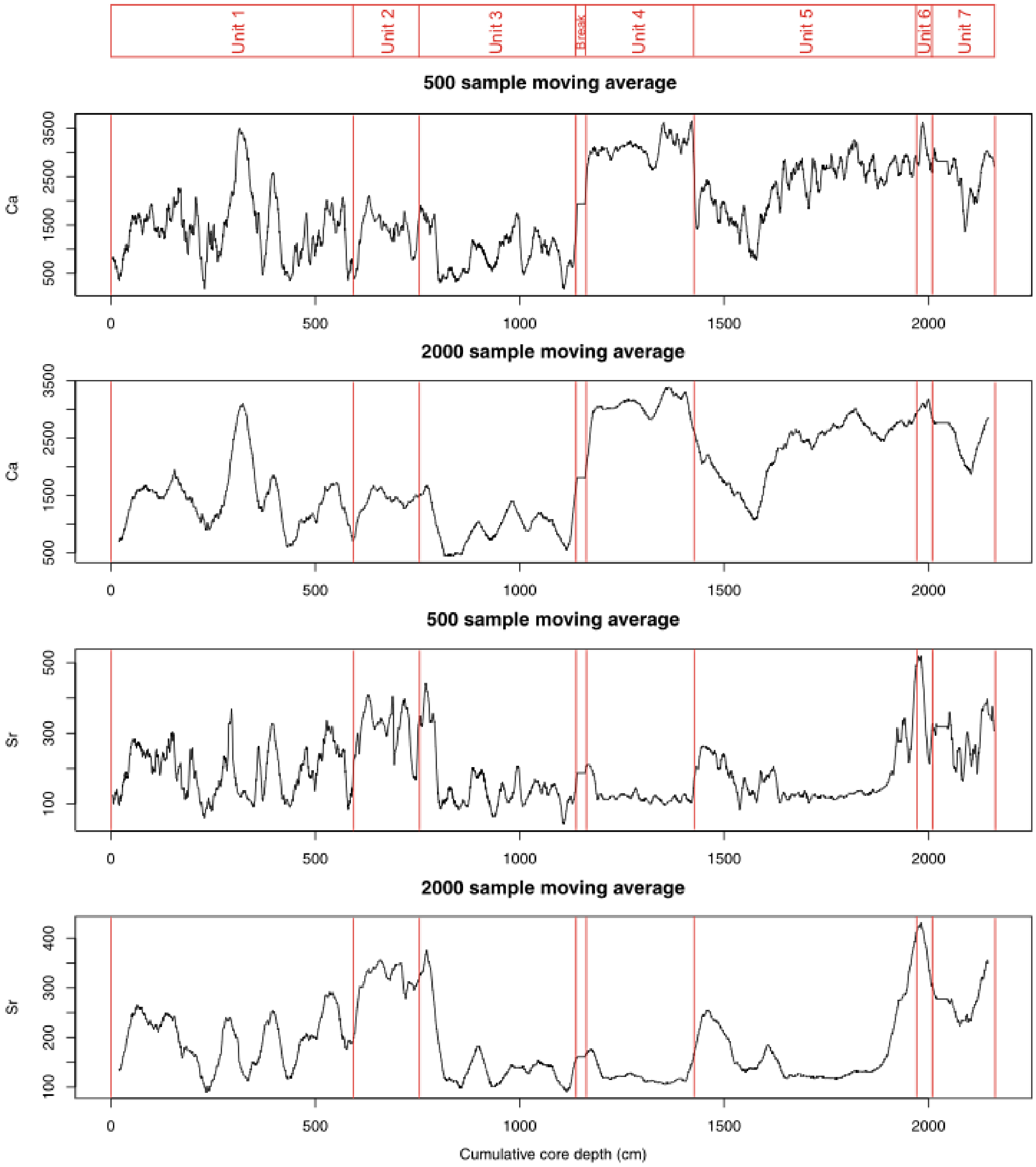


Figure 4.8: Stratigraphic diagrams of Ca and Sr (corrected peak area integrals) showing the Itrax derived values for these elemental components of NAR10. Plots are of 500 and 2000 sample running averages of the two elemental components to reveal change over roughly 10 and 40 year intervals respectively.

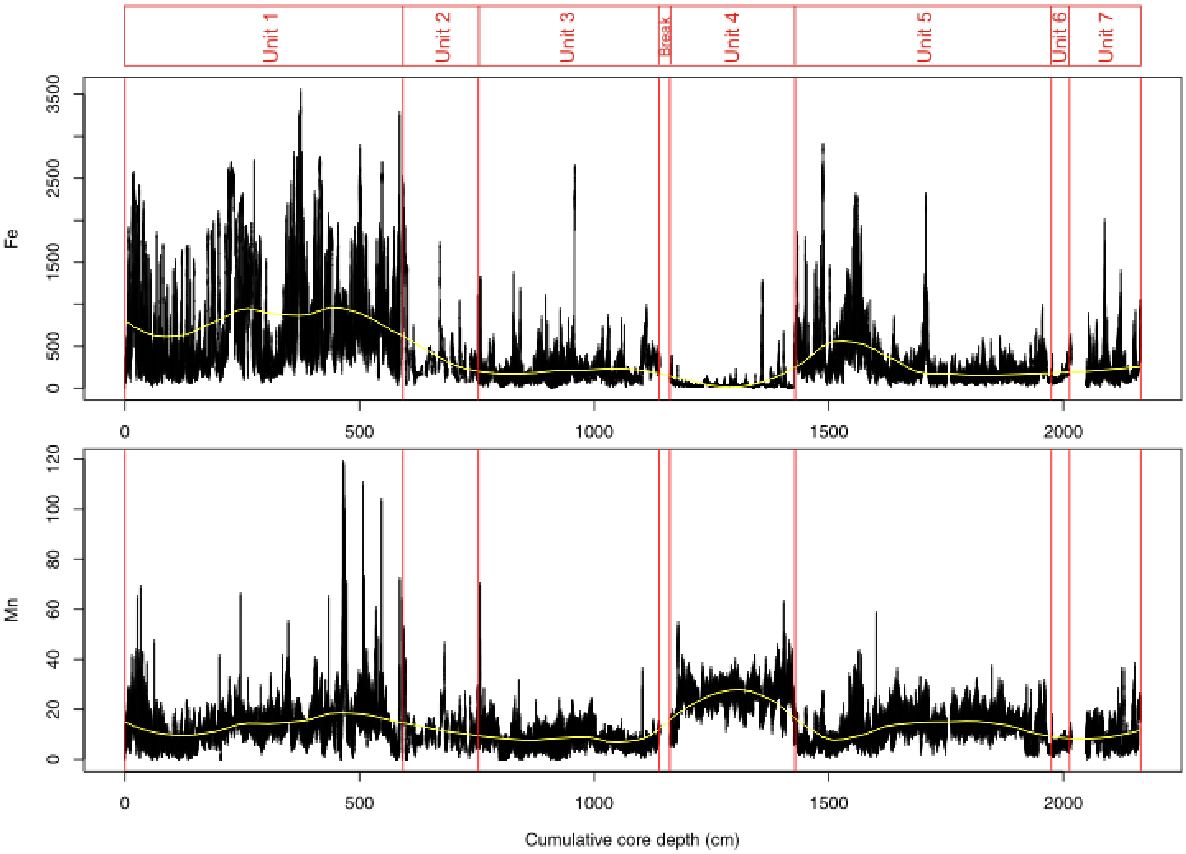


Figure 4.9: Stratigraphic diagrams of Iron (Fe) and Manganese (Mn) (corrected peak area integrals) showing the Itrax derived values for these elemental components of NAR10. Diagrams are plotted from modern times and lithological units are indicated. A 0.2 span loess smoother (yellow line) has been applied to the datasets to show longer-term change.

Stratigraphic profiles of Iron (Fe) and Manganese (Mn) variation (figure 4.9) also show a strong association with lithology, with key changes in the geochemistry occurring at points where there are significant changes in sediment colour and type. The bottommost unit 7 of NAR10, in terms of Fe and Mn concentration, shows moderate fluctuations in peak area values for both elements. In comparison to other parts of the core sequence, smoothed values of Fe (~400) and Mn (~15) suggest fairly low levels of deposition during unit 7. Fe and Mn values are low and constant throughout unit 6. Unit 5 is split into two distinct sections, with sub-units 5b, 5c & 5d showing low levels of Fe (range 0-1000) and Mn (range 3-39) and sub-unit 5a showing much higher levels of Fe (max 2800) and decreased levels of Mn (~10). The transition between unit 5a and unit 4 is abrupt, revealing a dramatic rise in Mn and a drop in Fe. The increase in Mn levels compared to the decrease in Fe levels during unit 4 signifies that the two elements are not responding together, as is the case in the preceding unit. Units 2 and 3 are very similar to each other with relatively low values of Fe (~300) and Mn (~10) and only moderate fluctuations in concentration. Several Fe peaks in units 2 and 3 (max 2600) indicate that Fe may be responding differently to Mn here also. The transition into unit 1 shows increasing Fe and Mn values (79 and 42% respectively). Unit 1 is very distinct in terms of Fe with very high and variable levels (range of 0-3500). The Mn values for this unit are not as variable but do show some elevated sections during sub-units 1a and 1e. Sub-unit 1c is also noticeable by a significant drop in Fe levels to below 500.

Running average plots (figure 4.10) show three distinct phases of change between Fe and Mn. With Fe, unit 1 and sub-unit 5a are the most visually distinctive with values exceeding 1000 in some cases. Also noticeable is the long-term increasing trend in Fe in the upper 6.5m of the core record. With Mn, unit 4 is by far the most noticeable zone of elevated Mn levels, and these levels remain constant for the entire unit. There are some other increases in Mn that are visually recognisable at around 5m too. Units 2 and 3 for both elements show lowered values and reduced variation. Unit 5, whilst split into two distinct sub-units in terms of Fe, in terms of Mn there is less variation in the values recorded resulting in a less pronounced separation of the unit for this elemental profile.

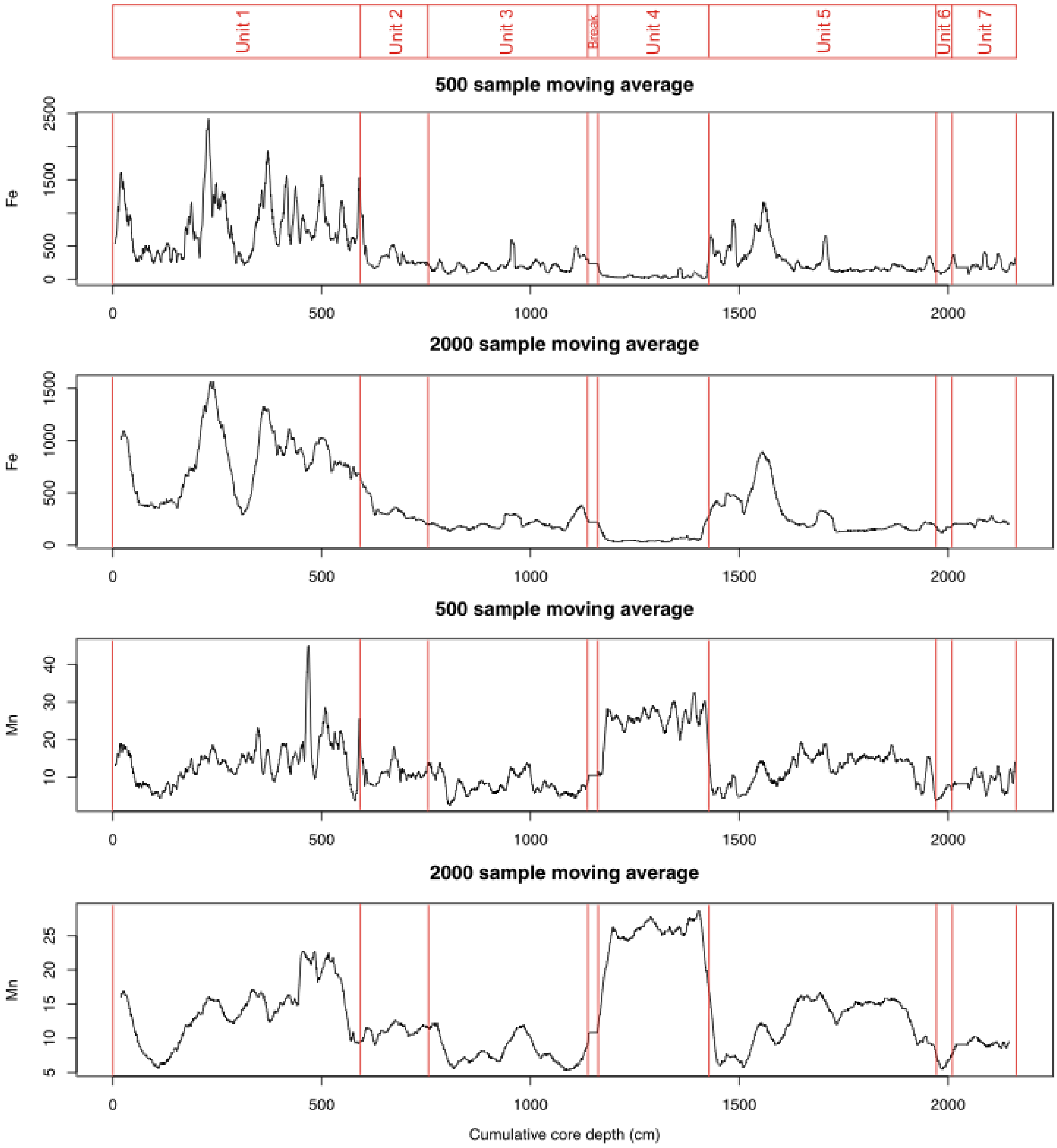


Figure 4.10: Stratigraphic diagrams of Fe and Mn (corrected peak area integrals) showing the Itrax derived values for these elemental components of NAR10. Plots are of 500 and 2000 sample running averages of the two elemental components to reveal change over roughly 10 and 40 year intervals respectively.

Figures 4.11-4.14 detail detrital elemental components of the NAR10 sediment sequence and represent the distribution of these detrital elements down core. A large component of the NAR10 sediment record is assumed to be of detrital origin as the sequence is commonly high in Fe, Ti, K, and to some extent Si, Rb, Zr, Zn and Cu. The most useful indicators of clastic input into the lake are Ti, Fe, Rb and K as the peak area integrals for these elements are relatively high and the Itrax system has identified peaks successfully. Presented here are the results for Ti, Si, K and Rb, with Fe values presented in figures 4.9 and 4.10. Other elements such as Zr, Zn and Cu show similar trends to the major clastic elements, but for the most part have low Itrax XRF peak area values. Considerable noise results from data with low peak area integrals, and can provide an unreliable indication of past climate/environmental conditions. Results for Zr, Zn and Cu can be seen in appendix 2. Lighter elements (e.g. Si and K) have lower peak area integral values because these are generally at the limits of detection. Their co-variance with other lithogenic elements like Ti, Rb and Fe reveals that changes in these elemental components can be classed as 'real'. Occasionally, Si is decoupled from the lithogenic component, and in this instance Si is principally biogenic in nature. Moving averages have been plotted for detrital derived elements for smoothing and highlighting purposes also.

Stratigraphic diagrams of Si and Ti (figure 4.11) show significant changes relating to the NAR10 sediment stratigraphy. The general pattern for Si is one of decreasing values from the base of unit 5 through to increasing values during unit 1 (range 0-15), forming a rough u-shaped pattern. The record is also highly variable, particularly towards the top of the core sequence where values are relatively high (above 10). Moderately low levels of Si are witnessed during unit 7, unit 6 and the latter half of unit 5. Values are by no means constant for these time periods and this is evidenced by a noticeable decrease in Si levels (~2.5) during sub-units 5b & 5c. Lowest Si deposition is associated with units 4 and 3 where values average around 1. This drop in Si is particularly noticeable due to the much higher values associated with sub-unit 5a, and which begin to develop afterwards during unit 2. The pattern of Si deposition for unit 2 highlights values slowly rising. A significant drop in Si can be seen towards the base of unit 2 which is distinctively different to the overall trend for the unit; here values reach zero in places. Unit 1 stands out because of the highly variable nature of the record. Si deposition is not constant, with lows of 2 and highs of 13 recorded. The most significant shift in value can be seen during sub-unit 1c where Si levels fall abruptly. In most recent times, it appears that Si deposition is declining with lower levels indicated.

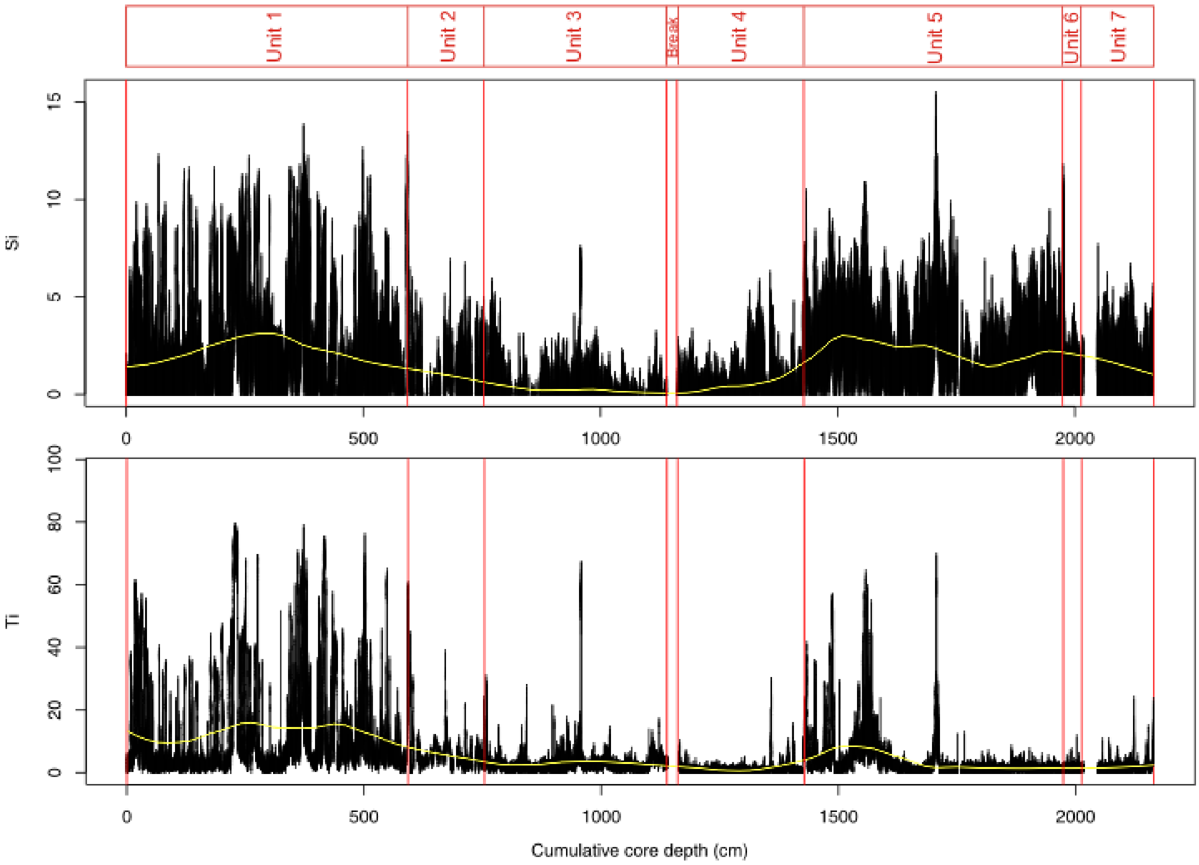


Figure 4.11: Stratigraphic diagrams of Silicon (Si) and Titanium (Ti) (corrected peak area integrals) showing the Itrax derived values for these elemental components of NAR10. Diagrams are plotted from modern times and lithological units are indicated. A 0.2 span loess smoother (yellow line) has been applied to the datasets to show longer-term change.

The Ti record (figure 4.11) shows a similar pattern in places, particularly in unit 1 where values can be high (above 40, average 22) and variable. Unit 7 indicates very low (around 5) and constant levels of Ti, a pattern which continues until sub-unit 5b. At this point in time, Ti values begin to dramatically increase, firstly peaking at ~17m and then more prominently at ~15.6m. Following these peaks in Ti, there is a long-lived deviation to low Ti which extends across units 4, 3, and to some extent unit 2. There is only one noticeable peak in Ti during unit 3 which is likely associated with a dense black sediment band observed in the core stratigraphy. During unit 2, Ti values begin to increase again. By unit 1, values have increased by 92% from those witnessed during unit 2. Whilst Ti is high on average, dramatic amplitudinal changes are also visually apparent during unit 1, revealing some dramatic lows in Ti for this unit also (range 0-79). Of importance is a deviation to low values during sub-unit 1c where values average around 5.

Moving average plots of Si and Ti (figure 4.12) confirm that Si is lowest during the middle of the core sequence with more modern and older sediments showing generally more elevated levels. Ti is most dominant during unit 1 and towards modern times, apart from a key event distinguishable during sub-unit 1c. Sub-unit 5a is also distinct; particularly because Ti values that precede this event are extremely low and invariable. The transition into unit 4 and throughout unit 3 is one of decline. Values remain consistently low until unit 2 where Ti deposition greatly increases, reaching very high values by unit 1.

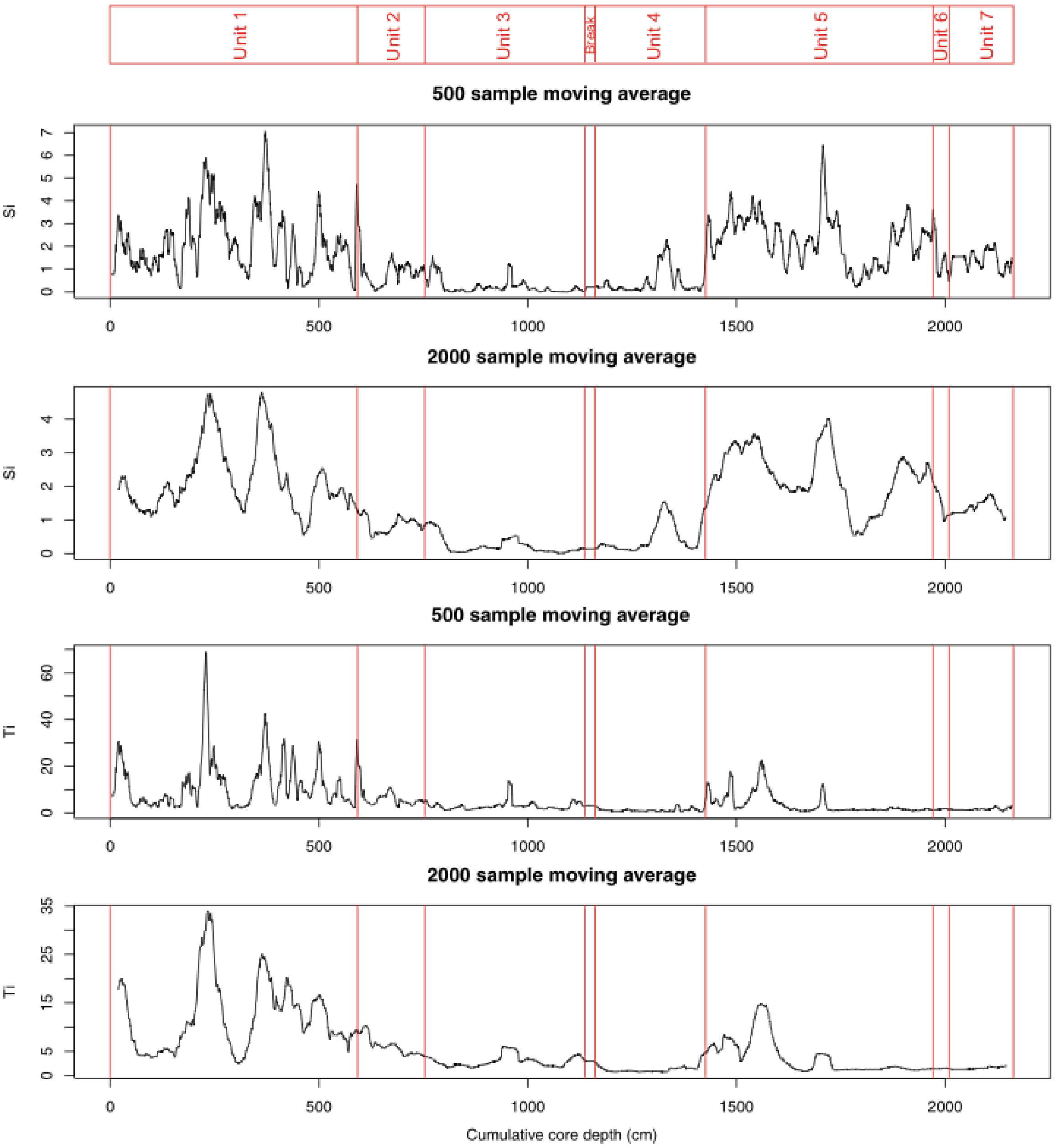


Figure 4.12: Stratigraphic diagrams of Si and Ti (corrected peak area integrals) showing the Itrax derived values for these elemental components of NAR10. Plots are of 500 and 2000 sample running averages of the two elemental components to reveal change over roughly 10 and 40 year intervals respectively.

Figure 4.13 details the down-core changes of Potassium (K) and Rubidium (Rb). Elemental variation clearly parallels sediment stratigraphy again, with unit 1 being the most distinctive. Due to their similar nature and patterns of change, K and Rb will be discussed together here. Detailing changes from unit 7 towards present times reveals very low and consistent levels of both K and Rb in early deposits. The base of the core sequence hints at slightly increased variability at this time for both elemental components, but generally, change throughout unit 6 and sub-units 5b, 5c & 5d is relatively small scale. Sub-unit 5a witnesses a change in conditions, as both levels of K and Rb increase significantly here (max 90 and 80 respectively). This abrupt shift to high values is made even more apparent by the abrupt drop that follows this event. The transition into unit 4 sees a reduction in Rb levels by 34% and K by 65%. Also noticeable is the increase in variability associated with the change to high values during sub-unit 5a. Unit 4 contains the lowest levels of K (average 5.6) and Rb (average 2.8) seen throughout the entire core sequence and values remain diminished until the transition into unit 3. Unit 3 is characterised by decreased levels of both K and Rb (below 20). However, the two elements begin to show a less similar pattern here with values of Rb starting to rise towards the base of the unit and values of K moderately fluctuating. There is an extreme peak noticeable in the centre of unit 3 associated with a dark black band in the sediment stratigraphy and forms a noticeable deviation from the norm. Unit 2 appears to be a transitional phase with increasing levels of both elements. Unit 1 sees a 52% increase in K values and a dramatic 97% increase in Rb values from unit 2. Unit 1 also reveals a highly variable record with very distinctive shifts, the most noticeable occurring during sub-unit 1c. Here values of K range between 0-120 and values of Rb between 0-140; values which have not been seen since the base of unit 5. This is also in stark contrast to unit 4 which has very low variability and a range of 0-20.

Moving average plots for K and Rb (figure 4.14) reveal a very similar pattern for the two elements to that witnessed by plotting stratigraphically. Patterns indicate that variability is highest during unit 1 and sub-unit 5a and lowest during unit 4. Most noticeable is the switch to low detrital values during sub-unit 1c, the increasing values post unit 2 and the stability of values between unit 7 and sub-unit 5b. Also of interest is the length of time that both K and Rb increase for, starting around 800cm. Whilst punctuated by some extreme events, this process of continually increasing detrital input is a clear trend that dominates the latter half of the core sequence.

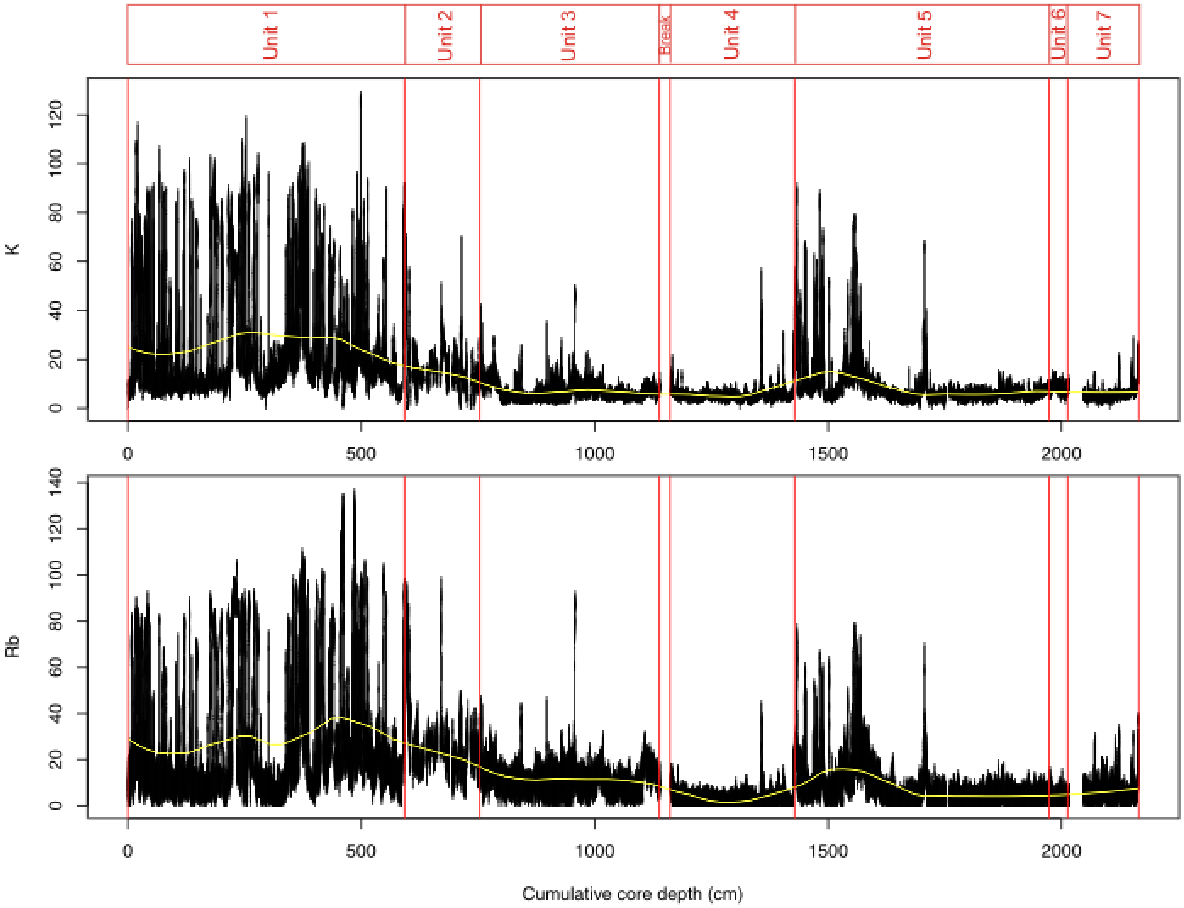


Figure 4.13: Stratigraphic diagrams of Potassium (K) and Rubidium (Rb) (corrected peak area integrals) showing the Itrax derived values for these elemental components of NAR10. Diagrams are plotted from modern times and lithological units are indicated. A 0.2 span loess smoother (yellow line) has been applied to the datasets to show longer-term change.

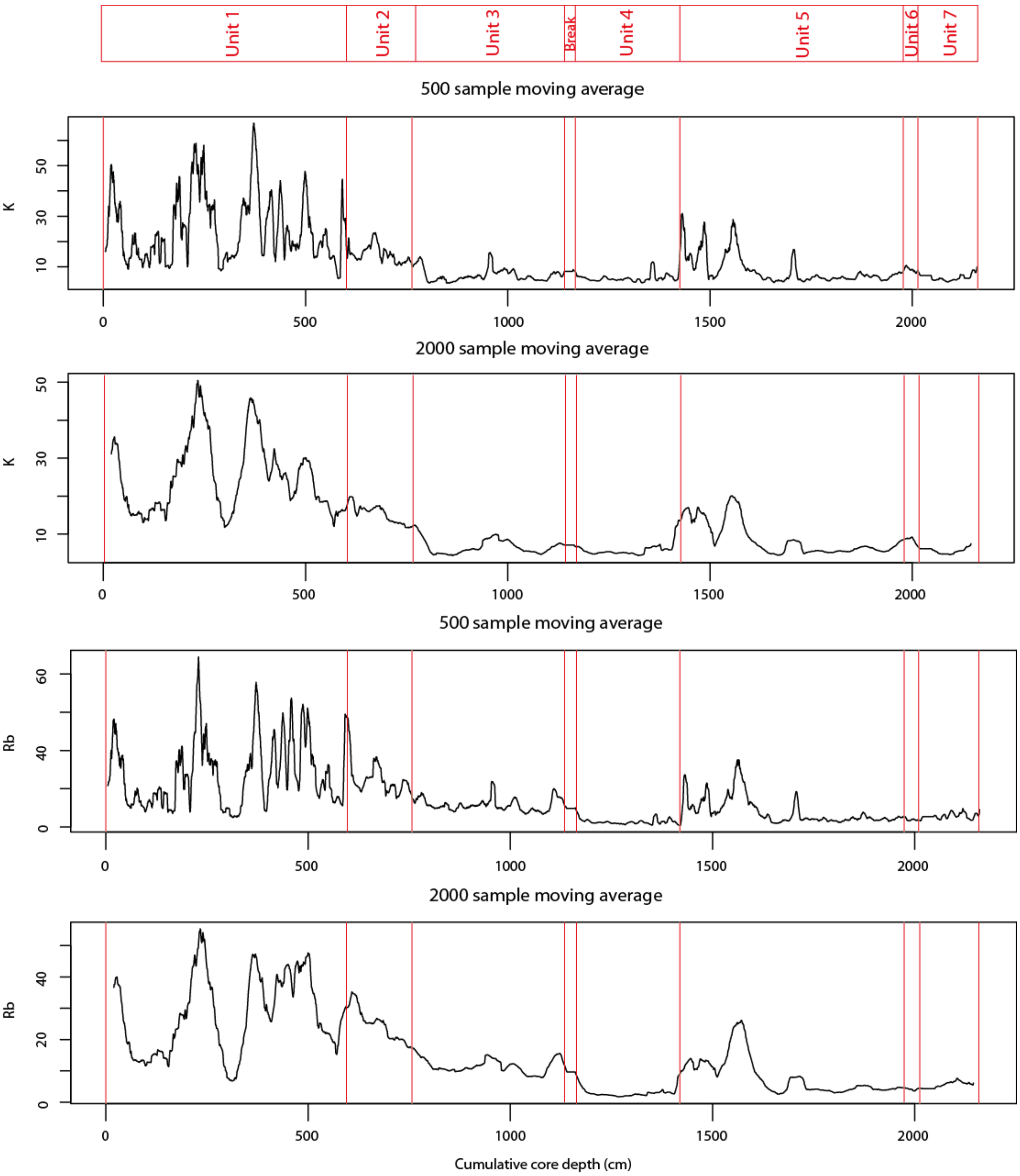


Figure 4.14: Stratigraphic diagrams of K and Rb (corrected peak area integrals) showing the Itrax derived values for these elemental components of NAR10. Plots are of 500 and 2000 sample running averages of the two elemental components to reveal change over roughly 10 and 40 year intervals respectively.

4.6. Portable XRF core scanning results

4.6.1. Portable XRF core scanning results overview

The elemental composition of the lake sediments was also investigated by another XRF scanning technique, in this case using a portable or handheld XRF scanner at lower resolution than for Itrax XRF scanning.

To check that trends in elemental abundances measured by Itrax XRF were correct and not made too inaccurate by sedimentary factors such as water content, organic content, surface undulations and porosity (Böning *et al.*, 2007; Kylander *et al*., 2011b; Tjallingii *et al*., 2007), Itrax data was supplemented by portable XRF scan results on the same NAR10 cut half-core sections. Portable XRF core scanning has also helped to get a better grasp on processes that relate to elements with lighter atomic numbers as the addition of helium purging helped detect these elements more robustly. Scanning was conducted at a much coarser resolution (every 8cm, over a 3mm spot) due to time constraints and because replication of values at the resolution scanned by Itrax (200 μm) is not needed for comparison purposes. The abundances of Ca, Sr, Mg, Ti, K, Si, Rb, Fe and Zn are examined here. Ti, Fe, K and Rb have been used as key indicators of clastic input into the lake, whilst Ca, Mg and Sr have been used as proxy indicators for carbonate deposition. Si is thought to represent clastic input, but can also be an indicator for lake productivity. At times, Zn too is related to the detrital suite. Presented here are the results for these key elemental components (figures 4.15-4.18).

Trends in elemental counts from the handheld XRF analyser were almost identical to those measured on the Itrax core scanner for the selected elements. Comparison of XRF scans for other elements not presented here has also yielded similarities between the intensity and pattern of measured peaks. This replication gives confidence in the higher-resolution Itrax results.

4.6.2. Portable XRF scanning results for selected authigenic elements

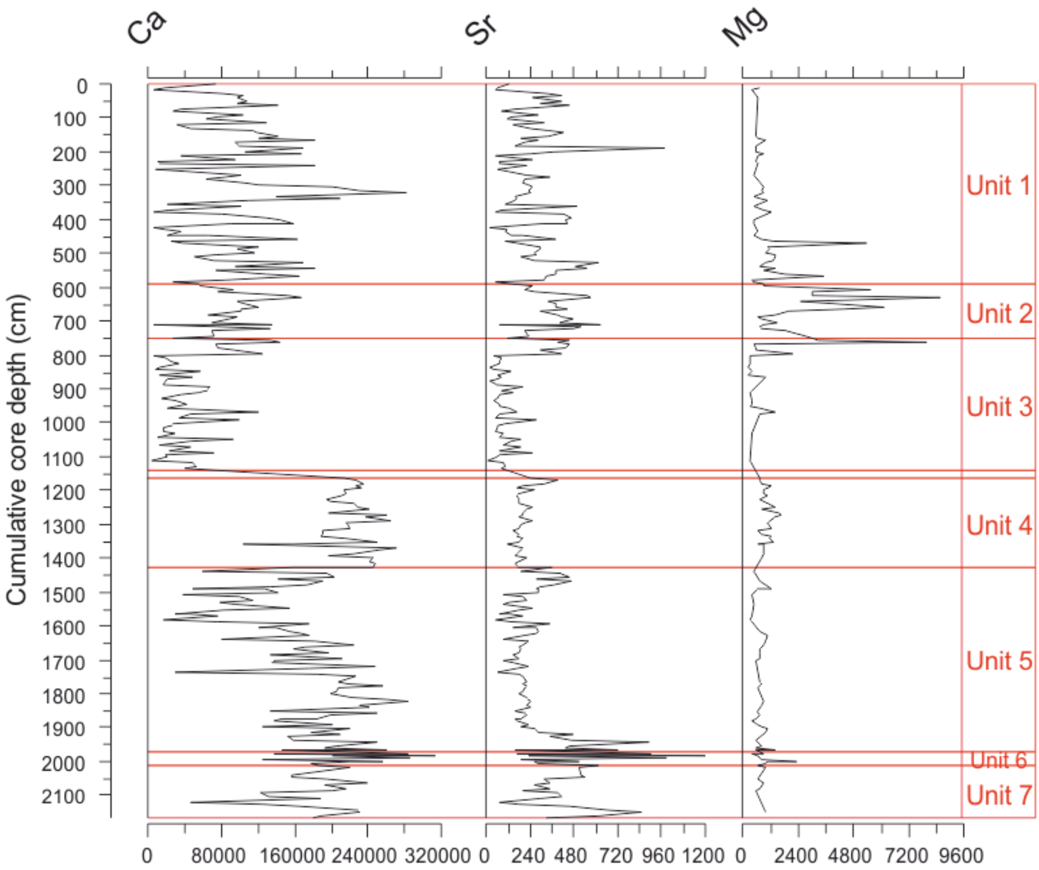


Figure 4.15: Stratigraphic diagrams of XRF handheld derived carbonate related elemental values (parts per million (ppm)) for NAR10. Diagrams are plotted from modern times and lithological units are indicated.

Figure 4.15 shows selected geochemical (carbonate related) elemental concentrations for NAR10 core sections scanned using the Niton X3 portable XRF analyser. Figure 4.16 shows these elemental components plotted alongside concentrations measured using Itrax core scanning techniques on the same sediment sequence but at much finer resolution. For comparison purposes, no smoothing was needed on the Itrax dataset because it is visually clear that the two correlate well. Generally, a very good parallel exists between the handheld XRF and the less quantitative (but higher resolution) Itrax datasets. Variations between the two datasets are therefore likely to reflect differences in sampling resolution, scanning technology and core variations only (Croudace *et al.*, 2006). One such difference can be seen at around 293cm sediment depth where the Itrax scanning documented an extreme peak in Sr (above 1148) but the portable XRF did not pick up this event; this was the result of the 8cm resolution used for handheld scanning which skipped this change in Sr.

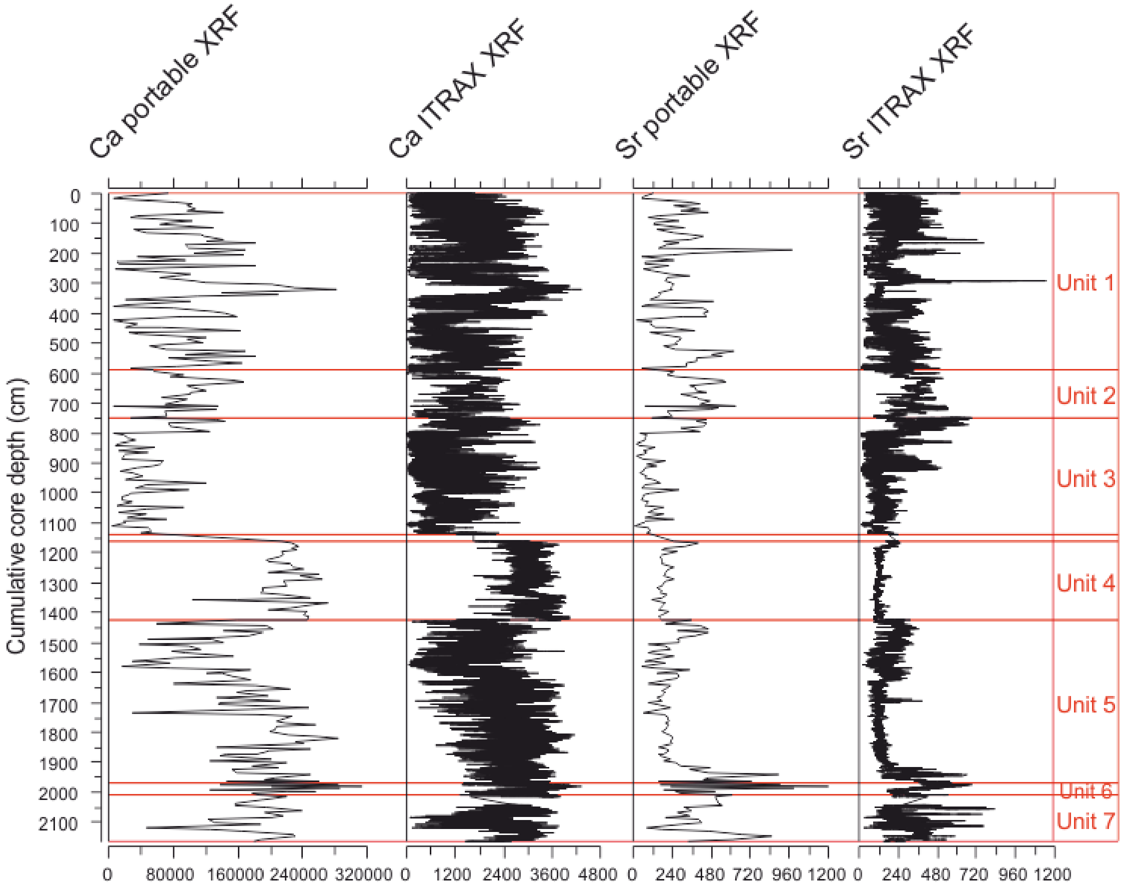


Figure 4.16: Stratigraphic diagrams of XRF handheld derived (ppm) and Itrax derived (corrected peak area integrals) carbonate related elemental values for NAR10. Lithological units are indicated. Mg results are not available from Itrax and therefore cannot be compared here. The diagram indicates that there is a clear similarity in the elemental profiles obtained from the two different core scanning techniques.

Overall, patterns of geochemical change extracted using handheld XRF scanning techniques are similar to those witnessed during Itrax XRF scanning for carbonate related elements, and provide a well replicated signal of down-core variability. Notice the inclusion of a Magnesium (Mg) profile here due to the increased sensitivity of the portable XRF to Mg concentrations (figure 4.15). At the start of the sequence, peaks in Sr are recorded and levels of Ca are moderately high. Values of both elements generally decrease during the middle of unit 7 and begin to increase again during the transition into unit 6. Unit 6 reveals very high levels of Sr (max 1200) and the first noticeable peak in Mg (2400). Above this point, Sr decreases quite significantly until 1500cm, whereas Ca remains relatively high and stable throughout sub-units 5b, 5c & 5d. Sub-unit 5a is distinct in that levels of Ca fall dramatically for the first time (lows of 40000), and is associated with smaller drops in Mg and Sr. Sub-unit 5a is characterised by significantly decreased values of all three elemental components at this time. The transition into unit 4 is abrupt with increases in Ca and decreases in Sr. Mg remains fairly constant for this section. Ca values for unit 4 are very high (~240000) and Sr values are remarkably stable. Unit 3 is similar to unit 4 in terms of Sr and Mg deposition, revealing low and stable conditions. Sr values here are the lowest seen throughout the entire core sequence (~112). The Ca profile for unit 3 is also low and seems to be responding in unison with Sr. The change between unit 3 and 2 is evidence by significantly increasing Ca, Sr and Mg values. Unit 2 is characterised by high peaks in Ca and Sr, but more importantly by Mg which dominants this unit (highs of 9000). Whilst Mg generally drops off by unit 1, another noticeable peak in Mg at 450cm is witnessed. Levels of Ca and Sr at the top of the core sequence are relatively high and fairly unstable, with some large-scale amplitudinal changes occurring. Mg on the other hand remains low and stable up to present day.

4.6.3. Portable XRF scanning results for selected lithogenic elements

Figure 4.17 shows selected geochemical (detrital related) elemental concentrations for NAR10 core sections scanned using the handheld analyser. Figure 4.18 shows these elemental components plotted alongside concentrations measured using Itrax core scanning techniques on the same sediment sequence but at much finer resolution. Variation in detrital elemental components is similar to that seen within the Itrax derived profiles. Broadly, Fe, Ti, Rb and K are visually closely related to each other. Si and Zn are generally also of detrital origin but at times can be unrelated to the clastic component.

From unit 7 through to sub-unit 5b, levels of detrital elements are low and constant apart from Zinc (Zn). Si increases when detrital elements are low, showing that at this time, Si is not likely related to detrital elemental deposition. There is a noticeable large drop in Si associated with sub-units 5b & 5c where Zn levels show a slight rise, hinting at a change in conditions here. Similarly, a distinct event occurs at sub-unit 5a where values of Si, K, Fe, Ti and Rb all increase and become highly variable, and values of Zn decrease. Unit 4 sees relatively high Si whilst levels of other detrital components remain low. Zn is poorly recorded through this section, as is primarily the case in sub-units 5b-d and may not be meaningful; this was mainly because levels of Zn were below the limits of detection. For all elements apart from Zn, lowest levels are reached during units 4 & 3, with one sharp peak in values associated with a dark black band situated in the middle of unit 3. Zn levels during unit 3 are relatively high (above 100), and it is likely that this pattern should have been witnessed during unit 4 also based upon the extrapolation of the few values obtained for this section. Unit 2 appears to be a transitional phase which sees slowly increasing levels of detrital components and moderately high levels of Si. Zn is generally low until the base of unit 2 where it visually begins to respond alongside other detrital elements. Unit 1 is characterised by high and varying levels of all elements with some short-term, large-scale shifts in value; variability in the record is greatest here. To note is the abrupt transition to lower values associated with sub-unit 1c and the stabilisation of Fe, Ti and Rb for sub-unit 1b.

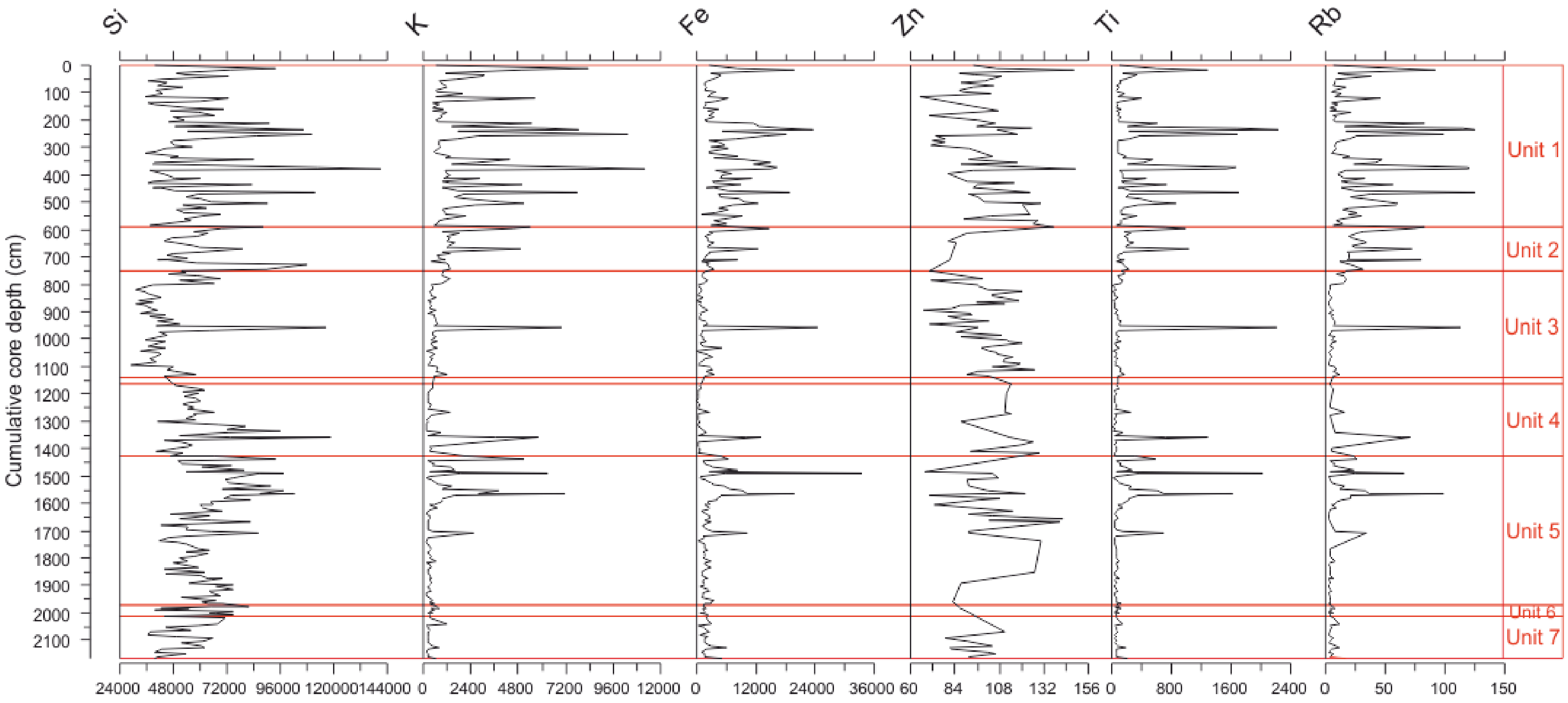


Figure 4.17: Stratigraphic diagrams of XRF handheld derived detrital elemental values (parts per million (ppm)) for NAR10. Diagrams are plotted from modern times and lithological units are indicated.

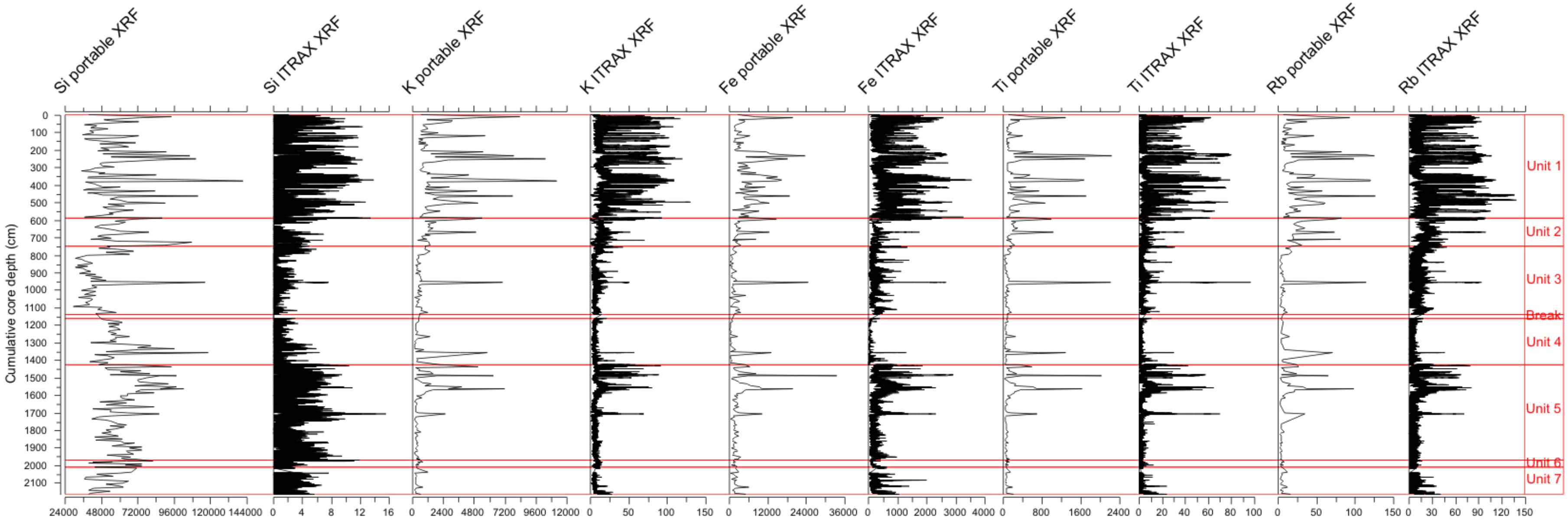


Figure 4.18: Stratigraphic diagrams of XRF handheld derived (ppm) and Itrax derived (corrected peak area integrals) detrital related elemental values for NAR10. Lithological units are indicated. Zn values from Itrax and XRF could not really be compared side by side due to the generally poor readings for Zn by Itrax. For the other detrital elements though, there is a very close match between the profiles obtained from the two different scanning techniques, providing some certainty for the pattern witnessed in both profiles.

4.6.4. Checks on the accuracy of Itrax core scanning results using handheld XRF data

Comparison of handheld XRF samples scanned every 8cm with Itrax XRF samples at 200 & 400 µm intervals shows that the two techniques reveal very similar patterns in geochemical variation. With this in mind, the question remains as to whether Itrax derived elemental data can be used on their own, and in association with other proxy indicators to help infer past climatic and environmental changes. To help address this, Itrax derived data were slimmed down to 3cm averages at every 8cm interval to compare, using statistical methods, against portable scanning results. Pearson correlation statistics for various elemental profiles showed generally high positive r-values and demonstrates that Itrax scan results can be replicated. Maxima and minima in Itrax Ca are consistently replicated by handheld XRF giving a relatively high r-value of 0.82. Similarly for other elements, namely Si, K, Fe, Ti, Sr and Rb, r-value scores are positive (0.5, 0.67, 0.69, 0.62, 0.66 & 0.67 respectively) and statistically significant at $p<0.05$ level. Only with Zn are r-values deemed low (0.1) and show no significant relationship. This mismatch is probably best explained by missing handheld XRF data where values were undetectable and a lack of parallel samples between records, and not because the profiles do not closely correspond.

Due to the replicability in records it is reasonable to suggest the Itrax data adequately record changes in the elemental composition at NAR10 and that any inferences made from these records can be used to facilitate an understanding of past climatic and environmental change. When using Itrax derived data, it is important to remember that numbers are sensitive to the settings of the XRF scanning machine and core related factors like organic levels, and that at best, Itrax data are but semi-quantitative. Nevertheless, handheld scanning has offered a means of checking the accuracy of Itrax XRF scans and has shown the technique to be a good estimate of change events. The replicability also allows the use of handheld XRF derived elements alongside Itrax derived elements, particularly lighter elements such as Magnesium which are of use to the interpretational process.

4.7. Portable XRF bulk sample scanning results

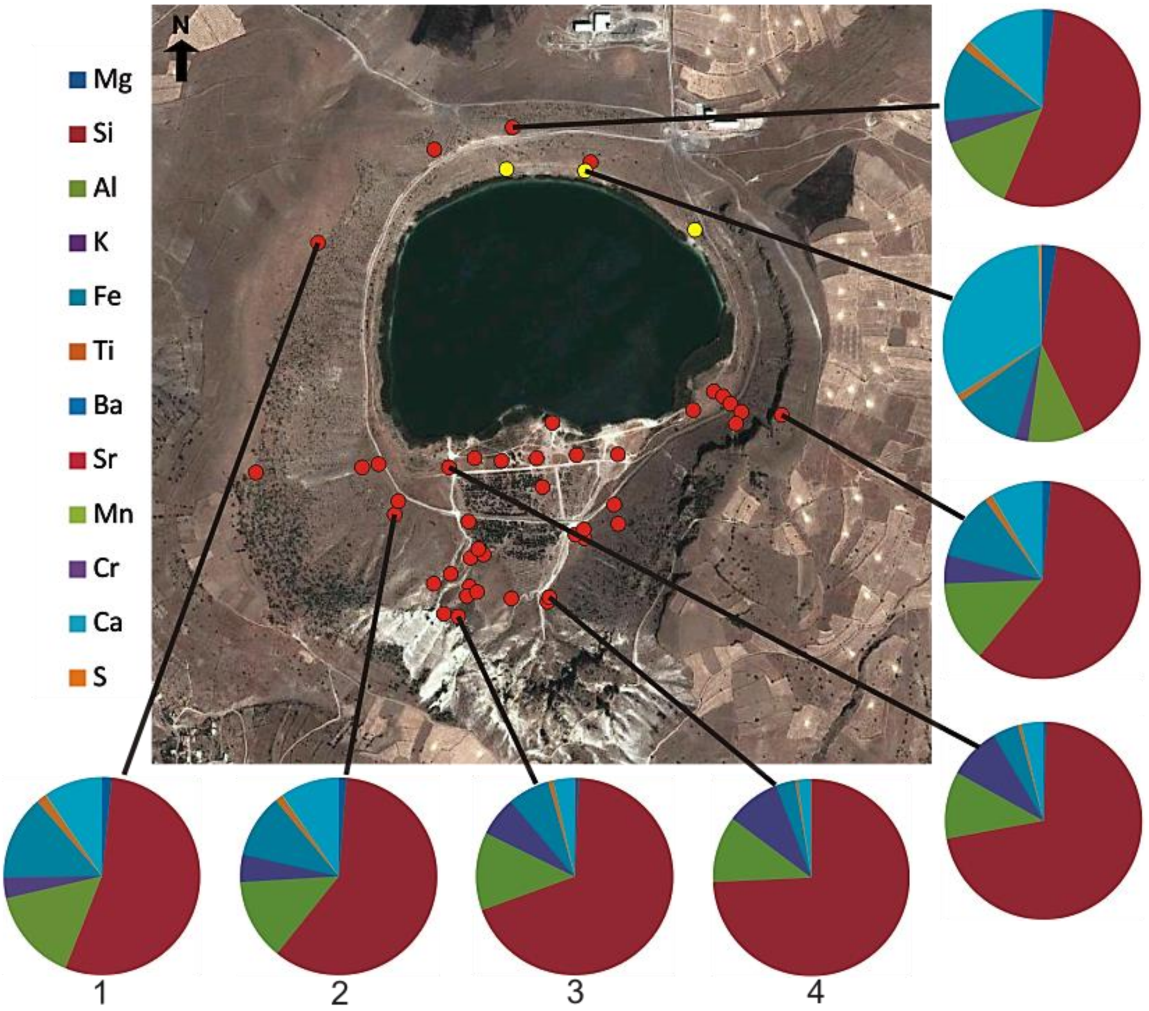


Figure 4.19: Nar catchment sample locations plotted onto a Google Maps image of Nar Lake. Indicated are the results of XRF portable scanning of bulk sediment samples for 8 selected areas to show variation across the site. Samples include: 1(SS22a), 2(SS12a), 3(SS7a), 4(SS8a), 5(SS10a), 6(SS19b), 7(SS5a), 8(SS3a).

Portable handheld XRF scanning on modern bulk sediment samples was conducted to compare to scanning results obtained for core samples to see what sort of elements are being eroded out of the catchment area today. Scanning gave the opportunity to look for distinct erosion profiles and how these vary according to sediment type. The full suite of results obtained can be seen in appendix 3. Figure 4.19 shows the results from bulk catchment XRF scanning of selected samples. Clearly visible is the large proportion of Si that is incorporated into the sediment profile, with highs also apparent in Fe and Aluminium (Al). The sediments today therefore seem to consist mainly of alumino-silicate minerals and iron oxides. The presence of K may also suggest some inclusion of feldspars, of which Fe may become incorporated. Generally, bulk sediment samples are higher in Si when there is influence from surrounding ignimbrite deposits, particularly to the south of the lake (e.g. sample 3). To the north, where deposits are generally sandier and influenced less by eroding unweathered volcanic deposits, there are higher proportions of Mg, Ca and Fe (e.g. sample 7). Some of these sand dominated samples represent a region of the lake edge thought to be a former lake shoreline. They clearly have a different geochemistry to that of the eroding hillsides. Interestingly, those samples taken from areas of modern day agricultural activity in the east show little variation from the other samples collected (e.g. sample 6). This reveals that perhaps cultivation activities are not intensive enough to alter the chemical signal of the sediment.

Lower values are witnessed for elements such as Ti, Rb and Mn which are more dominant in the Itrax derived profiles. Values for Zn, Copper (Cu) and Sr are also low. Concentrations of Rb, Zn and Ti are known to be underestimated by the scanning procedure though (Roy *et al*., 2010). Variations in other profiles such as Molybdenum (Mo), Niobium (Nb) and Chromium (Cr) are very minimal. Generally, values below 1000 ppm can be seen as low. Of major importance are the variations seen within Al, Si, K, Fe and Ca, as concentrations are usually high and error readings are small. Sample variations suggest that these elements are key erosion indicators at Nar Lake today.

4.8. Characterisation of possible ’tephra’ horizons using the Scanning Electron Microscopic (SEM)

NAR10 sediments include three distinct thick bands (figure 4.20), all of dark colour, and all consisting of allochthonous particles which may be volcanic in origin. These bands are observed on the geochemical profiles by exceptionally high values of certain elemental components (i.e. Ti) and appear very different to the rest of the core sequence. To investigate the nature of the deposits, bulk sediment samples of the horizons were scanned using a Scanning Electron Microscope (SEM) to help characterise the main sedimentary features present.

Figure 4.20: Photo of distinct black band visible in core section 01Ei of the NAR10 sediment sequence of unknown origin. Two other bands of this type are also visible in the core sequence.

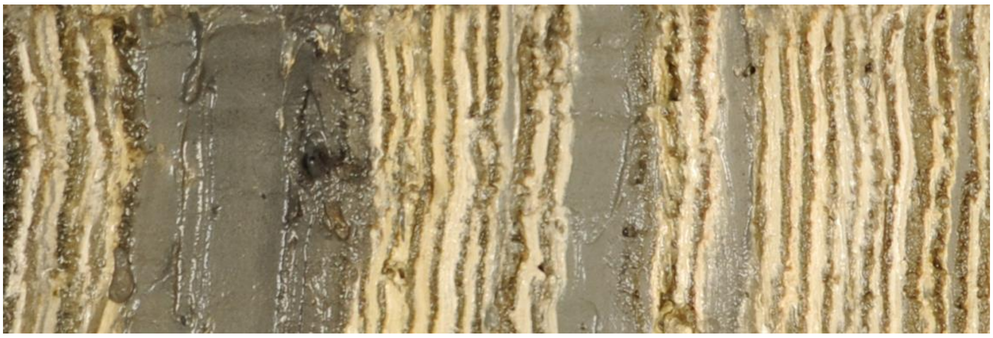


Figure 4.21: Photo of known ‘turbidite’ deposits from core section 01P1 of the NAR10 sediment sequence. Visually and geochemically these bands are different from the darker possible ‘tephra’ horizons seen in figure 4.20 above.

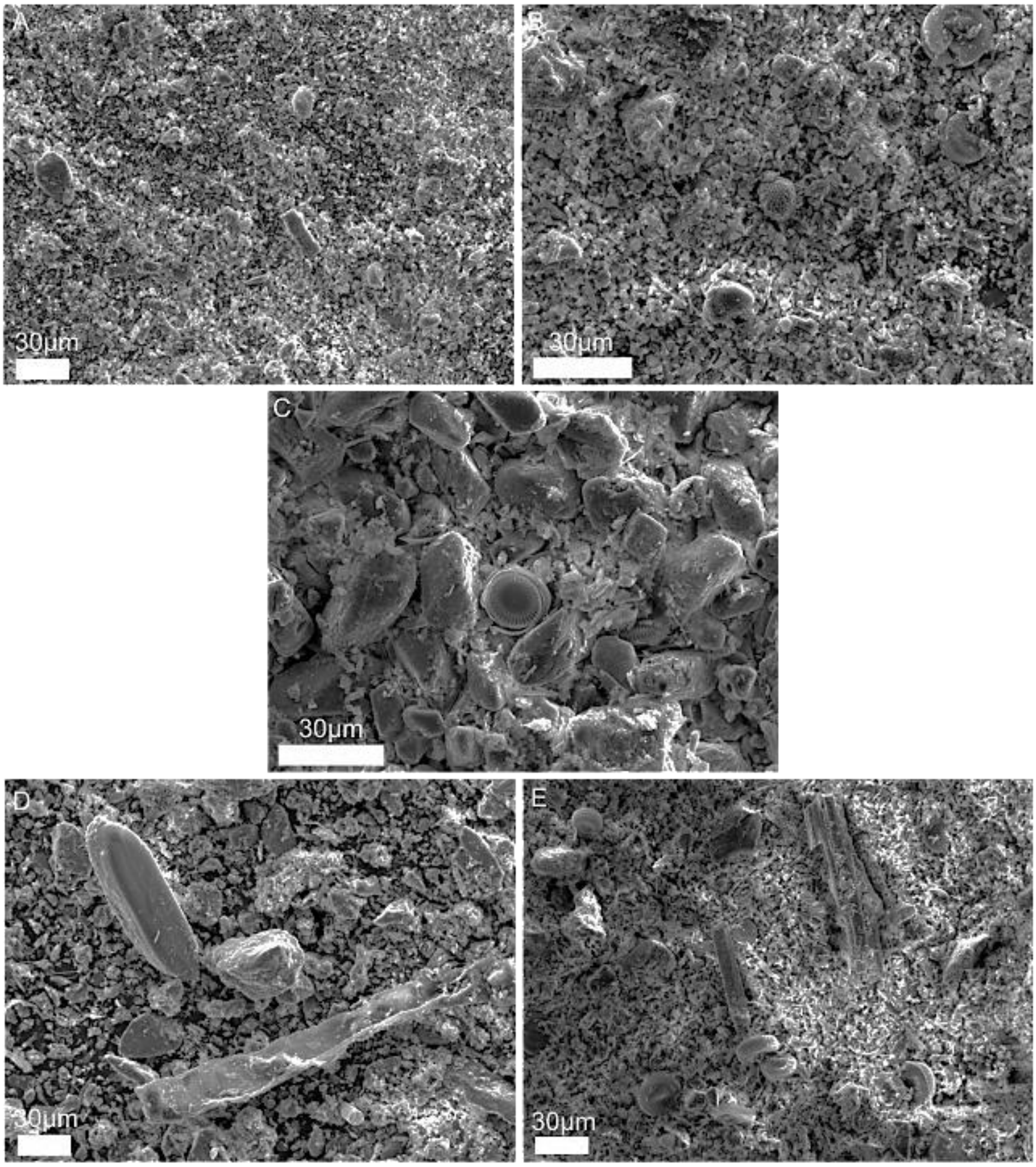


Figure 4.22: Scanning electron microscope images of ‘possible tephra’ samples and of clastic event layers taken from NAR10. (A-C) Dark bands of potential volcanic origin i.e. tephra layers, (D-E) ‘turbidite’ like bands of catchment derived material and clastic influx for comparison purposes.

For comparisons purposes, the SEM was also used to look at known ‘turbidite’ bands (figure 4.21) to identify what constituents make up clastic event layers; in theory volcanic derived deposits should appear different. Figure 4.22 shows the SEM images for ‘possible tephra’ samples. No clear signs of volcanic material were witnessed; particularly there was no evidence of sherds or reflective ‘glass like’ particles. Four different particle groups were witnessed; 1) carbonate nodules of both autochthonous and allochthonous derived, 2) non-silicified organic material but no plant remains, 3) biogenic silica, both pennate and centric diatoms, and 4) clastic materials, particularly alumino-silicates. Generally particles appeared as conglomerations of single particles silicified together. These four main components were confirmed by SEM EDX analysis which showed high intensities of Al, Si and Ca in all samples scanned. There were some sample specific variations, including changes in pennate and centric diatoms of various sizes, and the presence of chrysophycean cysts and algal ospores. No one sample was the same hinting at different sample histories; including the clastic layers. Post depositional alteration and digenesis may have occurred since deposition, therefore obscuring original depositional features. It is possible that suggested ‘tephra’ bands are merely catchment derived with small quantities of volcanic material incorporated into the matrix from the surrounding volcanic geology. This would explain the darker appearance of sediment bands and the distinctive geochemistry for these horizons.

4.9. Chapter summary

This chapter summarised the palaeo-data obtained from Nar Gölü and presented the major lithostratigraphic changes. The NAR10 composite core sequence appears to represent more than 13,000 years of sediment accumulation, most of which is annually laminated. The sediment profile has been split into 7 distinctive units representing significant changes in deposition and representing major sedimentation events in the lake’s history. Sediment profiles were scanned using an Itrax XRF core scanner for the rapid identification of elemental variability down-core to detect palaeoclimatic and environmental indicators at Nar Lake. The annually deposited Nar laminations were analysed at mainly 0.2mm resolution and show significant changes related to lithostratigraphic units.

The Itrax XRF data suggests that sediment composition is strongly controlled by Ca and Fe elemental components, which alternate seasonally between spring/summer and autumn/winter. Occasional clastic events are characterized by peaks in Fe, Si, Ti, K, Zr, and Rb, and some periods contain high levels of elements usually at the limits of detection such as Zn and Mg. Other elements which have been detected included Mn and Sr; Sr being linked to the authigenic component and Mn being associated primarily with changes in Fe. The general story is one of shifting lake conditions linked into authigenic processes (Ca and Sr) overprinted by lithogenic in-washed material (Ti and Fe). Several elements play multiple roles within the lake system. For example Si is principally linked with the lithogenic type elements, but it can also be disassociated from these elements, particularly Ti, suggesting a possible biogenic source for Si also.

The elemental patterns witnessed for authigenic and lithogenic elemental components during Itrax scanning were similarly witnessed using other XRF core scanning techniques. The high correlation between two XRF scanning techniques provide means of testing the reliability of the data expressed through Itrax and suggests that these data can be used with some certainty to reflect change events down-core. Some correlations between the two methods could not be made due to poor detection rates of some of the elements but the good replicability between the two datasets for other elemental profiles implies that Itrax scanning is a suitable method for geochemical studies. Modifications and improvements to the Itrax suite of elements were made using handheld XRF to increase the elemental range to include Mg and to improve values for lighter elements such as Si.

Total carbon analysis was also conducted using sediment from the NAR10 core sequence. Total carbon data suggests that the system is highly influenced by inorganic carbon levels particularly during sediment unit 4. The presence of total organic carbon in the Nar system appears to be mainly restricted to the base of unit 3 and unit 2, as levels for the rest of the core sequence are relatively low. Also evident in the total carbon record are changes in variability throughout the core sequence. Towards the top of the core, amplitudinal changes between low and high values are greater reflecting an increase in total carbon fluctuations for both TIC and TOC during unit 1.

To evaluate the information gathered from sedimentary and geochemical analysis on the NAR10 sediment sequence, various numerical analyses are provided in the next chapter. A combination of multivariate statistics and elemental comparisons will provide complementary information to aid interpretations of the geochemical data presented here. Comparisons with other Nar Lake and regional proxy datasets will also be conducted to strengthen and confirm inferences made regarding possible climatic and environmental histories portrayed by the shifting geochemical profiles.

5. Sedimentology and elemental geochemistry

Interpretation and synthesis of Nar Gölü results

5.1. Chapter introduction

This chapter provides an interpretation of the Nar Gölü sedimentological and geochemical results, and associated numerical analyses. Within this chapter, geochemical variations will be discussed in terms of changing lake status and shifting climatic and environmental conditions. This chapter also provides an interpretation of the Itrax core scanning results and sedimentary characteristics in relation to other studies conducted at Nar Lake (isotope (see Jones *et al.*, 2006), diatom (see Woodbridge and Roberts, 2011) and pollen analysis (see England *et al.*, 2008)), and published Eastern Mediterranean palaeo-climatic/environmental records.

5.2. Statistical analysis of geochemical data: elemental associations

5.2.1. Correlation analyses of Itrax derived elemental data

Itrax core scanning produces geochemical data recorded as peak area integrals. In the context of this study, looking at elemental concentrations in terms of *exact* counts or concentrations is not required for inferences into past climatic and environmental change. Of importance are the *relative* changes in elemental profiles down-core which relate to variation in lake conditions. Peak area and depth profiles for selected elements, specifically Ca, Sr, Si, Ti, Fe, Mn, K and Rb have already been plotted in chapter 4 and show clear changes relating primarily to sediment type. It is clear that elemental variation characterises both in-lake and out of lake processes but what is unclear from plotting stratigraphic profiles alone are the drivers behind these changes and the importance of the signals witnessed. Also, whilst these profiles show relative change for individual elements, the association between elements cannot be represented in this way and the strength of relationships cannot be quantified. Graphical representation of inter-element relationships is a simple yet extremely effective tool to evaluate the strength of a relationship. When used in association with correlation statistics, the main elemental composition of a sediment sequence can be determined (Boyle, 2001). Correlation matrices have therefore been constructed for the entire core length and individual lithostratigraphic units to show the strength of associations between paired elements for the NAR10 sequence (appendix 4). Table 5.1 highlights the key associations between elemental components for each lithostratigraphic unit as detailed in the correlation matrices; values stated have r-values above 0.5 or below -0.5, and are significant at the 0.001 level, and are therefore unlikely to be coincidental.

Correlation matrices of Itrax elemental data reveal that the coupling and decoupling of elements along the core sequence is related to lithology in part, with several elements playing key roles within the system. Although patterns associated with lithological units can clearly be visually identified from stratigraphical diagrams, variation is more distinctive when correlation coefficients are examined.

The elements which appear to correlate most commonly and most strongly in all units are Ti, K, Fe, and sometimes Rb and Si, which suggests a strong association with detrital input. Si is interesting as it can play a dual role within the lake, positively correlating with clastic elements Ti, Fe and K in units 1-3 (e.g. r-value of +0.88 Si vs. K unit 1) but not during units 4-7 (e.g. r-value of +0.22 Si vs. K unit 4) suggesting a changing combination of minerogenic and biogenic sources of Si. This dual nature of individual elements can be seen elsewhere in the sediment profile where Fe can be linked with either redox conditions in the lake or changes in detrital in-wash (Davison, 1993). A reasonably strong positive correlation between Fe and Mn in unit 2 (0.67) implies control by redox conditions here, whereas negative correlations to Ca (e.g. r-value of -0.65 unit 1) and positive correlations to Ti (e.g. r-value of 0.97 unit 2) for the rest of the core sequence suggests Fe is mainly of detrital origin. In unit 3, and to some extent unit 1, Ca is correlated with Sr (0.74 and 0.54 respectively) indicating that calcium carbonate precipitation is particularly important for these parts of the core sequence (Kylander *et al*., 2011a); other units (2,4,5,6,7) show very weak correlation of Ca and Sr (e.g. 0.26 whole).

More uncommonly, in unit 2, Pb (Lead) is strongly associated with Se and Br (0.69 and 0.73 respectively) which typically relate to organic rich layers (Croudace *et al.*, 2006). This relationship occurs during a suggested association between Fe and Mn (0.67 unit 2). Correlation of contaminant trace elements like Pb with Fe-Mn oxide concentrations within sediment profiles has been linked to remobilization but is unlikely to be a factor in most situations (Boyle, 2001). Lead can also be absorbed by organic-rich deposits during anoxic conditions which can be inferred from changes in Fe/Mn (Corella *et al*., 2011; Martín-Puertas *et al*., 2008). Low TOC values suggest low organic levels for most of unit 2 and may therefore imply that remobilisation of material in the lake drives the association between Pb and Se, Br at this time; however, some peaks in TOC towards the start of the unit could imply the uptake of Pb due to increased organic-rich sediments. Sulphur is another element which does not clearly relate to any of the key relationships witnessed, only strongly correlating alongside Fe in unit 6 (0.61). A strong positive relationship between S and Fe here is therefore likely related, in part, to digenetic iron sulphides (Corella *et al*., 2011). Generally, S is weakly positively correlated to detrital elements K, Ti and Zn (e.g. 0.12 S vs. Zn unit 7) and weakly negatively correlated to Be, Se and Sr (e.g. -0.02 S vs. Se unit 5) revealing that there is no relationship between sulphur and organic-rich facies, endogenic and exogenic processes.

Correlation coefficients indicate that certain elemental components are dominant in the sediment profile. Of importance seem to be carbonate related elements Ca and Sr, redox related Mn, detrital related components Fe, Ti, K and Rb, and Si which can be biogenic in origin. With this in mind, the association of these elemental profiles in relation to each other is looked at in greater detail using moving correlation coefficient plots of selected paired elements in the following section.

Table 5.1: Table highlighting significant correlations between Itrax derived elemental profiles for the whole core sequence and each individual Nar lithostratigraphic unit. Elements compared include: Si (Silicon), S (Sulphur), K (Potassium), Ca (Calcium), Ti (Titanium), Mn (Manganese), Fe (Iron), Cu (Copper), Zn (Zinc), Se (Selenium), Br (Bromine), Rb (Rubidium), Sr (Strontium) and Zr (Zirconium).

Lithostratigraphic unit	**Significant elemental relationships (strongly associated) (r<>0.6, p<0.001)**	**Significant elemental relationships (moderately associated)(r<>0.5, p<0.001)**
Whole	Si vs. K, Ti, Fe, Zn K vs. Ti, Fe, Zn, Rb, Zr Ca vs. Rb Ti vs. Fe, Cu, Zn, Rb, Zr Fe vs. Cu, Zn, Rb, Zr Zn vs. Rb Rb vs. Zr	Si vs. Rb K vs. Cu Ca vs. Fe, Zr Cu vs. Zn, Rb Zn vs. Zr
1	Si vs. K, Ti, Fe, Zn, Rb K vs. Ti, Fe, Zn, Rb, Zr Ca vs. Ti, Fe, Rb, Zr Ti vs. Fe, Cu, Zn, Rb, Zr Fe vs. Cu, Zn, Rb, Zr Cu vs. Zn Zn vs. Rb, Zr Rb vs. Zr	Si vs. Cu, Zr K vs. Ca, Cu Ca vs. Zn, Sr Fe vs. Sr Cu vs. Rb Zn vs. Sr Rb vs., Sr
2	Si vs. K, Ti, Fe K vs. Ti, Mn, Fe, Zn Ca vs. Rb Ti vs. Mn, Fe, Cu, Zn Mn vs. Fe Fe vs. Cu, Zn Se vs. Br, Pb Br vs. Pb	Si vs. Zn K vs. Cu, Se Ca vs. Se, Br, Pb Ti vs. Rb Mn vs. Se Fe vs. Rb Cu vs. Zn Zn vs. Rb
3	Si vs. K K vs. Ti, Fe Ca vs. Sr Ti vs. Fe, Zn, Rb Fe vs. Rb	Si vs. Ti Ca vs. Mn K vs. Zn Fe vs. Zn
4	K vs. Ti, Fe, Rb Ti vs. Fe, Rb Fe vs. Rb	Mn vs. Sr
5	K vs. Ti, Fe, Rb Ca vs. Fe, Rb Ti vs. Fe, Zn, Rb Fe vs. Rb	K vs. Zn Ca vs. Ti Mn vs. Sr Fe vs. Zn, Zr Zn vs. Rb
6	S vs. Fe K vs. Ca Mn vs. Sr	
7	K vs. Ti Ti vs. Fe, Rb	S vs. K, Fe K vs. Mn, Rb Ca vs. Rb Mn vs. Sr Fe vs. Rb

5.2.2. Moving correlation coefficient (MCC) plots

Moving correlation coefficient (MCC) plots have been used to assess how two elements are continually correlated over time. This statistical method is used to show pair-wise variation and the degree of correlation between two components within a single stratigraphic sequence, especially when the number of observations is large (as with Itrax derived data) (Dean and Anderson, 1974). Strong positive or negative correlations may be significant in the correlation matrices purely because of the high number of samples, using this method should hopefully reduce the bias potentially created by the number of Itrax data points.

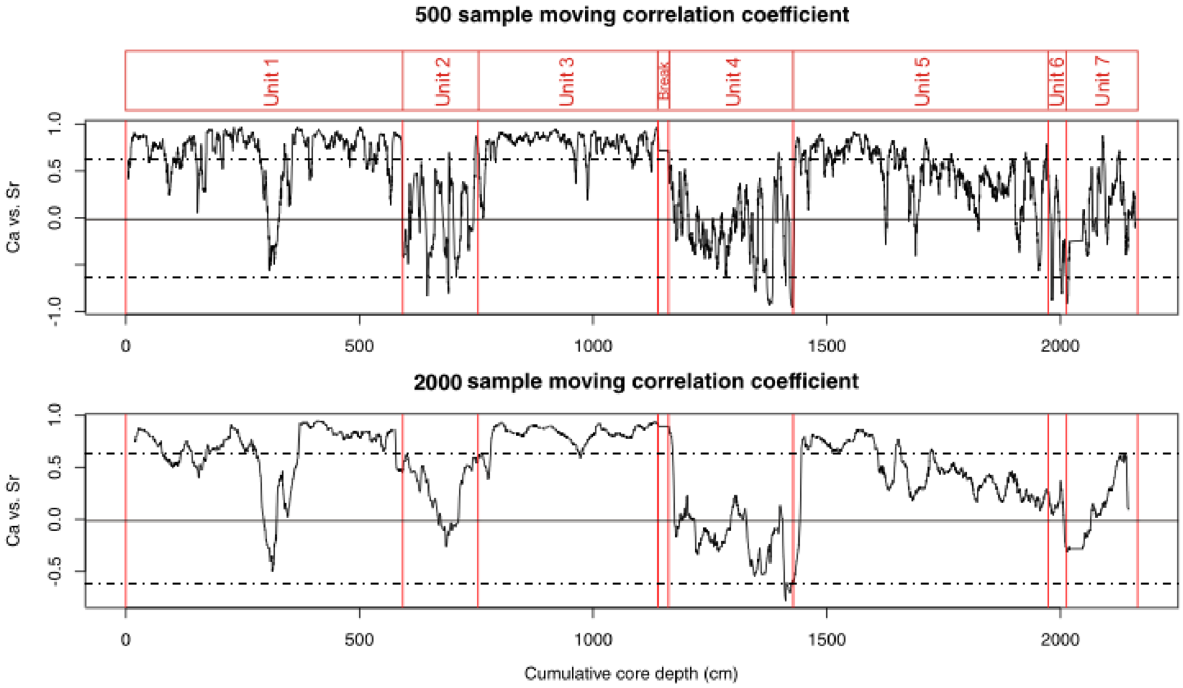


Figure 5.1: Running correlation coefficients for Ca vs. Sr (r-values). Plots are of 500 and 2000 sample running windows of the two elemental components to reveal change over roughly 10 and 40 year intervals respectively. R-values <>0.6 (dashed line) indicate strong positive or negative correlations.

Based on moving correlation coefficient plots of Ca vs. Sr (figure 5.1), it is clear that for the majority of the NAR10 record the two elements are positively correlated. There are distinctive periods though when the relationship between Ca and Sr changes and the two elements become decoupled, and even negatively related. Negative r-values are associated with units 2, 4 and 6, and sub-unit 1c (taking into consideration shifts in the record due to the averaging process). The strongest negative relationships can be seen in unit 6 and at the start of unit 4.

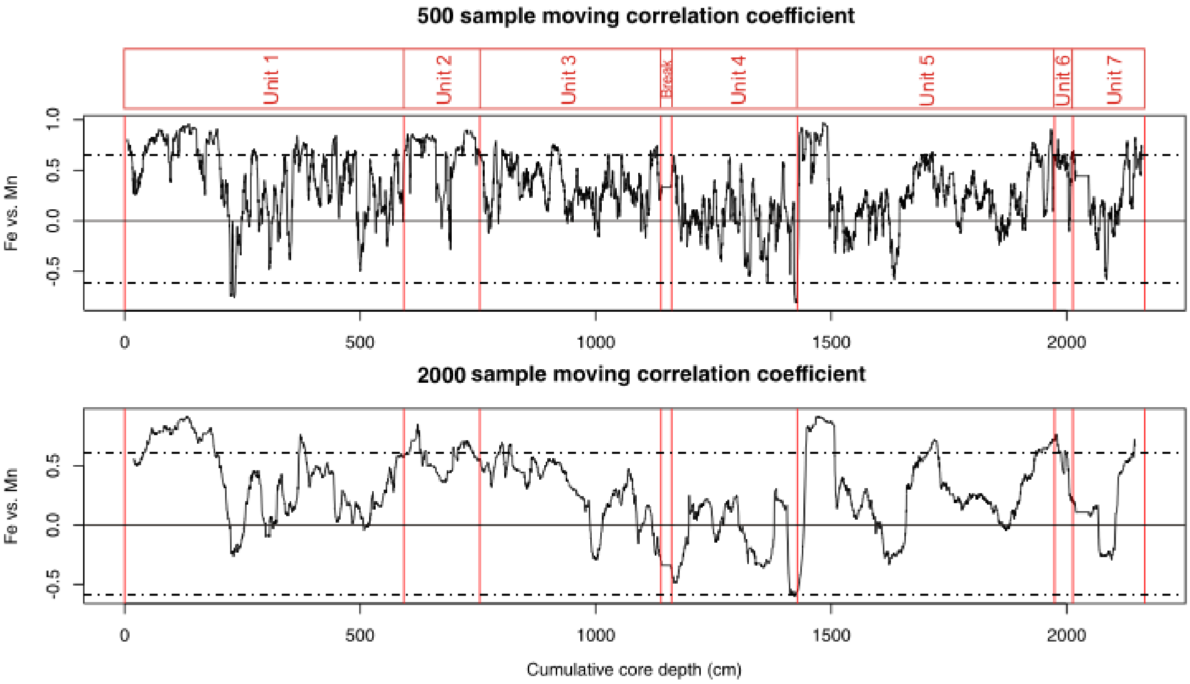


Figure 5.2: Running correlation coefficients for Fe vs. Mn (r-values). Plots are of 500 and 2000 sample running windows of the two elemental components to reveal change over roughly 10 and 40 year intervals respectively. R-values <>0.6 (dashed line) indicate strong positive or negative correlations.

Based on the MCC plots of Fe vs. Mn (figure 5.2), it is also clear that the two elements are positively correlated for most of the core sequence. There are distinctive periods though where the two elemental components negatively correlate, signifying a different depositional mechanism. Sub-unit 1c, the black sediment band in unit 3, unit 4, and the transitions between sub-units 5b and 5a, and 7b and 7a all indicate negative correlation coefficients. Variability is great which indicates that the relationship between Fe and Mn is constantly shifting, generally between strong and not so strong positive relations.

Strong positive Fe vs. Mn relationships are evidenced at the very top of the NAR10 sequence, during units 2 and 6, and at the bottom of sub-unit 5a. These core sections all indicate values over 0.5 and show that Fe and Mn are closely related during these phases.

Moving correlation coefficient plots of K and Rb, along with Ti and Fe (figure 5.3) have been created to see how detrital components respond to each other. Most noticeable is that all the plots indicate very few significant drops in value below 0 (r-value) showing that relationships between selected elements are generally always positive. Lower values seem to distinctly be associated with unit 4 and unit 6, although generally these units still remain positive in value. Unit 1 exhibits the strongest positive correlations with r-values barely getting below 0.5. Unit 2 also shows very strong correlations, particularly between Ti and Fe and Rb. The most extreme shifts in value are seen in Ti vs. K indicating that at times, K may not be as closely related to the detrital suite of elements.

Moving correlation coefficient plots of Si vs. Ti (figure 5.4) indicate that at most times, Si and Ti are positively correlated, i.e. that they have a positive relationship to each other. Change however is not always constant as these two variables do show some fluctuations over time, shifting from only slightly positive to strongly positive (r-values of 0.1-0.9). The strongest correlations exist during unit 1 but this is also a time of highest variability so some correlations are documented as weak. The weakest correlations exist within units 4 and 6. Unit 4 also shows the least variability in the record. The largest transition phases are seen from units 2 to 1 and from units 5 to 4 where values are either decreasing or increasing respectively. There are also noticeable shifts in the data associated with sub-units 1c, 3b and the start of 5a where r-values move more distinctly towards the negative or positive end of the spectrum. The shift at 3b shows a clear peak (r-values above 0.7) and is distinctly different from the surrounding sediment matrix of unit 3; the peak coincides with a possible ‘tephra’ band (see section 4.8) in the sediment sequence which records high Ti values.

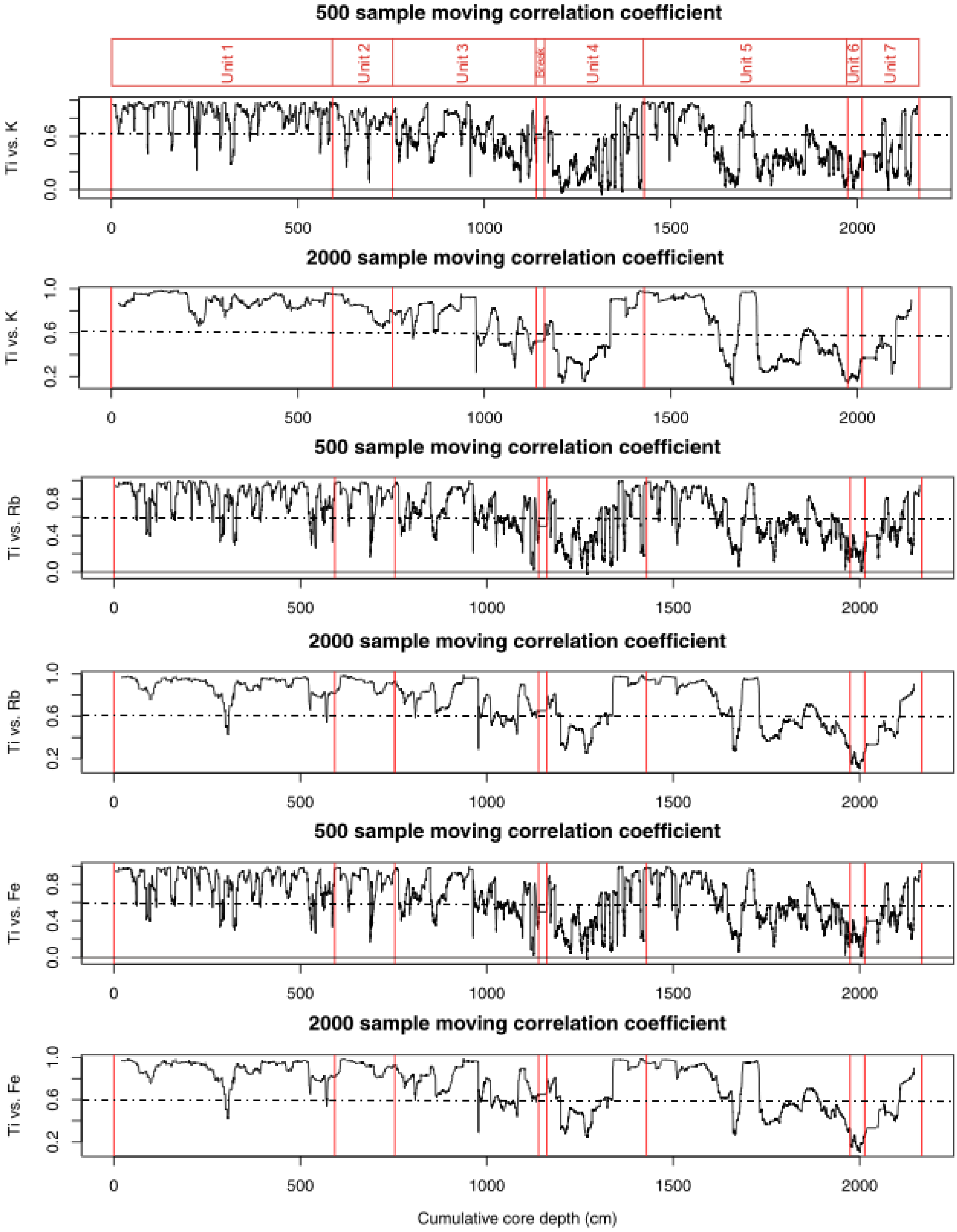


Figure 5.3: Running correlation coefficients for Ti vs. K, Ti vs. Rb and Ti vs. Fe (r-values). Plots are of 500 and 2000 sample running windows of two elemental components to reveal change over roughly 10 and 40 year intervals respectively. R-values <>0.6 (dashed line) indicate strong positive or negative correlations.

At certain times, relationships between these two elements become negative. When Si and Ti are negatively correlated, Si does not form part of the lithogenic suite of elements of which Ti is usually associated (Kylander *et al.*, 2011a). Although these negative relationships are not strong (r-values of around -0.1), the existence of several negative correlations implies that Si is not terrigenous in origin for short periods during the transition to sub-unit 5a, units 4, 3, 2, and the very top of unit 1 (although temporal accuracy is altered slightly by grouping samples into time windows). The shift to more negative correlation coefficients may be driven by primary production (biogenic silica) of Si (Cohen, 2003). The relationship between Ti and Si is therefore not straightforward.

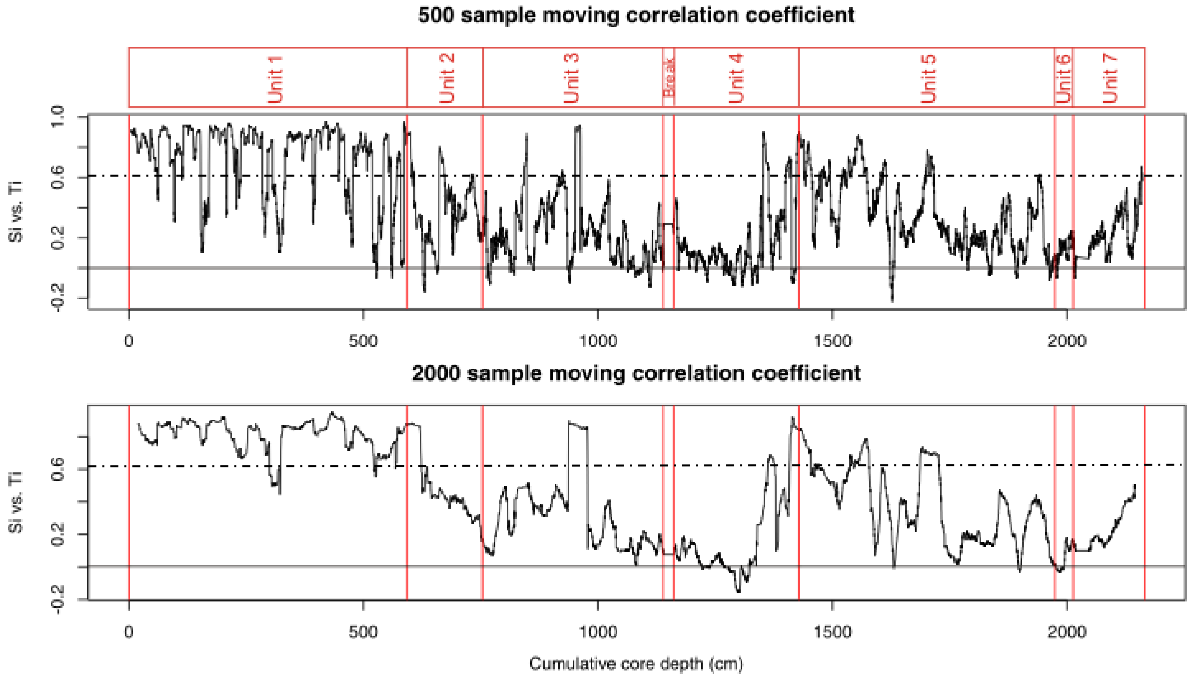


Figure 5.4: Running correlation coefficients for Si vs. Ti (r-values). Plots are of 500 and 2000 sample running windows of the two elemental components to reveal change over roughly 10 and 40 year intervals respectively. R-values <>0.6 (dashed line) indicate strong positive or negative correlations.

5.2.3. Scatter plots for selected elements

Scatter plots have also been used to look at changing relationships between two elements over time. Figures 5.5 & 5.6 show individual scatter plots for each lithological unit to show how the relationship between Ti and Fe and Ti and K changes over time. These few elements have been selected because both Fe and K appear to respond differently to the detrital suite at times, which is represented here by the Ti profile. Scatter plots have been used to identify times when the relationship between Fe, K and Ti may not be linear, i.e. when they become decoupled. This data will complement the patterns witnessed in the MCC plots.

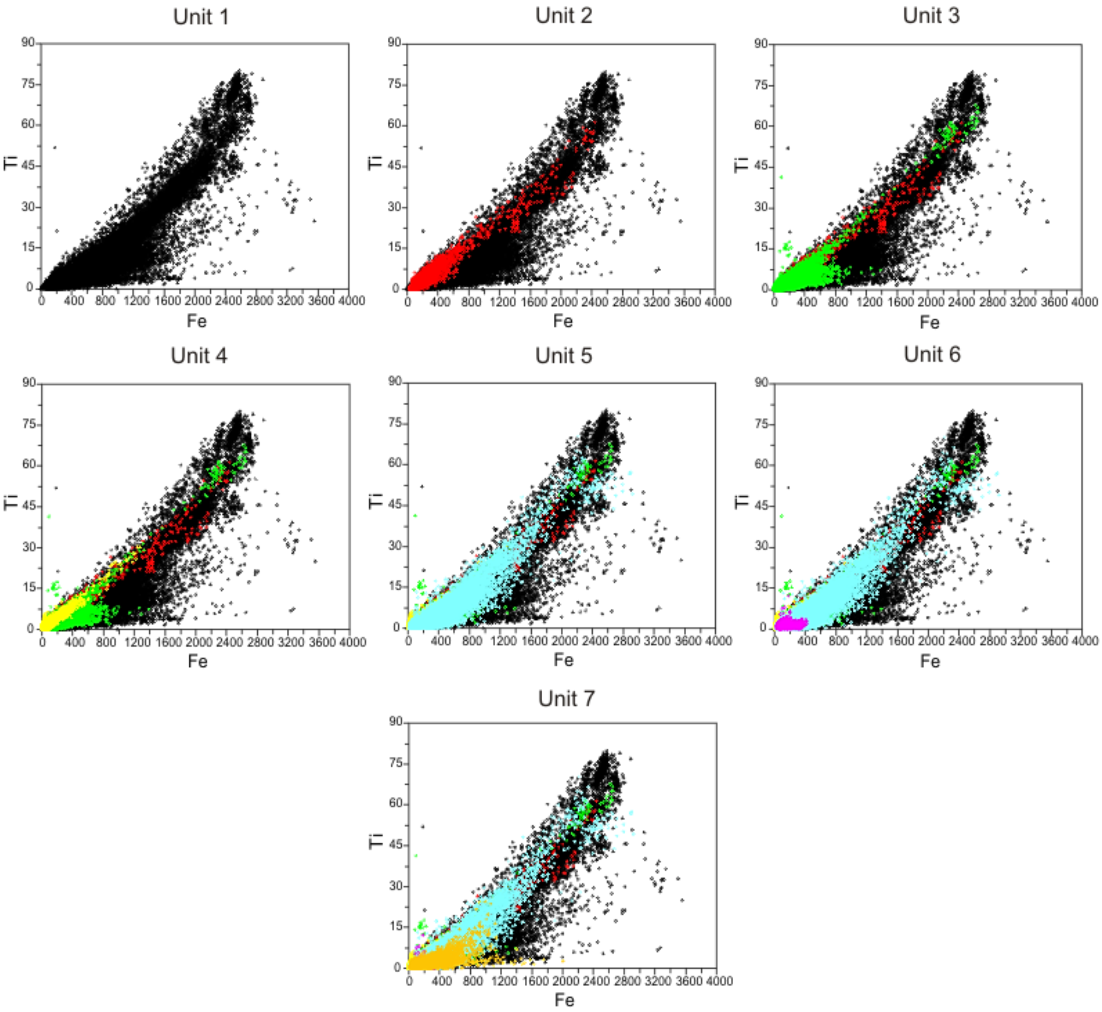

Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7

Figure 5.5: Scatter plot of Fe vs. Ti to show how the two elements vary over time. Each unit has been plotted separately to show the changing nature of the lithostratigraphy. Unit1 (black), Unit 2 (red), Unit 3 (green), Unit 4 (yellow), Unit 5 (light blue), Unit 6 (pink), Unit 7 (orange).

Fe and Ti (figure 5.5) appear to have a fairly linear relationship but this relationship is not constant over time. Unit 7 shows a preference for high Fe in place of Ti and largely there is a very weak relationship between the two elements. Unit 6 is the most distinctive with very low levels of both Ti and Fe and no clear linear relationship. Unit 5 reveals a linear relationship for the first time in the core sequence but there are some samples which do not fit the overall pattern; individual samples can be high in Fe but low in Ti. Unit 4 shows a very linear relationship also, with higher values for Ti than Fe recorded. Unit 3 is unique as it incorporates some samples that plot out very differently to the rest of the data for that unit, thus showing values at both ends of the graph. The high values relate to a dark black band in the sediment stratigraphy. Units 2 and 1 show similar results to unit 5, where the relationship between Fe and Ti is linear.

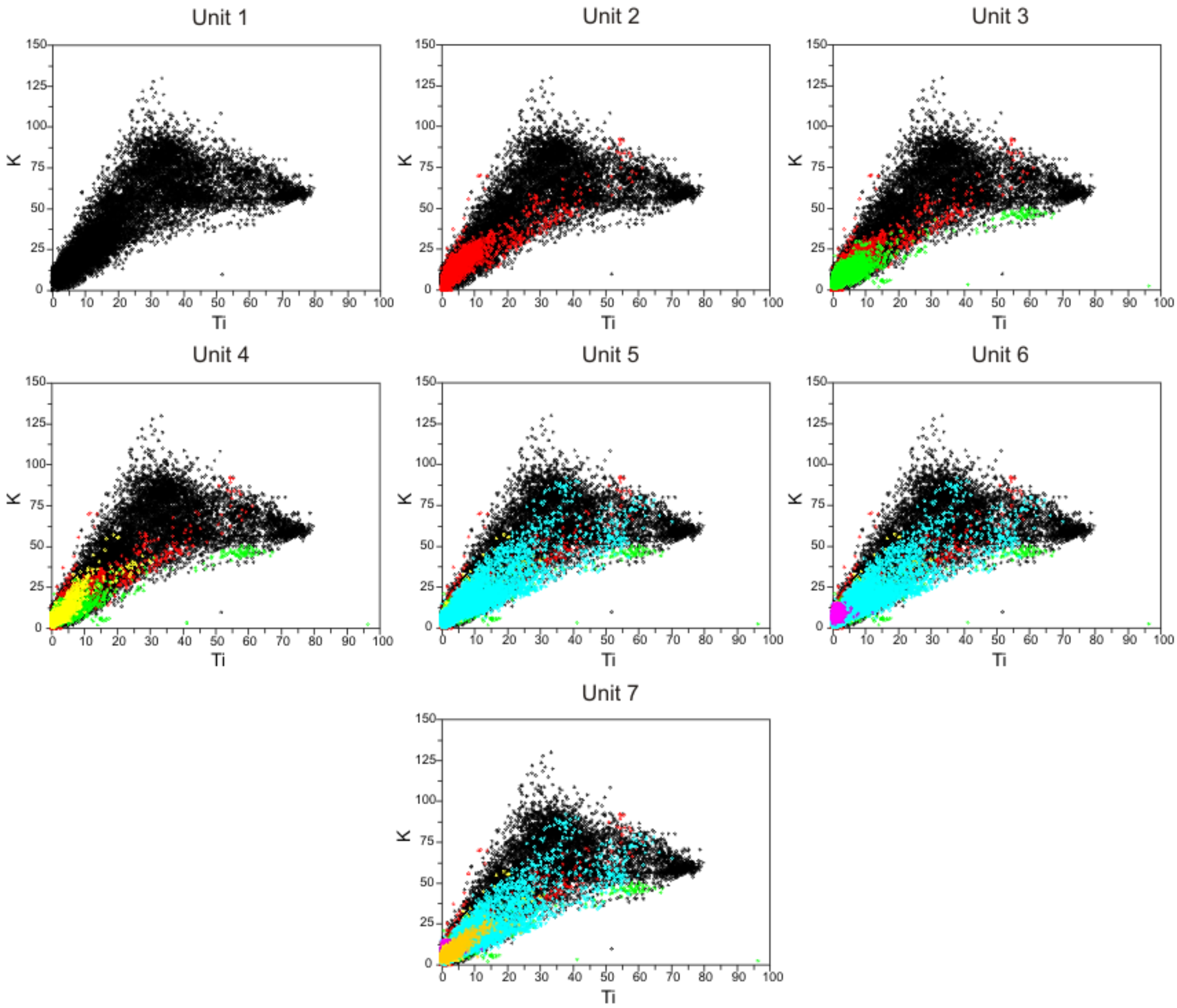


Figure 5.6: Scatter plot of Ti vs. K to show how the two elements vary over time. Each unit has been plotted separately to show the changing nature of the lithostratigraphy. Unit1 (black), Unit 2 (red), Unit 3 (green), Unit 4 (yellow), Unit 5 (light blue), Unit 6 (pink), Unit 7 (orange).

The relationship between Ti and K is somewhat different (figure 5.6). The relationship is linear in part but there are both positive and negative relationships visually apparent. Generally when values of Ti are highest, then K is not as high. There seems to be a maximum peak reached by 35 Ti and 75 K from which values begin to become negatively correlated. This pattern in the dataset hints that at times, K and Ti may not be as closely related as at other times. Looking at the changes by unit we see a small but linear relationship for unit 7, a similar pattern to that witnessed in unit 4. Unit 6 shows that K is often poorly correlated with Ti here and indicates that the elements are generally out of phase for a time. Unit 5, as seen by the Ti vs. K scatter plot reveals a generally linear relationship. The relationship between K and Ti in unit 4 is similarly linear. Unit 3 shows a split between the samples again with most samples plotting out in the lower ranges but with some clustering at the extreme Ti end also. Values in unit 2 are far more bunched together in comparison apart from some with high Ti. The greatest variability is witnessed in unit 1 where samples seem to plot out in a boomerang shape, indicating that perhaps there are two different relationships here.

5.2.4. Ratios for selected elements

Due to the semi-quantitative nature of the values obtained from Itrax XRF core scanning and factor related detection rates, it is also useful to plot elemental values as ratios to another element to avoid these issues (Francus *et al*., 2009; Rollinson, 1993). The ratios chosen for presentation in figure 5.7 have been selected based on known behaviours of elements and ratio proxies. For instance, Zr/Rb can be used as a proxy for changes in grain size (Kylander *et al*., 2011a) and lower values of Ca/Sr can signify higher evaporation and salinity, and lower lake levels (Cohen, 2003). Figure 5.8 shows ratios of select elements alongside titanium as this is generally a very conservative element, and not affected too greatly by transport or weathering processes compared to other elements (Young and Nesbitt, 1998). This enables the assessment of the role of other elemental components (which are perhaps more variable in character) alongside an index for lithogenic input (Marsh *et al.*, 2007), particularly in the absence of aluminium which is more commonly used as a detrital devisor (Rothwell and Rack, 2006). Ti-normalised element ratios are expected to better represent endogenic and authigenic processes.

Rb and Zr can be used to acquire grain size information due to their associations with clay particles and medium-coarse silts respectively. Lower values of Zr/Rb therefore reflect typically finer-grained sediments and higher values reflect coarser material (Dypvik and Harris, 2001). There is also generally no alteration to the Zr/Rb ratio over time from weathering or mobility making it a reasonable ratio to use for looking at grain size fractioning characteristics of lake sediments (Wang *et al.*, 2008). Figure 5.7 highlights changes in the Zr/Rb ratio for NAR10. Typically, sediments at the start of the sequence show high values of Zr/Rb which vary significantly, which is in contrast to latter deposits which are lower and fluctuate only moderately. There are exceptions to this pattern with a distinct drop in Zr/Rb values associated with sub-unit 5a (below 5) and some high values recorded for unit 1 (max 40). Lowest levels of Zr/Rb are witnessed during unit 2 and the start of unit 1. Decreasing values are also evident at the transition between unit 4 and unit 3 but a break in the sequence at this point obscures the movement to lower values.

The Ca/Sr ratio is another commonly used proxy for looking at changing lake conditions from Itrax data. Principally it is used to locate enhanced Sr levels and therefore the presence of high-Sr aragonite which requires a shallow water source to precipitate (Rothwell *et al.*, 2006). The Ca/Sr ratio is linked in to Ca and Sr in-lake precipitation of calcium carbonates (Kylander *et al.*, 2011a). Figure 5.7 highlights the changes in Ca/Sr at NAR10. Unit 7 reveals moderate but highly fluctuating levels of Ca/Sr which decrease during unit 6 to values below 10. The start of unit 5 reveals relatively high levels of Ca/Sr but the values drop again towards the end of unit 5. The transition into unit 4 sees another jump to high Ca/Sr levels, the highest values recorded (above 40) for the entire core sequence is witnessed in unit 4. Unit 3, 2 and the start of unit 1 in contrast witness the lowest Ca/Sr levels for the NAR10 sequence, with relatively stable values recorded. An abrupt change in conditions is noticeable during sub-unit 1c where Ca/Sr values are as high as those seen in unit 4. The latter half of unit 1 records moderate levels which can fluctuate greatly.

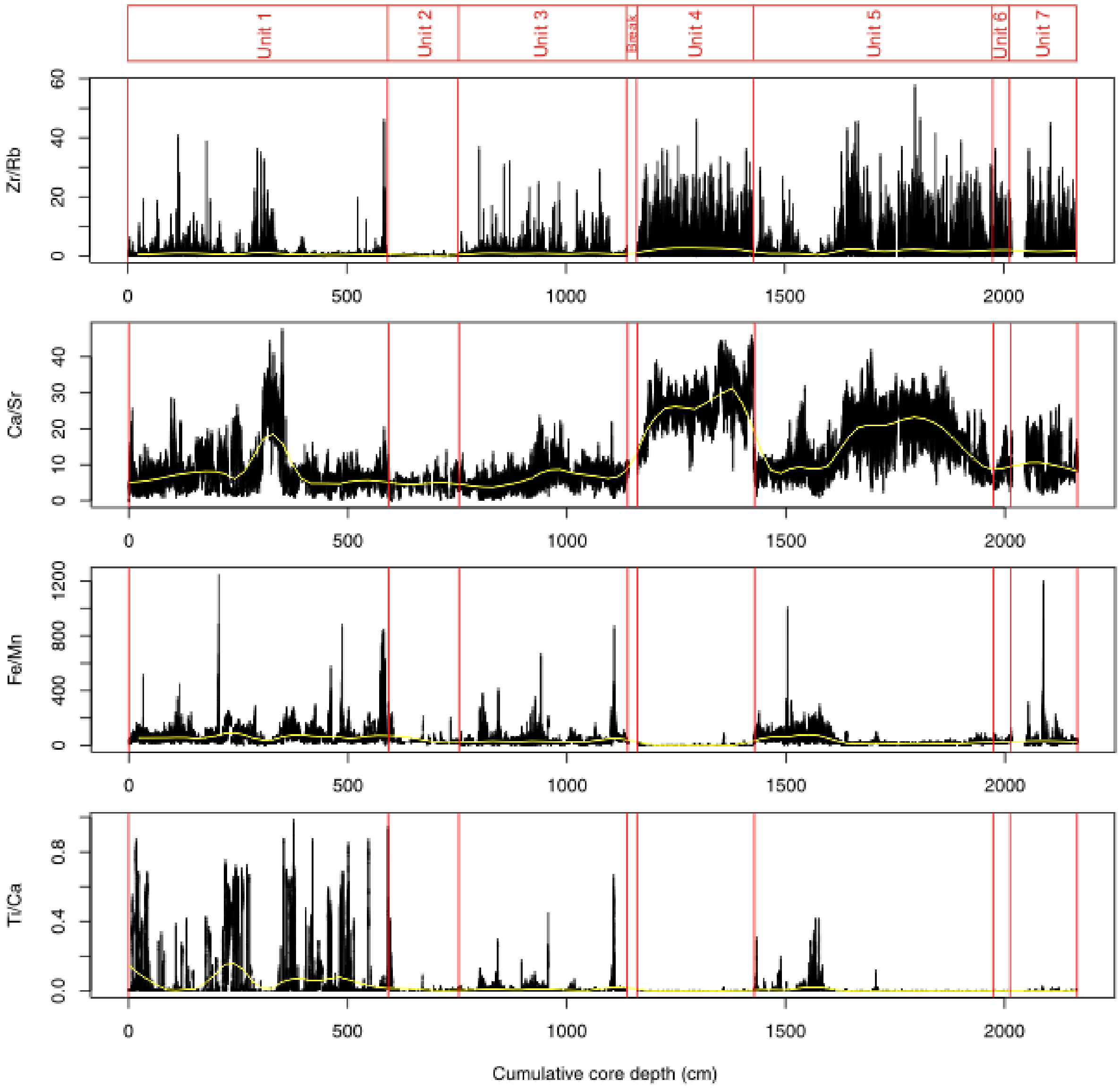


Figure 5.7: Stratigraphic diagrams of ratios between two selected elements for NAR10. Diagrams are plotted from modern times and lithological units are indicated. A 0.1 span loess smoother (yellow line) has been applied to the datasets to show longer-term change.

The Fe/Mn ratio has been used as an indicator of palaeo-redox conditions in lakes as smaller amounts of Mn and larger amounts of Fe are released from the sediments to the water under oxygenated (oxic) conditions (Schaller and Wehrli, 1996; Schmidt *et al.*, 2008). Therefore low values of Fe/Mn should indicate more oxygenated bottom water conditions and the separation of Fe and Mn (Marsh *et al.*, 2007). Figure 5.7 highlights four distinct low points in the Fe/Mn ratio, associated with sub-units 5b, 5c & 5d, and units 6, 4 and 2. Values in unit 4 are the lowest for the entire core section and barely get above 0. The rest of the core sequence sees moderate levels of Fe/Mn with highly fluctuating conditions. Unit 1 and sub-unit 5a witness particularly high amplitudinal changes with values reaching 1200 in places. A similar high peak is evidenced in unit 7 also, though average values are lower in this unit.

Figure 5.7 displays the results for Ti/Ca also. This ratio is not as widely used but has been used here to indicate the dominance of carbonate and detrital components for each lithographical unit. Ca typically represents carbonate precipitation in the lake and Ti typically corresponds to clastic influxes, the relationship between the two therefore should be informative of the importance of either input at a set time. The latter half of the core sequence shows very low levels of Ti/Ca and therefore high carbonate deposition. Similarly, unit 4 is characteristically low in Ti/Ca with values barely getting above 0. High Ti/Ca is noticed during sub-unit 5a, and unit 1. Unit 3 is also moderately high in Ti/Ca at times. Unit 1 is the most visually distinctive with highly variable values documented and dramatic amplitudinal shifts between samples (0-0.8).

Figure 5.8 documents elemental changes in relation to Ti. Si/Ti ratios are widely used as an indicator of biogenic silica to identify phases where Si may relate to alumino-silicates or diatom productivity as a component of their frustules (Peinerud, 2000). Determination of Si by the Itrax scanner is not particularly sensitive and it is important to understand that this can produce a high signal/noise ratio (Marsh *et al.*, 2007). The Si/Ti ratio at Nar Lake is interesting as it shows very high values for the beginning of the core sequence which slowly fall towards more modern times. This switch to lower values around unit 4 indicates a 645% change in Si/Ti. This over simplified pattern though obviously contains more time specific changes like the abrupt drop in values to below 5 associated with sub-unit 5a. Sub-unit 1c is also noticeable in terms of low Si/Ti. Generally the record fluctuates greatly, with the biggest amplitudinal changes witnessed in units 7, 6, 5 and 4.

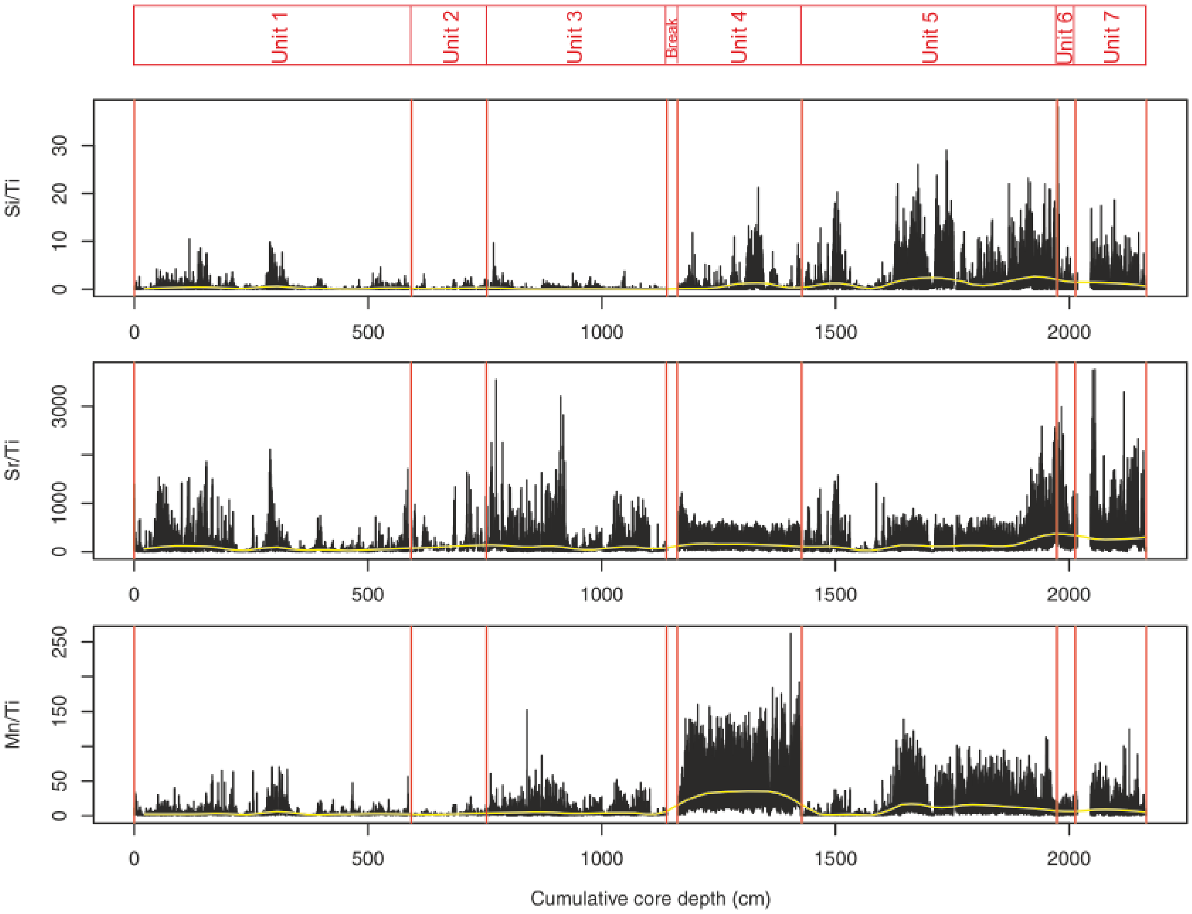


Figure 5.8: Stratigraphic diagrams of ratios between two selected elements for NAR10. Diagrams are plotted from modern times and lithological units are indicated. A 0.1 span loess smoother (yellow line) has been applied to the datasets to show longer-term change.

Sr/Ti and Mn/Ti ratios are shown in figure 5.8 also. Changes in these ratios have no specific climatic or environmental implication but reflect changes in elemental components alongside a stable detrital devisor (Ti). Sr/Ti reflects carbonate deposition where SrCO3 is co-precipitated with CaCO3 and Mn/Ti reflects the mobility of manganese in the lake water. For unit 7, values are high for the Sr/Ti record. Unit 6 is characterised by a decrease in values which peak again towards the end of the unit. Unit 5 shows lower Sr/Ti values but only after a period of transition from unit 6. Very stable values are documented for unit 4 and do not fluctuate greatly from values of around 500. The rest of the core sequence shows more variability with higher values recorded for the base of unit 3 and lower values for unit 2 and the top of unit 1. Sr/Ti values are relatively high for the base of unit 1 in comparison to the start of the unit.

The Mn/Ti ratio shows some significant changes also. The most visually dominant change is noticed in unit 4 where values are relatively high (above 150). Values are also high at the start of the core sequence apart from unit 6 where there is a distinguishable drop in Mn/Ti levels. Lower values are also evidenced during sub-unit 5a where values drop below 5. Material deposited after unit 4 is dominated by generally lower levels of Mn/Ti with only subtle variations in values recorded.

5.2.5. Principal Components Analysis

Principal components analysis (PCA) was carried out using C2 statistical software on the NAR10 elemental dataset (14 elements by unit) to help describe the main variance witnessed by a few key factors and to confirm relationships already established by correlation matrices, scatter plots, MCC plots and ratios. PCA analysis (figure 5.9) confirms the inverse relationship witnessed between elements of detrital origin (e.g. Ti) and those associated with organic matter (e.g. Br) and endogenic mineral phases (e.g. Ca). The first eigenvector represents 44% of the total variance, and is controlled mainly by detrital elements (Ti, Fe, Si, Zn, and Cu) at the positive end and Sr at the negative end which is linked in to calcium carbonate precipitation. Positive sample scores on PCA axis 1 represents higher clastic input into the lake and characterises periods of increased sediment influx from the surrounding catchment. Interestingly, the grouping of Rb and Zr at the positive end of PCA axis 1 associates these elements with clastic input too, but as these two elements also plot out separately from the detrital elements it signifies that grain size could be a factor driving NAR10 variation. The second eigenvector represents only 13% of the total variance and is identified by Br, Se and Pb at the positive end and Ca and Mn at the negative end. Positive scores may indicate higher organic matter content, whereas negative scores reflect changing redox status and carbonate precipitation levels. PCA axis 2 suggests that on the whole, Ca is unrelated to detrital components. Interpretation of eigenvector 3 (9% of total variance), controlled by Sr at the negative end and Mn, Pb at the positive end is more complex. The partial inclusion of Ca, Br and Se into positive axis 3 gives clues though to its nature, which is defined here as being reflective of moist, anoxic and less saline conditions when positive. At the negative end, the presence of Sr may indicate decreased precipitation levels (and lake water) and thus increased salinity (Müller and Wagner, 1978). Sr-rich hydrological conditions suggest a brackish lake with a dominance of aragonite formation (Martin-Puertas *et al.*, 2011). It is likely that PCA axis 3 is reflecting the type of carbonate deposition.

Figure 5.10 shows bi-plots of the PCA results per lithostratigraphic unit against the first and second PCA axes, which are the two dimensions likely to reflect signals of interest. The PCA bi-plot for unit 7 shows that axis 1 explains 27% of the total variance consisting of strong Ti and Fe, and Sr at the opposite end. Of some difference to other units though is axis 2 (11% of total variance) which shows organic elements of Se and Br plotted out against Mn and K. Associations between Mn and K can be indicative of weathering and in-lake cycling in summer. Axis differences in unit 6 are less clear than unit 7, with both axis of the bi-plot only representing 37% of the total variance. PCA axis 1 for unit 6 consists of an organic component of Se, Br and Pb at the positive end and a carbonate weathering component of K and Ca at the negative end. In contrast to all the other units, detrital components of Fe and Ti plot out on PCA axis 2 indicating their decreased importance during unit 6. Unit 5 probably shows the clearest two eigenvectors, with axis 1 reflecting detrital versus authigenic and axis 2 reflecting organic moist versus nonorganic dry. Interestingly, an extreme cluster of values is evident in the PCA bi-plot for unit 4 which coincides with a dark grey clay-rich band in the sediment profile. PCA axis 2 for unit 4 represents only 12% of the total variance and is dominated by Mn at the positive end and Sr at the negative end. PCA sample scores for unit 3 are the largest seen for any unit (up to 8.5 for axis 1) and reveal a clear distinction in those samples of 'normal' detrital origin and those of 'abnormal' detrital origin. Extreme positive scores of eigenvector 1 coincide with a black band in the sediment profile. This black band discussed in section 4.8 is possible tephra material. It is similar in nature to the dark band witnessed in unit 4. PCA axis 2 during unit 3 is similar to that from unit 2, reflecting seasonal adjustments between organic and authigenic processes. Unit 2 indicates a lack of Ca control on PCA axis 1 in contrast to other units and instead helps to account for the 24% variance as seen on PCA axis 2. The separation of Sr and Ca shows a shift in carbonate formation processes and suggests substitution of Sr from precipitating $CaCO_3$ (Saalfield, 2012). The dominant role of Ca, Se and Br on axis 2 is merely reflecting seasonal varve formation as deposits switch from carbonate rich to organic rich. The PCA bi-plot for unit 1 indicates a very strong detrital component to the sediment signal as eigenvector 1 represents more than 50% of the total variance. This clastic element is in direct opposition to allochthonous calcium carbonate precipitation as indicated by the presence of Ca and Sr on the negative axis.

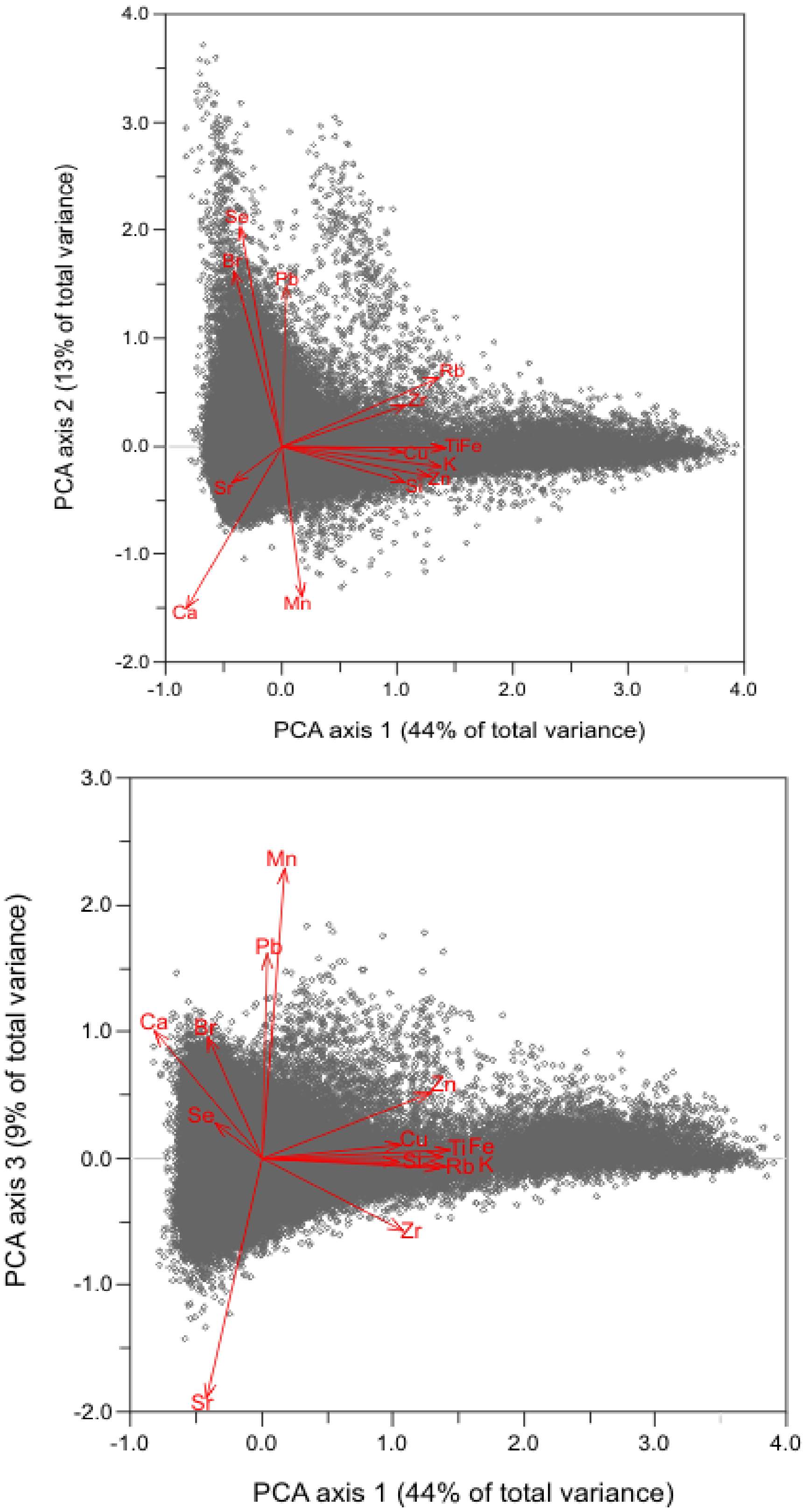


Figure 5.9: PCA bi-plots of axis 1, 2 and 3 for NAR10 Itrax derived elemental data. Sample scores are highlighted by dark grey dots and species scores are highlighted by red vector lines.

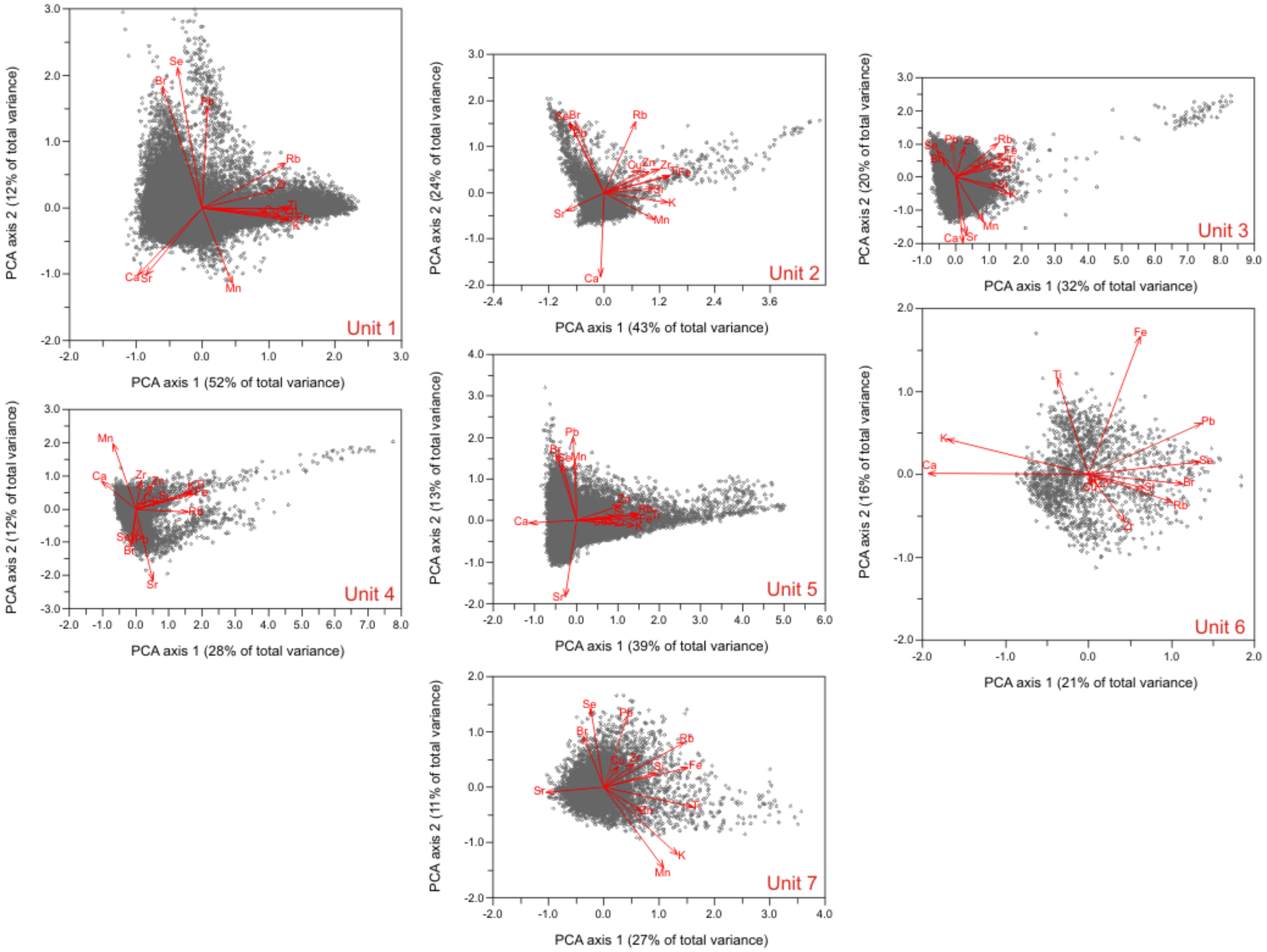


Figure 5.10: PCA bi-plots of axis 1 and 2 for all units of NAR10 Itrax data. Sample scores are highlighted by dark grey dots and species scores are highlighted by red vector line.

5.3. Comparison of total carbon proxy and Itrax derived elemental data

5.3.1. Organic carbon related component

Scattering of the XRF x-ray signal during core scanning is classed into two types depending upon energy loss, these are termed Rayleigh (coherent) and Compton (incoherent) scatters. The intensity of scanning is dependent upon the condition of the sediment being measured and thus a ratio of the two may be informative about sediment type. Jenkins (1999) suggests that the ratio of incoherent to coherent (Inc/Coh) will have a greater value when sediments contain more organic matter and a lower value when measuring inorganic materials. As a qualitative measure, the Inc/Coh ratio could therefore be used to discuss organic deposition at Nar Gölü. The potential of this method will be tested by comparing the Inc/Coh ratio obtained during the Itrax XRF scanning procedure to the total organic carbon results to see how useful Inc/Coh can be as a measure of organic levels at Nar Lake.

Figure 5.11 shows a comparison between the Inc/Coh ratio from the Itrax XRF data and the total organic carbon (TOC) curve. Visually there seems to be a good correlation between the two for units 1 and 2. Units 3 and 4 seem to show a breakdown in the relationship. The lower part of the core sequence seems to show a return to a more positive correlation between the two. Using Pearson's correlation statistics on the two profiles to see how they compare over time reveals a similar pattern to this. For the whole sequence, correlation statistics provides an r-value of 0.35. Highest r-values (0.38) are associated with unit 1, with positive values also during unit 6 (0.31). Unit 2 and unit 3 reveal reduced r-values of 0.16 and 0.12 respectively. No correlation exists for units 4 & 7 which revealed an r-value of 0.01. The Inc/Coh ratio may be used as a qualitative measure of the amount of organic carbon within the NAR10 sediments during unit 1 (0-592cm) due to the overall good correlation between Inc/Coh and TOC. Although this provides a faster estimation of down core TOC, quantifying organics in this manner is not particularly robust. Comparison of samples down-core reveals that on the whole, samples do not co-vary as maxima in TOC are not reproduced by the Inc/Coh ratio and vice versa. The fact that the Inc/Coh ratio does not correspond precisely with TOC for the rest of the core sequence suggests that the scattering of the XRF signal may be related to factors other than organic level, such as porosity, water content and undulated surfaces. More likely is that the TOC sample size and reliability of results may play a part in the low correlation scores seen. Incomplete combustion of the sediment sample and problems with sample weights during TOC analysis limit the scope of this record to show a clear and precise pattern of organic level change over time. It is reasonable to suggest therefore that the Inc/Coh may be a truer reflection on changes in the organic component for NAR10.

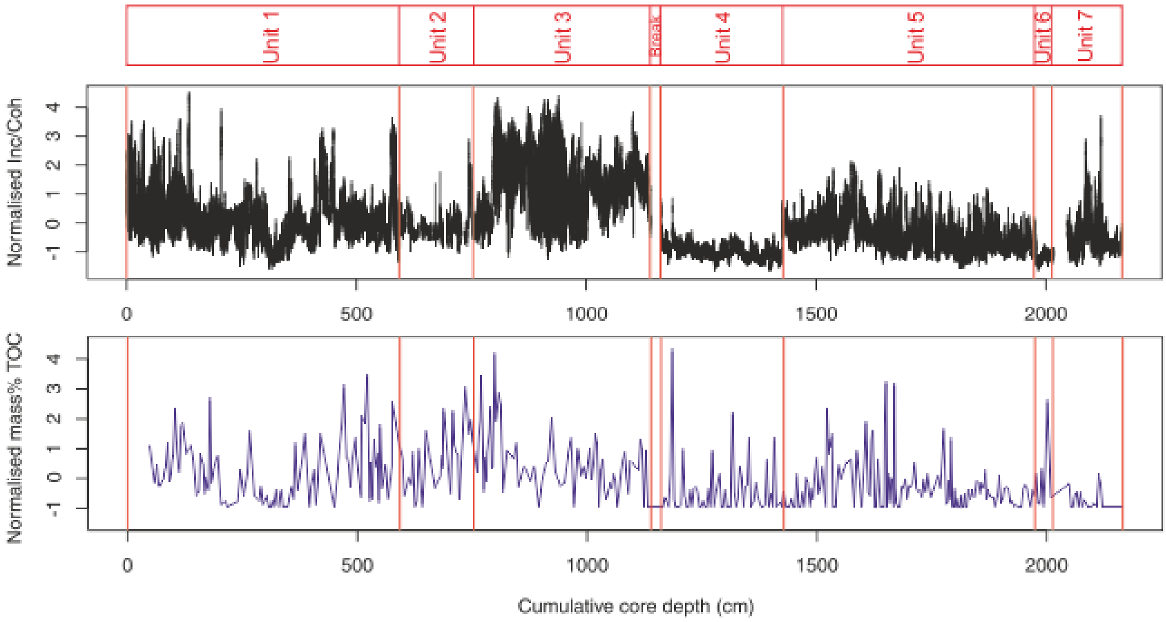


Figure 5.11: Stratigraphic plot of Incoherent/Coherent ratio against total organic carbon percentages, alongside cumulative core depth. Values have been normalised to 0 mean and 1 standard deviation to allow the two datasets to be plotted side by side.

5.3.2. Inorganic carbon related component

Total inorganic carbon (TIC) measures the amount of inorganic carbon contained within the lake sediment. TIC values can be related to a number of factors such as rate of carbonate precipitation. Due to its close association with carbonate processes, TIC should correspond to the Ca values obtained from XRF geochemical scanning as this element is also generally associated endogenic carbonate processes, particularly during the formation of $CaCO_3$ (Ohlendor *et al*., 2010). As long as Ca profiles are controlled by the proportion of authigenically precipitated calcite in the lake, then XRF derived Ca peak areas should reflect changes in TIC percentages. As a qualitative measure, Ca could therefore be used to discuss the amount of inorganic carbon. To test this relationship, normalised Ca and TIC were plotted alongside one another to see how the two profiles co-vary over time (figure 5.12).

Figure 5.12 outlines the relationship between Itrax derived Ca values and the total inorganic carbon (TIC) curve. Visually there seems to be a good correlation for most of the core sequence, with the most extreme rises and troughs picked out by both datasets. Units 3 & 4 seem to show the least correlation between the two records. Using Pearson's correlation statistics on the two sequences to see how they compare over time reveals that on the whole, the two variables correlate closely. Correlation statistics for the whole sequence provide an overall r-value of 0.62 which indicates that Ca and TIC strongly positively correlate. Highest r-values are associated with unit 6 (0.53), with reasonably positive values witnessed for unit 1 (0.52), 7 (0.49), 5 (0.44) and 2 (0.44). Visually, unit 3 seems to show the least correlation between the two variables but statistics indicate that there is still some similarity (0.31). Low correlations could be the result of Ca replacement by Mg and Sr as dolomite and aragonite during unit 3 (Dean, in prep). Visually, unit 4 seems to co-vary moderately well but actually this unit reveals the lowest r-values of just 0.29 indicating that at this time Ca and TIC are not closely related. The picture obtained for unit 4 may be skewed though due to the low TIC values obtained for some samples which could have resulted in a reduced r-value. Generally, Itrax derived Ca may be used as a qualitative measure of the amount of inorganic carbon within the NAR10 sediments due to the overall good correlation between the two. This therefore provides a more fine-tuned and faster estimation of down core variations in TIC for this study and shows good reliability in the data gathered for both proxies.

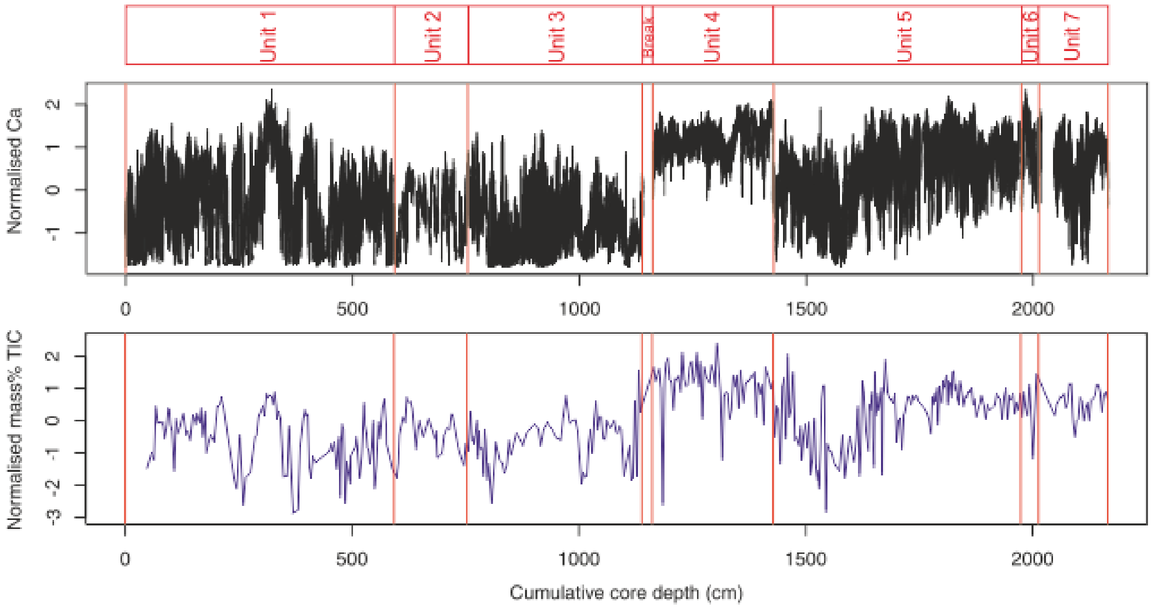


Figure 5.12: Stratigraphic plot of corrected peak area integrals of Ca against total inorganic carbon percentages, alongside cumulative core depth. Values have been normalised to 0 mean and 1 standard deviation to allow the two datasets to be plotted side by side.

5.4. Synthesis of geochemical records

5.4.1. Overview of Nar Gölü chemostratigraphy

There are 7 key zones distinguishable in the sediment stratigraphy and geochemistry; these have already been identified as units 1-7 (figure 4.1). Stratigraphically constrained cluster analysis produced a total of 10 key zones for the Nar geochemical data (figure 5.13) but the most important boundaries between zones actually mirrored the lithostratigraphic boundaries. The other three clusters all lie within the already distinguished sediment units. The similarity between the visually defined units and the cluster analysis has prompted the synthesis of data by sedimentary unit only, with sub-unit variations highlighted. Thus the influence of climatic/environmental and limnological variability on the composition of Nar Lake's geochemistry (figure 5.13) will be discussed in relation to stratigraphy, with dates indicated where available.

5.4.2. Unit 7 (ca. 14000-12900 years ago)

Visually, the sediment stratigraphy for unit 7, which dates around the Late Glacial, consists of abrupt alternations between beige and dark olive brown homogenous silts and thin laminations. In the main, this period is quite variable showing moderate amplitudinal changes in both carbon content and geochemistry (figure 5.13). Inorganic carbon content (TIC) is reasonably high for this period (average 10.5%) and the organic carbon content (TOC) is in contrast low, particularly for the very start of the core sequence. The darker sedimentary bands identified in this unit however correspond with relatively elevated levels of TOC and decreases in TIC. This pattern is similar to the pattern witnessed by normalised Ca (figure 5.12) and Inc/Coh, with darker coloured sediments associated with very high Inc/Coh ratio values (figure 5.11). Lighter beige sediments and sections with fewer varves show a different pattern, with much higher TIC values recorded. High peaks in TIC also correspond well with elevated levels of carbonate related elements, particularly Ca (figure 5.12). The high values recorded for carbonate related elements and low biogenic silica suggest that authigenic precipitation of carbonate dominates during lighter sediment bands (Heymann *et al.*, 2013; Marzecova *et al.*, 2011). Sub-unit 7a, dating to ~13596-12900vys, is characterised by much higher organic carbon levels and decreased Ca. Ca/Sr values (figure 5.13) are also heightened during this phase which suggests an increase in lake water levels as high Ca/Sr is typically a proxy for greater moisture availability (Rothwell *et al.*, 2006). This is in contrast to the period prior to ~13596vys which consists of lower Ca/Sr values and therefore may represent a period of drier hydrological conditions.

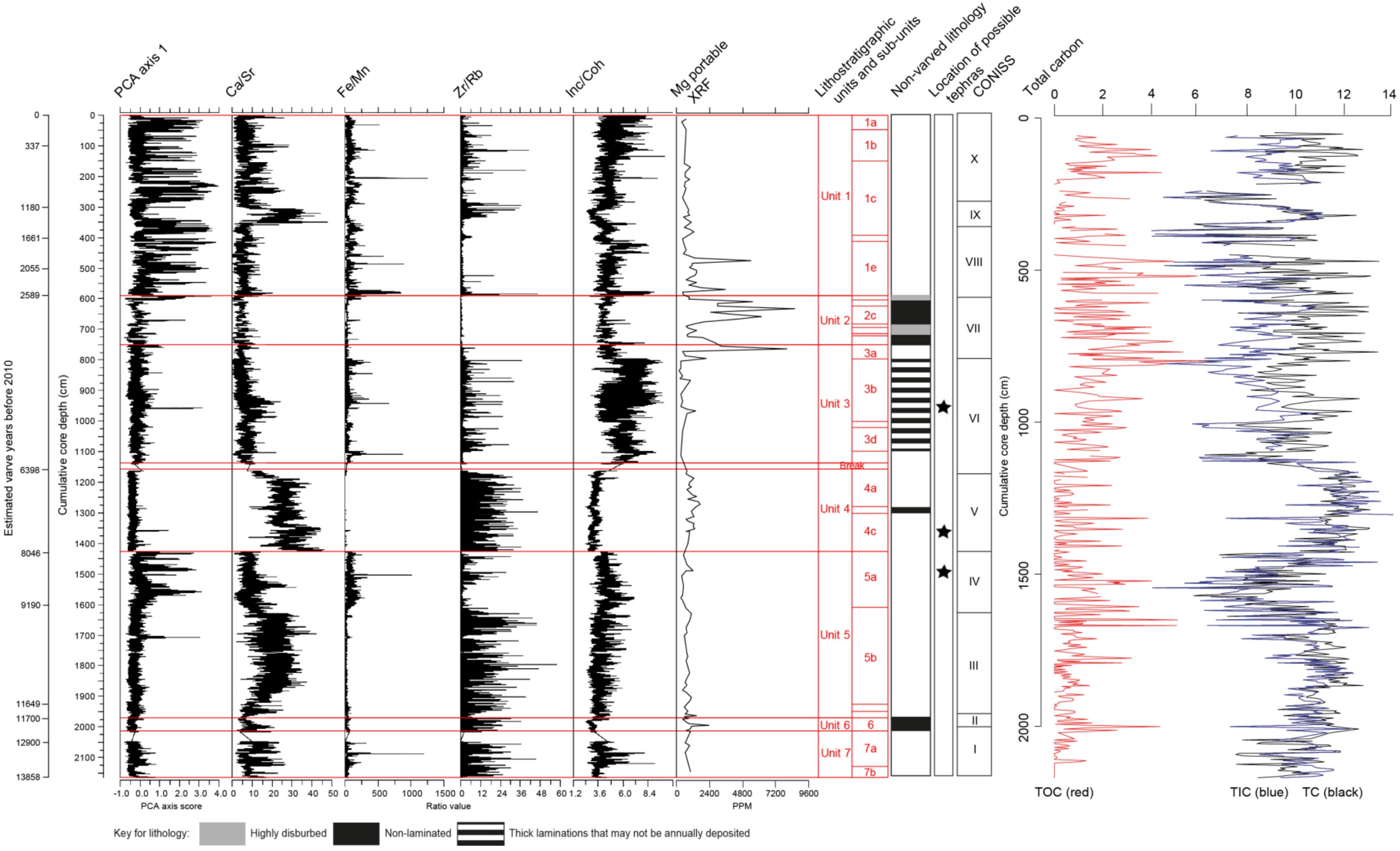


Figure 5.13: Summary of chemostratigraphy for Nar Lake. The proxies presented were selected based upon their usefulness for showing key geochemical changes down core. Geochemical variations are also shown alongside sedimentological data, results from constrained cluster analysis and the total carbon record.

Unit 7 also shows relatively low values associated with detrital elements (see PCA axis 1) (figure 5.13) but values rise slightly during the inferred moister hydrological phase associated with 2128-2033cm sediment depth. The presence of higher Fe/Mn values (figure 5.13) at this time also supports ideas relating to deeper lake waters as high Fe/Mn is generally associated with anoxic lake conditions and increased water depths (Chirinos *et al.*, 2005). High values of Fe and detrital input at this time however may be pushing Fe/Mn values up and thus the ratio cannot always be used as an indicator of lake depth. Increased sediment input from the catchment could have been caused by higher amounts of precipitation, which would have increased surface runoff into the lake by rainfall in the near vicinity, or it could have been caused by greater spring melt from snow. The presence of distinct laminations suggests deeper lake conditions and clear seasonality, with enough substantial seasonal turn-over of the lake to deliver enough organics for the formation of distinct varve couplets (Hedges and Keil, 1995). Seasonal turnover and therefore summer stratification of Nar Lake indicates anoxic lake bottom waters which fits well with higher Fe/Mn levels (Dean, 1993).

5.4.3. Unit 6 (ca. 12900-11700 years ago)

Unit 6 is readily distinguishable by a change in sediment colour from grey varves to lighter grey/beige marl without any laminations. The unit is completely homogenous with very little visible change in sediment stratigraphy. The unit is also evidenced by a decrease in elemental variability, mainly due to the unchanging or mixed nature of the sedimentary deposit. Total carbon results (figure 5.13) though suggest that two periods of change existed in this unit, ending and starting at around 2001cm sediment depth respectively. The change within sediment unit 6 is also noticeable by geochemical variations relating to carbonate and detrital deposition (figure 5.13).

Visually the beginning of unit 6 is not very different chemically from sediments deposited at the end of unit 7 and likely reveals a continuation in sediment formation. The first half of unit 6 consists of lower TIC and higher TOC, higher Ca/Sr and relatively little detrital influence (figure 5.13). It is possible that these geochemical parameters are reflecting generally moister lake conditions, which is particularly evidenced by increased Ca/Sr values (Cohen, 2003). Once waters were deep enough, organic preservation would have improved (Hedges and Keil, 1995) and thus may explain the slight increase in TOC here. The Inc/Coh ratio (a proxy for organic levels) (figure 5.11) however, shows only a slight elevation in the amount of organic material being deposited in the lake at this time, and values are greatly reduced from unit 7. The absence of laminations, lower Inc/Coh values and generally reduced Fe/Mn values suggest lake levels were shallower than in unit 7. Lower lake waters are substantiated by large calcareous nodules and distortions towards the end of this depositional phase, and relatively higher levels of carbonate deposition as outlined by increased Ca (figure 5.12). A dry and evaporative event following the deposition of fairly moist material may have diagenetically altered the sediment appearance and could help explain the somewhat confusing geochemistry for this phase which could be inferred to represent both wetter and drier conditions.

The latter half of unit 6 is evidenced by higher TIC, Ca and Sr (figure 4.7), and lows in Ca/Sr (figure 5.13). The potentially short-lived excursion to more moisture availability following unit 7 was disrupted by a return to exceptionally dry and evaporative conditions, and therefore lower lake stands. This is confirmed by increased oxygenation of lake bottom waters as suggested by lower Fe/Mn values (figure 5.13). Whilst low in terms of the rest of the core sequence, slightly raised levels of biogenic silica (as outlined by the Si/Ti ratio (figure 5.8)) are also documented for the latter half of unit 6. If lower lake waters did persist then more light would have reached the lake bed and may have influenced the growth of diatom communities at this time. If lake waters receded then much of the exposed material on the basin sides would have been prone to some erosion. Slightly elevated levels of K (figure 4.13) indicates some weathering but relatively low levels of detrital in-wash (figure 5.13) suggest that on the whole, the surrounding catchment and lake edge was moderately stable. Stability likely resulted from reduced levels of precipitation. Reduced precipitation levels would have meant that sediments surrounding the lake were not subjected to increased water induced erosion. It is also likely that snow deposits made little impact on material entering the lake at this time.

5.4.4. Unit 5 (ca. 11700-8046vys B.P.)

Early Holocene sediment is marked by a sustained level of inorganic carbon matter and a continuation of low clastic input (figure 5.13). A shift from a prolonged arid phase during unit 6 may have led to episodes of high inorganic carbon sediment input into the lake post event due to re-working of previously exposed shoreline deposits. The slight fall in TIC (figure 5.13), Ca (figure 5.12), detrital levels and low values for K (figure 4.13) (a weathering indicator) suggest that this did not occur at the onset of unit 5. In fact, decreased clastic input from ~11700-9190vys suggests landscape stabilisation for an extended period of time following unit 6. Within unit 5 there is a shift in lake condition and this unit has thus been divided into sub-units based on patterns of carbonate and detrital derived geochemical change (figure 5.13). These have been classified as sub-units 5b-d (1974-1606.2cm; ca. 11700-9190vys B.P.) and sub-unit 5a (1606.2-1428.2cm; ca. 9190-8046vys B.P.).

Sub-units 5b-d indicate a significant change to stable conditions following a period of what seems to be changeable but generally dry conditions during unit 6. This stability is evidenced by only subtle changes in redox conditions, detrital input and carbonate precipitation (figure 5.13). At the start of unit 5, there are slightly elevated levels of Sr (figure 4.7) which are likely relic deposits of Sr from the unit below precipitated during lower lake stands and decreased precipitation (Műller and Wagner, 1978). TIC and Ca (figure 5.12) are relatively high here and annual laminations are clear and distinctive. The presence of laminations during low Fe/Mn values (figure 5.13) is puzzling given that varves would not normally form under oxygenated lake bottom waters (Dean, 1993). It is possible that oxic conditions are reflected because of reduced seasonality and/or lake turn-over during the spring and autumn months rather than lower lake waters per se (Magyari *et al.*, 2009). It is also possible the low Fe/Mn values relate to the lack of detrital material entering the lack at this time (figure 5.13) and thus a reduced level of Fe in the lake system. The formation of varves suggests it is likely that the lake level rose from unit 6 and conditions became more nutrient rich, a condition expressed by high diatom productivity and high Si/Ti values (figure 5.8) at this time too. The increased water level would have submerged near shore settings and expanded the lake surface area which would have introduced more nutrients into the lake waters accelerating secondary carbonate productivity from algal communities. A noticeable excursion in Ti levels (figure 4.11) at 1708.2cm (9966vys) is associated with a decline in biogenic silica shortly beforehand. Decreased aquatic communities and an increase in clay related elements (e.g. Ti, Fe) may imply a short lived excursion to drier and cooler conditions.

Sub-unit 5a is characterised by dramatic shifts in detrital and generally fine grained input centred at 1574.2 cm (9072vys), with five other important peaks occurring at 1503.2, 1485.2, 1468.2, 1448.2 and 1432.2 cm (8599, 8419, 8303, 8169 and 8065vys respectively). Detrital elemental profiles show significant high peaks during this phase and relatively variable conditions (figure 5.13). Clay mineral and clastic influx at this time forms a major component of the sediment sequence indicating control by allochthonous processes. At this time also, Fe/Mn ratios (figure 5.13) suggest increased lake bottom anoxia, lake water stratification during the summer months and enhanced seasonal extremes. Grain size is small as indicated by the Zr/Rb ratio (figure 5.13), as is Si/Ti (figure 5.8) for most of the time. Lows in Ca and Sr (figure 4.7) suggest that carbonate deposition was reduced (Kylander *et al.*, 2011a), but it is likely that some of the carbonate signal is diluted because of high clastic elemental readings. A slight rise in Inc/Coh and TOC values (figure 5.11) may indicate more terrestrial organic material entering the lake with the detrital elements. It is postulated that during sub-unit 5a, conditions were drier in the catchment than the rest of unit 5, with shifting moisture levels relating to changes in seasonal precipitation patterns. Lack of moisture availability in the catchment would have been enough to trigger frequent landscape instability and erosion of catchment material into the lake water (Giguet-Covex *et al.*, 2011). The change in nutrient supply would have also been enough to disrupt biological communities in the lake thus lowering levels of biogenic silica at this time. Heightened levels of detrital in-wash may also be explained however by human activity within the lake catchment which could have potentially disturbed the stability of soils and by increased volcanic eruptions as may be evidenced by the presence of a possible tephra horizon during sub-unit 5a.

5.4.5. Unit 4 (ca. 8046-6398vys B.P.)

Lacustrine sediments deposited throughout unit 4 consist of thin (mm scale) and very faint but visible laminations compared to sediments deposited earlier. Organic carbon is relatively low in unit 4 but inorganic carbon is exceptionally high (figure 5.13), and reaches levels not seen elsewhere in the core sequence. Unit 4 is also markedly different in terms of geochemistry, with relatively low detrital values recorded and remarkably high calcium concentrations (figure 4.7). These changes are linked in with the occasional deposition of calcareous granules of biochemical origin and a huge increase in Mn deposition (figure 4.9). Higher aquatic productivity is evidence by slightly elevated levels of Si/Ti (figure 5.8) but in comparison to units 7 and 5, these values are low. The high inorganic carbon content, as well as high Ca and low Sr (figure 4.7) in unit 4 suggests conditions are strongly controlled by calcium carbonate precipitation (Treese *et al.*, 1981). The indication of oxic conditions by low Fe/Mn (figure 5.13) could imply sediment fixing of Ca which would result in increased levels (Boyle, 2001). A lack of seasonal turnover of lake waters as potentially implied by low Fe/Mn could also be considered as a function of stable yearly rainfall levels, and therefore high Ca values in this instance would relate to in-lake chemical precipitation as a result of sustained moisture levels (Arnaud, 2013, pers. comm; Heymann *et al.*, 2013). More stable and year-round precipitation levels may also be substantiated by only faint winter laminae and enhanced carbonate summer laminae.

Based on very low detrital influence at this time (figure 5.13) it is also possible to assume little influence of eroded catchment material on lake geochemistry. The surrounding landscape must have been very stable and soil erosion was decelerated for a time. Lack of clastic influence could be characteristic of a moist phase which encouraged greater catchment vegetation and soil cover and therefore a reduction in landscape instability during unit 4. It could also be characteristic of relatively reduced human activity in the catchment and therefore less human-induced landscape disturbance. A one-off event does occur at 1356.2 cm (7588vys) where levels of Ti, Fe, Rb, Si and K (figures 4.9, 4.11 and 4.13) increase significantly and signify a sudden and short lived influx of clastic material. This is evidenced to by a dark grey clay band in the sediment stratigraphy and SEM scans (figure 4.22) indicating increased input of alumino-silicates (detrital type material). It is likely that this event is similar to other large detrital peaks witnessed in sub-unit 5a. The cause of this event could be decreased moisture availability, destabilisation of the surrounding landscape or the deposition of volcanic material (see section 4.8). Generally, constant conditions persisted during unit 4 as variation in geochemistry is often minimal (figure 5.13). Fluctuating conditions are barely witnessed and highlight the unchanging nature of the climatic/environmental state at this time.

5.4.6. Unit 3 (ca. 6398vys B.P.-?)

Unit 3 is characterised by thick laminations in the sediment stratigraphy (figure 5.13) that cannot be confirmed as annual deposits. Organic matter values rose considerably as highlighted by increased Inc/Coh values and elevated TOC levels in relation to unit 4 (figure 5.11); with the most rapid rise evident towards the base of the unit and into the transition with the next lithostratigraphic unit. Visually, unit 3 is markedly different with dramatic colour changes between bands and the deposition of bright white carbonate rich lamina. Both are strongly linked to shifts between precipitated carbonates and up-core increases in organic levels. Unit 3 also signifies the start of reduced Si/Ti (figure 5.8) and therefore diatom biological activity in the lake, which remains low until present times. Carbonate deposition at this time was not controlled by increased biogenic productivity in the lake and is likely to relate more firmly to non-biological endogenic processes. Grain size (Zr/Rb), clastic input, biogenic silica and precipitated carbonate (figure 5.13) are on the whole reduced for this time period but some changes in these components are seen and signify partially alternating conditions in lake state.

High peaks in detrital elements are witnessed at 1107.7, 958.5, 897, 842.8 and 804.4cm sediment depth. These peaks show that at times, the influence of clastic material was greater than at other times, and highlights increased catchment instability for short abrupt episodes. The most distinctive peak is at 958.5cm and is witnessed by a dark black sediment band in the stratigraphy. SEM scanning (figure 4.22) of this band was conducted as it have characteristics of a tephra horizon. Another significant elemental component of unit 3 is Sr (figure 4.7), with values shifting from below 200 to above 400 (peak area integral value) at two points in the sequence. These shifts correspond to 925.9-858.9cm and 805.1-741cm sediment depth. Co-precipitation of Sr and Ca at this time suggests endogenic precipitation (Kylander *et al.*, 2011a) of aragonite, a signal confirmed by XRD analysis (Dean, in prep). Aragonite carbonates likely cause the bright white laminae documented in the sediment stratigraphy, particularly towards the top of the unit sequence. Lake level and moisture availability is hard to interpret during unit 3 but generally reduced Fe/Mn and Ca/Sr values suggest that lake levels were lower than in unit 4. The presence of detrital in-wash events however suggests less stable conditions than in unit 4.

5.4.7. Unit 2 (>2600vys B.P.)

Sediments in unit 2 are very distinctive as most of the unit is non-varved. Laminations are rare, and where apparent they are thin and often disturbed. Hard carbonate concretions dominate the unit; concretions can be as large as 3cm in diameter and extremely tough to break apart. Considering these deposits are carbonate rich, the total inorganic carbon values recorded are relatively low (average 8.78%) (figure 5.13). Normalised Ca values (figure 5.12) also suggest that during unit 2, calcium carbonate deposition (in the form of calcite) is reduced. The start of the unit corresponds to relatively high levels of organic carbon (average 1.86%), a pattern witnessed towards the end of unit 3 also (figure 5.13). These values tail off by the end of unit 2 as TIC rises. The Inc/Coh ratio in contrast suggests primarily low organic levels for the whole of unit 2 besides the transition with unit 3 (figure 5.11) and it has been suggested that this proxy offers a better representation of down-core changes in organic levels.

The high inorganic content and lack of visible laminations towards the bottom half of unit 2 may be indicative of a low lake level. The nodular nature of deposits also indicates extreme drying at this time, with water levels significantly reduced. The interpretation of lower lake stands is substantiated by the Fe/Mn ratio (figure 5.13) which highlights an oxic lake state and therefore oxygenation of bottom lake waters. Organic matter decomposition occurred due to higher oxygen levels at the bottom of the lake. In addition, the lack of yearly stratification and continual ventilation of the water-column can be inferred from sediment homogenisation. The strong presence of Sr and Mg (figures 4.7 & 5.13) at this time also indicates that there was extreme drying. Magnesium supersaturation in unit 2 (figure 5.13) indicates intense evaporative conditions and increased salinity (Hubert-Ferrari *et al.*, 2012), and thus higher levels of aridity.

The presence of some varves and a small amount of organic matter preservation towards the start of the unit suggests that water levels may have periodically been higher as the breakdown of organics did not occur readily and conditions must have been anaerobic enough to preserve varve formations. With increased water depth, bioturbation would have been reduced and thus enhanced the deposition of organics. Relatively low levels of Si/Ti (figure 5.8) suggest low productivity at the lake during unit 2. The slightly elevated peaks in Si (figure 4.11), though, is interesting as detrital elements are generally minimal here which suggests that the Si profile may show some variation in biogenic silica and diatom productivity. The reduction in erosion indicators (figure 5.13) and therefore clastic input into the lake may be a consequence of a buffering effect from growth of littoral vegetation if water levels were relatively higher at the beginning of this phase. The lack of organic matter for most of the unit (figure 5.13) however implies that reduced detrital values relate primarily to another mechanism of change, possibly reduced human landscape disturbance and/or reduced surface erosion from wetter climatic conditions. Less precipitation may have resulted in less detritus material being transported into the lake.

5.4.8. Unit 1 (ca. 2589vys B.P.-present)

During unit 1, the return to varved sediments and absence of hard carbonate nodules suggest a return to anoxic and higher lake level conditions. Relatively stable average carbonate and organic conditions after unit 2 implies little mean change between these two phases. More extreme values in both TIC and TOC (figure 5.13) however imply that conditions were far from stable and in fact fluctuated on a frequent basis. The deposition of Ti, Fe, K, Si and Rb as highlighted by the PCA axis profile in figure 5.13, suggests increased input of catchment material on the lake setting during unit 1. The coincidence of clastic matter and relatively high levels of TOC (figure 5.13) may imply enhanced terrestrial organic matter input at this time. This change in hydrological condition to higher lake stands and increased sedimentation is reflected in the Fe/Mn ratio (figure 5.13) which is likely not only indicating highs in detrital Fe but also a switch back to stratified lake waters and therefore potentially wetter climatic conditions. Increased precipitation may have caused greater erosion of soils and may explain the large rise in detrital values witnessed. Given the fact that unit 1 is relatively modern in age, it is also interesting to consider the role of humans on the pattern of clastic in-wash witnessed. Increased human disturbance and activity within the lake catchment may also explain an increase in detrital elements here.

Five distinctive switches in lake status are evident in unit 1 associated with 592.7-340.1 (sub-units 1e-c), 340.1-281.8 (sub-unit 1c), 281.8-203.1 (sub-unit 1c), 203.1-41 (sub-units 1c-b) and 41-0cm (sub-unit 1a) sediment depth. These changes are mainly evidenced by shifts between low detrital, high carbonate and high detrital, low carbonate values. The first period of change associated with sub-units 1e-c seems to span a period between ca. 2589-1394vys, ending at an estimated calendar age of AD616 and is characterised by unstable fluctuations in clastic material and very low carbonate deposition. Sediment and geochemical change between 340.1 and 281.8cm (estimated to date between ca. 1394-1096 vys B.P.) is the most distinct shift in unit 1. It is identified by increased carbonate deposition of co-precipitating Sr and Ca (figure 4.7). Slight increases in Si/Ti (figure 5.8) are evident during high carbonate stands and may imply some control by algal communities. Increases in pH during algal blooms in the summer months may increase the amount of precipitated calcite and this would be witnessed in the elemental profiles by high Ca and Sr. High calcite levels could also signify increased moisture levels. Grain size also increases in line with the change from detrital dominated material as inferred by Zr/Rb (figure 5.13). The shift at 281.8-203.1cm (ca. 1096-841vys) shows a reversion back to detrital dominated deposition and finer grain materials. Carbonate deposition is remarkably low for this time and suggests reduced moisture availability. The next change dated to ca. 841-80vys shows a similar pattern to the second visual period of change. The final change in geochemistry occurs at ca. 80-0vys and is evidenced by a dramatic increase in detrital elements and increased visual evidence of large scale clastic in-wash events by thick ‘turbidite’ inclusions. At this point in time, Si (figure 4.11) is incorporated into the detrital suite and signifies low primary productivity. Grain size is also dramatically reduced (figure 5.13). A rise in TOC and drop in TIC is interesting and may indicate increased terrestrial derived organic material. As these are modern sediments dating to the Turkish Republic Era (1923-present), the role of human populations and agriculture on the surrounding landscape is an important concern for this time. Increased clastic input shows heightened erosion and landscape instability for this last phase of change.

5.4.9. Synopsis of Nar Gölü chemostratigraphy

Combining elemental and sedimentary datasets from Nar Gölü produces a number of different conclusions regarding changes in lake hydrology and environmental variations. Fluctuating conditions between moist and dry are noticeable throughout the Late Glacial period and into the Holocene. The Early Holocene in contrast is evidenced by very stable conditions and higher lake levels. Carbonate production by algal communities was extremely high at this time and likely explains some of the high carbonate deposition here. Catchment erosion also had no significant effect on the lake until sub-unit 5a. At this time, increases in detrital in-wash relates to amplified landscape instability and soil degradation. In unit 4 clastic influxes are significantly reduced showing a marked change from conditions during sub-unit 5a. Constant precipitation levels are suggested from Fe/Mn ratios which signify oxygenated bottom lake waters and from faint laminations. A strong relationship between organic content and thick, possibly non-annual laminations exists for unit 3. Aragonite formations likely increased the relatively reduced carbonate signal at this time; generally low carbonate precipitation is controlled by reduced biological activity in the lake. Extremely low lake levels and evaporative conditions persisted in unit 2 and this is well documented in the sediment stratigraphy by hard carbonate concretions and no varve deposits. A strong detrital component for unit 1 suggests control principally by external sources. The return of laminations also implies higher lake levels at this time. Unit 1 is dominated by highly variable shifts in elemental geochemistry and therefore represents frequently fluctuating conditions.

Whilst some understanding of hydrological conditions at Nar Lake have been produced for select time periods, the exact interplay between climatic and environmental factors is hard to justify through elemental synthesis alone. It is therefore necessary to look at the NAR10 geochemical record in relation to other proxy records from the lake and to data from other regional records to better understand the variable nature of hydrological conditions at Nar Lake and to relate this history of change with the pattern of change witnessed elsewhere in the region.

5.5. Nar Gölü multi-proxy comparisons

5.5.1. Comparisons to the Nar Gölü oxygen isotope record

The moisture balance history of a lake can be determined from oxygen isotope ratios if they have been isotopically modified by evaporative processes (Anderson *et al.*, 2001). Increased evaporative rates cause δ^{18}O enrichment whilst decreased evaporative rates result in δ^{18}O depletion. Positive oxygen isotope values (enriched) have thus been associated with drier climatic conditions whereas negative values (depleted) signify a wetter climate. In the Eastern Mediterranean, lake level shifts have predominately been related to changes in the precipitation-evaporation (P-E) ratio and are thus principally controlled by changing climate (Jones *et al.*, 2006; Roberts *et al.*, 2008).

Oxygen isotope work conducted on the Nar Lake sedimentary record has progressed in two stages. Firstly, oxygen isotope studies on spring/summer precipitated carbon were conducted in 2001 & 2002 by Matthew Jones (Jones, 2004) for the last 1720 years at yearly and sub-decadal resolution on samples from the NAR01 and NAR02 core sequences. Subsequently, Jonathan Dean (Dean, in prep) has studied isotope values from the NAR10 core sequence for a period from around 14,000 yrs. B.P. to present day.

Isotope studies from the NAR10 record are still in progress and will form part of a doctoral thesis submission (Dean, in prep). In light of this, only a low resolution profile of the isotopic changes throughout the Late Pleistocene & Holocene are used in the comparisons here but this should be sufficient enough to detail the fundamental shifts between wet and dry. The full record from the NAR01/02 sequence is available for comparison purposes.

Jones (Jones, 2004; Jones *et al.*, 2005; Jones *et al.*, 2006) identified significant shifts between wet and dry conditions at Nar Gölü during the late Holocene from water oxygen isotope ratios; these changes were driven by precipitation and evaporation. If, as suggested in section 5.2.4, the Ca/Sr ratio and carbonate mineralogy record are driven mainly by precipitation-evaporation levels then the Nar Lake isotope record and the Itrax XRF data should show similar shifts between wet and dry. To see if this is the case, a comparison is made between the Ca/Sr, TIC and δ^{18}O records from Nar Lake (figure 5.14).

In total, significant shifts between wet and dry are identifiable in the combined NAR01/02 and NAR10 isotopic records. Also noticeable is the dominance of wetter conditions prior to 6300 years ago (roughly end of unit 4; 1161.2 cm) with drier conditions persisting thereafter. In the more highly resolved isotope record from NAR01/02, three shifts from positive to negative values are recorded between AD 486-561, AD 1393-1429 and AD 1949-1987 (Jones, 2004; Jones *et al.*, 2006). These finer detail changes are not clearly identifiable in figure 5.14, which was constructed to highlight the broader and more major shifts occurring over long time spans and therefore only indicates drier conditions for the period after AD 1400.

The most important shifts in Ca/Sr occur simultaneously alongside δ^{18}O shifts between wet and dry, with the most noticeable changes happening between 1953-1625cm (important wetting trend) and 750-590cm (important drying trend) sediment depth. The wettest period on record therefore occurs between ca. 11649-9292 vys. B.P. (9639-7282 B.C.) and the driest period found between ca. ~4500-2596 vys. B.P. (~2490-586 B.C.). It appears that the Ca/Sr and oxygen isotope record respond in a similar fashion to changes within the lake system and that the Ca/Sr ratio is an indicator of P-E ratio and as a result lake level changes also. A correlation value of -0.64, significant at <0.05, suggests that there is a clear negative relationship between the two variables as is witnessed in the sedimentary profiles.

The TIC record does not respond as clearly to changes in P-E ratio as Ca/Sr, even though the patterns of TIC and $\delta^{18}O$, on the whole, are comparable. More negative isotopic values from 1130-1070cm for instance coincide with generally reduced levels of TIC, a reversal of the pattern that would be expected if TIC and P-E ratio were related, suggesting that TIC responds to more than just P-E adjustments. This reversal in the patterns witnessed can also be seen from 1190-1133cm and 1070-1010cm where positive peaks in $\delta^{18}O$ are matched by increased TIC. It appears that from 1190-1010cm the TIC record may respond to P-E changes but to lag the $\delta^{18}O$. A Pearson's correlation value of -0.33, significant at <0.05, implies that at times there is a weak negative relationship between the oxygen isotope and TIC records but suggests that in many instances, the two proxies may not be responding in parallel to lake system changes.

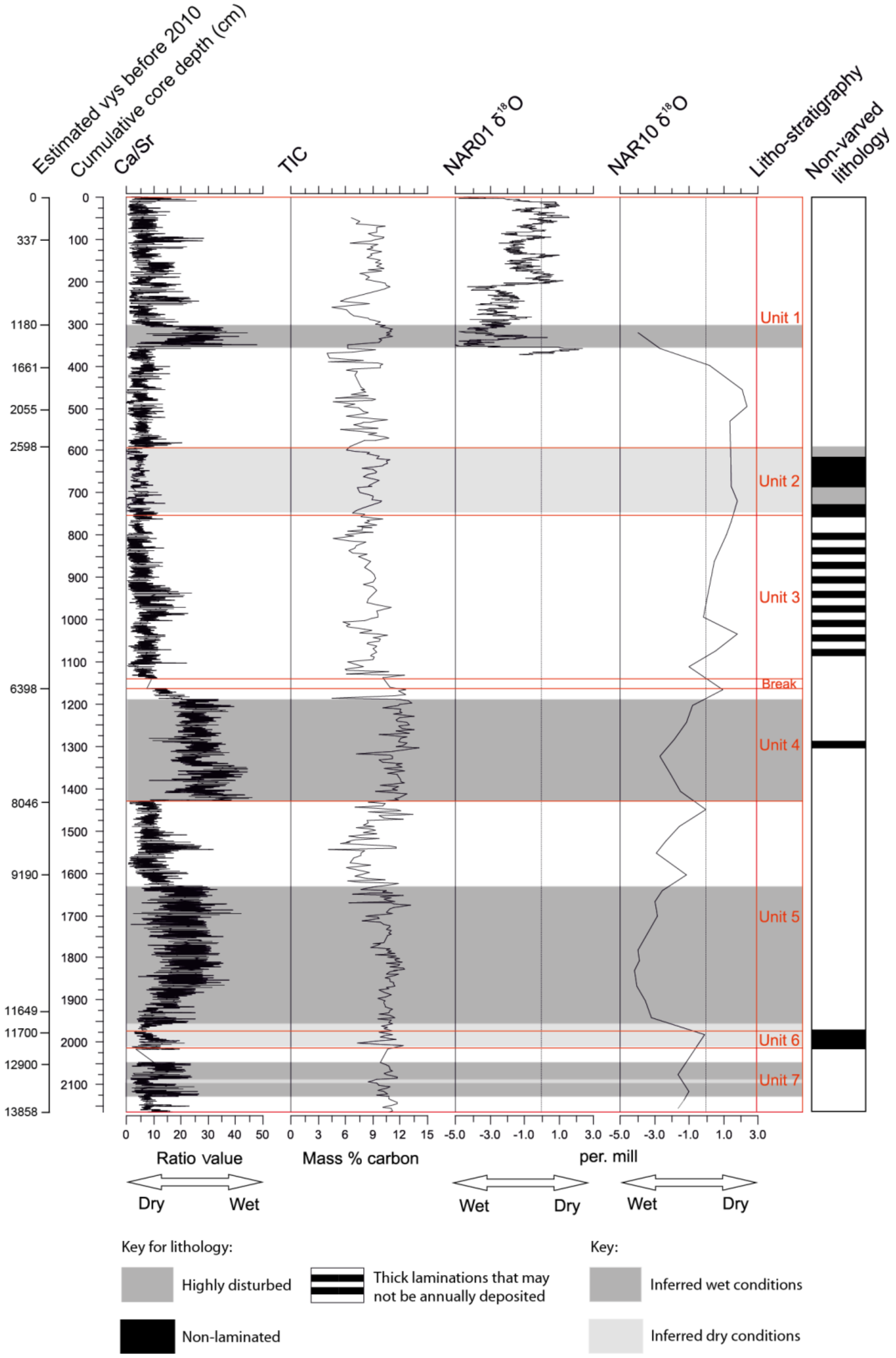


Figure 5.14: NAR10 Ca/Sr and TIC record presented alongside the NAR01/02 (Jones *et al*., 2006) and NAR10 (Dean, in prep) oxygen isotope stratigraphy, sedimentary stratigraphic units and lithology. Periods of major drying are indicated by light grey boxes and periods of major wetting are indicated by dark grey boxes. The overall pattern of change witnesses wetter conditions in the early Holocene in comparison to the late Holocene.

The non-stationary relationship between TIC and $\delta^{18}O$ is not driven by a lack of response to changes in the lake's hydrological system but because TIC levels can also be controlled by carbonate productions within the lake (Marzecova *et al.*, 2011), particularly by calcite (Ca), aragonite (Sr) and dolomite (Mg) precipitation in the case of Nar. The close correspondence between Ca and TIC (section 5.3.2) during periods of less resemblance to the oxygen isotope data suggests a greater control on TIC production by in-lake carbonate formation, which could be biologically led (Marzecova *et al.*, 2011). Alternatively, the presence of high Ca would likely result in greater isotopic enrichment and more positive $\delta^{18}O$ values relative to other carbonate precipitates (Yuan *et al.*, 2006)

5.5.2. Comparisons to the Nar Gölü diatom record

Diatoms are useful biological indicators of palaeoclimate and preserve well in lake cores (Woodbridge, 2009). Their changing characteristics are related to the lake environment and thus their response mechanisms can be used to infer past climate trajectories and cycles (Woodbridge, 2009). Diatom sensitivity to a variety of ecological conditions means that changes in climate can be inferred from changes in species abundance, species diversity, species distribution and the ecological requirements of 'indicator species'. Certain species are selective in terms of lake level and nutrient supply, which are in turn related to precipitation levels, solar output, wind, nutrient upwelling and erosion/terrestrial input (Kilham *et al.*, 1996). Diatoms are also heavily influenced by altered erosion levels and increased nutrient supplies to the lake environment as a result of human impact and anthropogenic activity within the surrounding landscape (Selby and Brown, 2007).

Woodbridge (2009) and Woodbridge *et al.* (Woodbridge and Roberts, 2010, 2011; Woodbridge *et al.*, 2010) analysed the NAR01/02 and NAR06 diatom record and found that diatoms are useful indicators of climate change and anthropogenic influence at Nar Lake over the last 1720 years at the decadal time resolution. They concluded that Nar Lake water was most saline, and thus climate was more arid prior to AD 540 in comparison to the rest of the period studied (Woodbridge and Roberts, 2011). A postulated 5th century AD drought episode (Woodbridge and Roberts, 2011) was likely the last pronounced dry phase of a series of drought events to have punctuated the latter half of the Holocene in central Anatolia (Kuzucuoğlu *et al.*, 2011) and is also evident in the oxygen isotope record at Nar Lake (Jones *et al.*, 2006). Four key diatoms zone were identified (Woodbridge and Roberts, 2011) highlighting significant shifts in regional water balance and lake conductivity. Drier periods were evident from AD 270-540 & AD 800-950 and wetter episodes were evident from AD 540-800 & after AD 950. From AD 1400-1960 there is a decoupling of the $\delta^{18}O$ isotope values and diatom inferred conductivity reconstruction which is thought to relate to increasing influence of human processes on the diatom record. Isotope data suggests that climatic conditions at this time were relatively dry but the lack of response from the diatom community cannot corroborate this pattern.

Busby (2011) extended the diatom work which was completed by Woodbridge and others by analysing the diatom record from the newly extracted NAR10 sediment sequence. For his diatom study, 59 samples were selected from the NAR10 lake cores covering a period from ~14,000 vys. B.P – 1720 vys. B.P. Diatom inferred conductivity and diatom class studies resulted in the identification of 7 distinct diatom zones highlighting changes in diatom inferred salinity and possible lake level changes. On the whole, the conductivity record shows an increase in salinity during the mid-late Holocene which peaks at 800cm sediment depth. Diatom analysis (Busby, 2011) details that the start of the NAR10 core sequence documented fairly wet climatic conditions with associated high lake stands and freshwater, whilst the latter half of the core sequence saw established drought and a reduced water balance.

To see how the geochemical record from Nar Lake related to the diatom stratigraphy from the same core sequence, a comparison was made between PCA axis 1 sample scores, the Ca/Sr ratio, the Mg record, diatom species abundance, diatom ecological preferences and diatom inferred conductivity (figure 5.15). If the presence of Mg in the core sequence relates to heightened salinity (as suggested in section 5.4.7) then there should be clear links with the diatom inferred conductivity record. Similarly, if the PCA axis scores (representative of detrital influx) and Ca/Sr ratio (representative of moisture balance) are indicative of shifting environmental and climatic changes then there should be some parallel with components of the diatom record which are said to have uniquely responded to climatic/environmental shifts (Woodbridge, 2009).

Comparison of the diatom history at Nar Lake with the NAR10 geochemical record (figure 5.15) reveals a subtle relationship in the response of these proxies. The links between species abundance, ecological preference, conductivity and lake geochemistry is non-stationary through time and on the whole, recognised changes in lake geochemistry only partially coincide with significant shifts in the diatom record. The fact that the records appear only slightly related may be connected to the different response characteristics of each individual proxy or the fact that human presence and land use practices could have also influenced the patterns witnessed. Comparisons made to planktonic + facultative planktonic diatom abundance and conductivity changes are also made less usable by the fact that changes in these profiles are heavily driven by the prevalence of certain diatom species and reflect changes in diatom abundance rather than lake conditions alone.

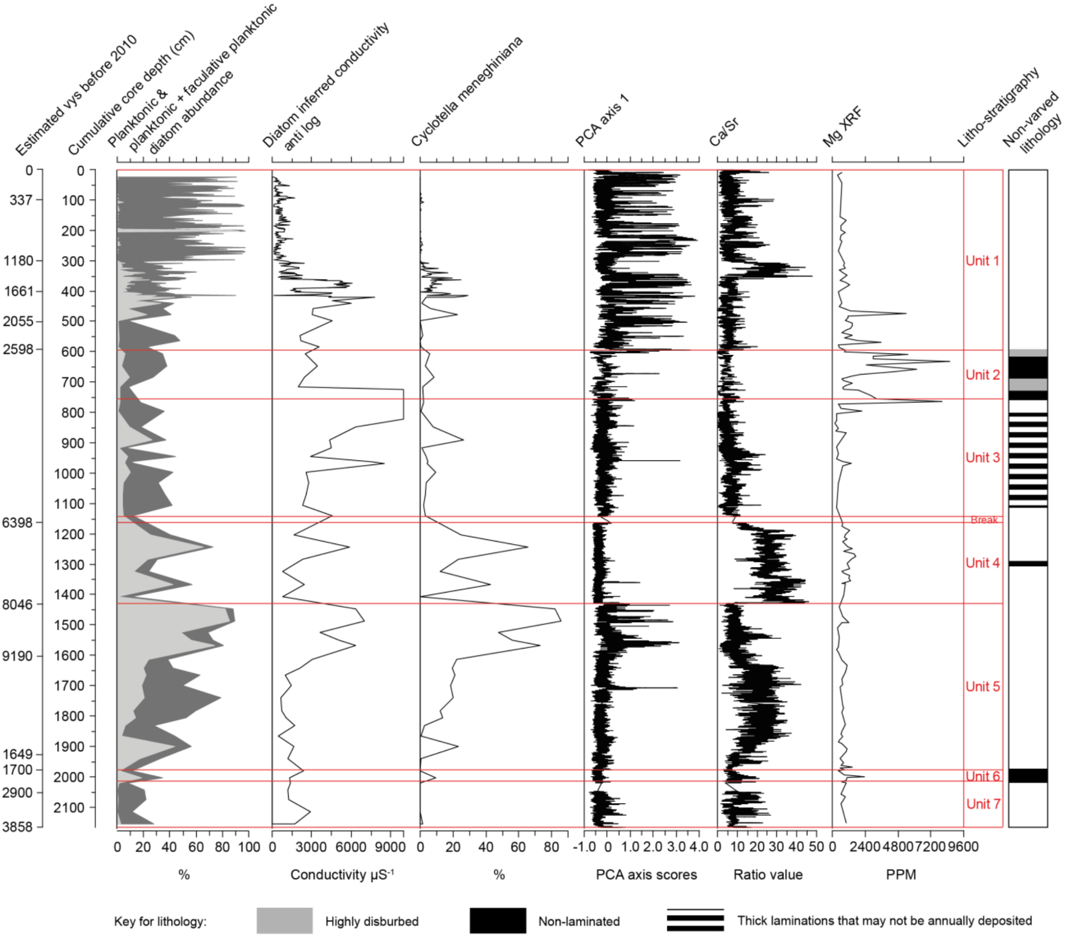


Figure 5.15: NAR01/02 and NAR10 diatom stratigraphy presented alongside PCA axis 1, Ca/Sr and Mg from NAR10. Diatom inferred conductivity and the planktonic & planktonic + faculative planktonic diatom abundance have been used to explore the whole Nar Lake diatom dataset. *Cyclotella meneghiniana* species has been included to highlight correspondence to other proxies. All data presented with lithostratigraphic units and non-varved lithology.

The relationship between diatoms and elemental geochemistry is not ‘strong’ but may be significant in terms of understanding and corroborating changes in the lake’s history. Most noticeable is the possible link between *Cyclotella meneghiniana* species and PCA axis1 (figure 5.15). Whilst the records are not similar throughout the whole core stratigraphy, it seems that increases in PCA axis values, which reflect increased detrital influx in to the lake, often coincide with increases in *Cyclotella meneghiniana* abundance. This is clearest during sub-unit 5a (1606.2-1428.2cm) and the first half of unit 1 (592.7-340cm), and may imply that nutrient changes and other limnological changes driven by increased clastic input into the lake are advantageous for the growth of *Cyclotella meneghiniana* populations. The sedimentary record may therefore also preserve seasonal biological responses corresponding to terrigenous summer/autumn fluxes as it is apparent in the sediment stratigraphy that clastic bands are most prevalent between the summer and autumn sub-laminae.

Although some sub-units seem to suggest a correspondence between PCA axis 1 and *Cyclotella meneghiniana* abundance, there are parts of the Nar core sequence where the relationship is inversed, such as during unit 4 (1428.2-1161.2cm, 8046-6398 vys. B.P.) and part of unit 1 (340-0-cm, 0-1394 vys. B.P.). Unit 4 suggests high *Cyclotella meneghiniana* populations during minimal detrital input and the base of unit 1 suggests low *Cyclotella meneghiniana* populations during heightened and variable clastic influx. Deciphering why the relationship between the two proxies is non-stationary would require further work but changes in source material, nutrient loading relating to human-land use practices, climate-related variables and limnological conditions may explain why the relationship is complex.

Although it has already been suggested that the planktonic + facultative planktonic record can be deceptive, the fact that it relates closely to the Ca/Sr ratio in places suggests that, at least in part, it is representative of changing lake status. A prevalence of benthic type (bottom dwelling) diatoms is encouraged by shallow water conditions which increase the amount of oxygen and light reaching the lake bed and allow for greater colonisation of the lake bottom and near shore zone (Cohen, 2003). The abundance of benthic and littoral type species therefore can be used as a proxy for past water level changes (Barker *et al.*, 1994) as higher numbers of benthic and lake edge diatoms would be expected during lower lake waters. Ca/Sr ratio can also be used as a palaeoclimate indictor to understand lake level and salinity changes, with lower ratio values reflecting lake shallowing and high salinity (Cohen, 2003). The abundance of bottom and littoral dwelling diatom species (% not planktonic or facultative planktonic (figure 5.15)) and Ca/Sr ratio should show a similar pattern to each other if both can be related to changes in lake level. On the whole, decreases in Ca/Sr correspond to increases in none planktonic and facultative planktonic diatom abundance (apart from sub-unit 5a). The similarity is most noticeable after unit 4 as both records suggest an abrupt and prolonged shift to lower lake stands and ultimately drier climatic conditions at this time.

5.5.3. Comparisons to the Nar Gölü pollen record

Pollen counts have become the basis for many palaeoenvironmental studies (Birks and Birks, 1980) and pollen collected from lake sediments are commonly used to develop interpretations of past climate conditions (e.g. Baruch and Bottema, 1999; Eastwood *et al.*, 2007b; Rossignol-Strick, 1999; Van Zeist and Woldring, 1978). Pollen recovered from lake cores can also be informative about past vegetation change, landscape development and human impact (England, 2006). Pollen was the main source of evidence for England (England, 2006) and England *et al.* (2008) who analysed the pollen profile for the Nar Gölü NAR01/02 sediment sequence and identified that human influence has been a major driver of vegetation change in the Nar Lake catchment for the last 1720 years. Four distinct ecological phases were recognised by England *et al.* (2008) documenting shifts from a dominate arboriculture phase during Roman and early Byzantine times (AD 300-670) to increasing intensification of dryland cereal cultivation from the late Ottoman Empire onwards (AD 1830-2000). A marked increase in tree pollen and a decrease in anthropogenic indicator species from AD 670-950 imply a period of agricultural abandonment and decline in human landscape impact related to a cultural decline phase.

Comparison of the NAR01/02 pollen changes with the NAR10 geochemical record is only possible for the top 1720 years as pollen investigation of the NAR10 sediment sequence is not complete. The most significant shifts in the pollen record are tied heavily into anthropogenic factors and are characteristic of changes in human land-use practices. If the PCA axis 1 scores are related to landscape instability it may be possible to identify periods of extra detrital influx during times when pollen data suggests heightened landscape changes. High detrital influx is evident from ~520-340cm (c. 171 BC - AD 616) which coincides with inferred Hellenistic/Roman/early Byzantine agricultural production and low detrital input is evident from ~340-280cm (c. AD 616-914) which coincides with landscape abandonment and woodland regeneration. From 280cm towards present day, PCA axis 1 scores suggests fluctuations between high and low detrital input, with the top most ~40cm (AD 1930-present) corresponding to relativity high levels of clastic material input into the lake environment. Interestingly, this also coincides with the pollen story of agricultural intensification after AD 1830. Comparison of the pollen and geochemical data therefore may suggest a similar response to landscape use and human activity.

The fact that the Ca/Sr and PCA axis 1 proxy profiles can be reversed at certain times also points towards a possible climatic influence on both the geochemical and pollen records. During high Ca/Sr values from ~360-300cm (c. AD 550-832), and therefore increased regional moisture levels, there is overlap with inferred woodland regeneration in the pollen record. The offset in dates (AD 550-832 for Ca/Sr and AD 616-914 for PCA axis 1, and AD 670-950 for pollen) may suggest a slow response of vegetation to amelioration in climate and increased precipitation. This moist phase is also picked out in the isotope record (figure 5.14) (dated to 560-750 AD (Jones *et al.*, 2006)) so it is possible to assume some correspondence between Ca/Sr and the pollen data. Nevertheless, the lack of a climate signal in the NAR01/02 pollen analysis (England *et al.*, 2008), and a dating off-set implies that the human-land use signal may dominate in this case.

5.5.4. Summary of Nar Gölü multi-proxy comparisons

Comparisons to the Nar Gölü oxygen isotope, diatom and pollen records have shown there to be considerable similarity between the climatic and environmental history recorded between these proxies and the Nar Lake geochemical and sedimentary record. Shifts between wet and dry as recorded by $\delta^{18}O$ values are also seen in the Ca/Sr ratio and partially in the levels of TIC documented. Changes in detrital influx recorded by PCA axis 1 may be linked to the diatom species assemblage as increases in *Cyclotella meneghiniana* can correspond to greater clastic input. Lake level variation as recorded in Mg, Ca/Sr and diatom abundance proxies highlight increasing salinity and shallowing of lake waters from the mid-Holocene. Comparisons between pollen data and PCA axis 1 scores show considerable similarity in the timing and length of inferred land-use practices and detrital influx variations suggesting a possible link between clastic indicators and human presence. However, this interpretation remains sceptical at present given a similar correspondence between the pollen record and Ca/Sr inferred water availability at times.

Variability in the Nar records appears replicated between proxies and this substantiates environmental and climatic reconstructions made and gives credit to the palaeo-limnological story. It highlights the importance of relying on multiple proxies from the same core to build up a more accurate picture of change. Especially where proxy relationships are non-stationary and reliance on only one parameter may portray an inaccurate picture of change. This is seen in the Nar record for instance where TIC and oxygen isotopes may not be responding in parallel to lake alterations. Ultimately, the different proxy records relate to a range of factors but the fact that both abiotic and biotic indicators are often synchronous suggests records are complimentary in their ability to reconstruct palaeolimnological changes.

To make reconstructions from the Nar Lake geochemical and sedimentary records more credible, it is also useful to identify differences and parallels to other multi-proxy studies which document change at similar spatial and temporal scales. This will be attempted in the following section.

5.6. Comparisons with Eastern Mediterranean palaeo-climatic archives

5.6.1. Comparisons with Eastern Mediterranean archives, an overview

Itrax derived XRF geochemical data (chapter 4), sediment variability (chapter 4) and comparisons with other Nar Lake data (this chapter) suggest that the NAR10 record is influenced, at least in part, by shifts in palaeoclimate, which in turn result in shifting hydrological conditions. The Ca/Sr and the Mg profiles record principally shifts between low and high lake level, saline and non-saline conditions driven largely by changes in precipitation and evaporation. The first PCA axis and associated detrital elements may also relate to changes in catchment moisture balance when not aligned with human driven catchment disturbance. These selected proxies suggest that there have been wide variations in the amount of moisture available within the Nar Lake system over the last ~14,000 years with periods of increased aridity occurring mainly from ~6300 vys ago. The period preceding ~6300 vys. B.P. is associated with a much wetter climate state in general but is punctuated by drier episodes between ca. 12900-11700 cal. yrs. B.P. and c. 9190-8046 vys. B.P.

Comparison of the Nar Gölü palaeo-records with other regionally relevant datasets may show if the shifts witnessed from the NAR10 material occur at the same time, and to the same degree, as the climatic changes suggest by other proxy records. Identifying where parallels may exist and where records diverge could highlight the unique aspects of the Nar geochemical record and outline changes that are localised to the Nar setting, i.e. changes relating to non-climatic factors.

Türkeş and others (Türkeş and Erlat, 2003; Türkeş *et al.*, 2009) show that there is a strong regional signal to precipitation and temperature patterns across Turkey and define changes in present day climate by statistically selected regional groupings. If it is assumed that these regional relationships existed in the past then palaeo-records from the same regional group should respond to the same variation in past climate behaviour. With this in mind, Nar Lake proxies have firstly been compared to proxies from Eski Acıgöl and Tecer Lake which are situated within the same Central Anatolian climatic region as Nar Lake (the Continental Central Anatolia zone (CCAN)) (figure 5.16), and may therefore show very similar climate histories to those discussed in this thesis. The Nar Lake data have also been compared to other key Eastern Mediterranean palaeo-archives (figure 5.16) and where possible to highly-resolved datasets as these are precisely dated and relate more closely to the sampling resolution used in this study. The Eastern Mediterranean offers a range of rich and high-quality archives, across different spatial and temporal scales, making it possible to shed light on the wider climatic aspects of the Nar Lake geochemical record and can be used to support inferences made regarding past climate shifts.

Figure 5.16: Geographical distribution of sites discussed in text and in relation to the Continental Central Anatolia climate zone (CCAN). References for each site can be found in-text. 1. Nar Gölü (Lake), 2. Eski Acıgöl, 3. Tecer Gölü (Lake), 4. Gölhisar, 5. Van, 6. Soreq Cave, 7. Sofular Cave.

5.6.2. Nar Gölü and regional climate patterns

5.6.2.1. Comparison to the Eski Acıgöl proxy records

It is advantageous that Nar volcanic crater-lake is situated in close proximity to another former crater-lake which lies within an old volcanic caldera, named Eski Acıgöl (1270masl: 38°33'01''N, 34°32'41''E) (Roberts *et al.*, 2001). Eski Acıgöl crater-lake is also partially annually laminated prior to c.6500 cal. yrs. B.P where the lithology switches to mainly non-laminated silts. The similarities with Nar Gölü in terms of the ability to date by annual layers and in terms of location make Eski Acıgöl a good site to contrast to the Nar Lake record as both should record similar climate histories.

The record from Eski Acıgöl (Jones *et al.*, 2007; Roberts *et al.*, 2001; Woldring and Bottema, 2001) (figures 5.16 & 5.17) shows a dominance of planktonic diatoms and the presence of laminated silts for part of the core sequence dating to >16000 to c.12900 cal. yrs. B.P. suggesting that deep water conditions prevailed in the crater-lake at this time, as is observed in the Nar record between ca.13600 to 12900vys. B.P. (although dating remains uncertain here). Both records reveal stepwise changes likely driven by changes in precipitation and temperature for the Glacial to Interglacial transition. It is likely that both lakes experienced similar climatic conditions during the Late Pleistocene due to their proximity to each other and that variation in sedimentary characteristics between archives is the result of lake individualities alone.

The end of the Pleistocene is marked by a dramatic shift to drier and cooler conditions, with this change being synchronous at both Nar and Eski Lakes (ca.12900-11700 cal. yrs. B.P.) (figure 5.17) Lows in Ca/Sr and organics at Nar, and positive oxygen isotope values and low tree pollen at Eski reveal a clear shift to dry and evaporative conditions, and therefore lower lake stands. This event, recorded at both sites, likely relates to the Younger Dryas cooling event which disturbed Northern Hemisphere climate between approximately 12900-11700 yrs. B.P. (Alley, 2000; Bakke *et al.*, 2009). The transition into the Holocene sees another dramatic shift in climate at both Nar and Eski (figure 5.17), with proxies responding to increases in effective moisture balance. The early Holocene at Eski Acıgöl shows a slow increase in arboreal pollen as a response to a more favourable water balance and relatively negative isotopic values. At Nar, this change is discernible from high Ca/Sr values and low Fe/Mn values, both indicative of deep fresh waters, and is complimented by high Zr/Rb values, indicative of finer grained sediments and deposition during more humid conditions.

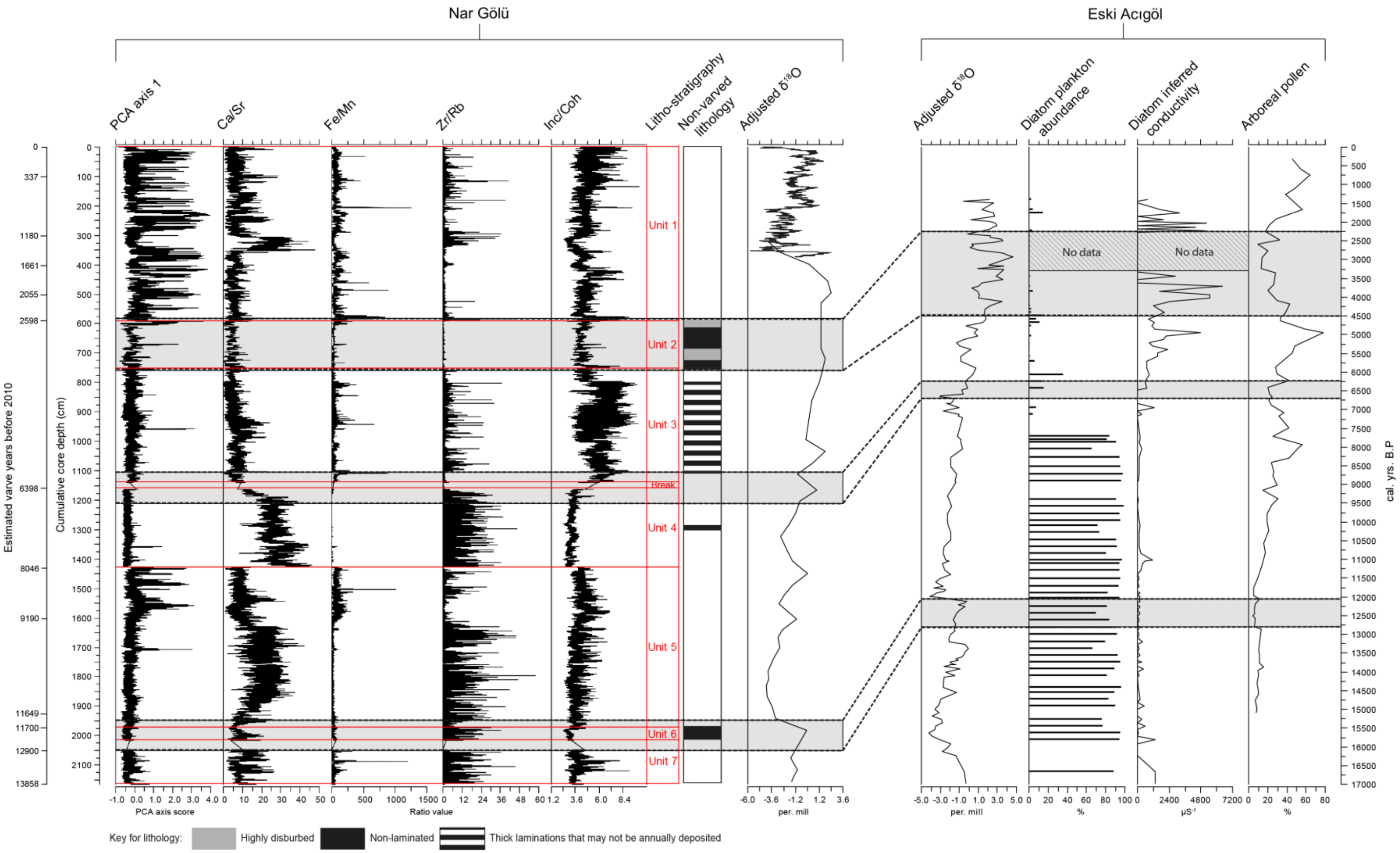


Figure 5.17: Comparative proxy data from crater-lakes Nar Gölü and Eski Acıgöl. Comparing PCA axis 1 (detrital influx indicator), Ca/Sr (moisture indicator), Fe/Mn (redox indicator), Zr/Rb (grain-size indicator) and Inc/Coh (organic content indicator) data from Nar Lake to δ^{18}O (moisture indicator), diatom plankton abundance (lake level indicator) and arboreal pollen (mainly moisture indicator) data from Eski Acıgöl to understand past hydro-climatic regimes.

The record at Nar indicates a major change in lake status around 6500-6000 vys. B.P., which is highlighted by a decrease in Ca/Sr, and is suggestive of a shift to drier climatic conditions and a retreat of lake waters (figure 5.17). Comparatively, the Eski Acıgöl record also shows a shift towards drier climatic conditions between ca.7500-6250 yrs. B.P., which is evidenced most clearly by a decrease in planktonic diatom species, a fall in tree pollen (partly climate driven) (figure 5.17), increase in salinity and the cessation of laminations. The oxygen isotope record at Eski Acıgöl for part of this period (ca.7150-6500 cal. yrs. B.P.) suggests wet conditions and matches more closely to the high Ca/Sr values, and therefore higher moisture availability recorded at Nar Lake from ca. 8046-6500 vys. B.P. (figure 5.17). Whilst contradictory in nature, the proxy records at Eski as a whole have been interpreted to represent a period of drier hydro-climate and lake shallowing, as have the records at Nar Lake after 6500 vys. B.P. Both records show that by 6500 cal. yrs. B.P., regional moisture levels begin to reduce with lake waters receding in response.

Extreme arid conditions were established at Eski Lake by 4500 cal. yrs. B.P., with the driest period documented between 3250-2250 cal. yrs. B.P. as highlighted by the complete absence of diatom remains. This story is not too dissimilar to the Nar Lake record which shows the driest conditions during sedimentary unit 2, estimated to date to ca. 4500/3500-2589 vys. B.P. The two crater-lake records are therefore in agreement that the hydro-climate of central Anatolia altered significantly during the mid-Holocene from a relatively substantial water surplus to increased aridity. Drier climatic conditions were manifested in significantly altered $\delta^{18}O$ values, increased salinity and the absence of varve formation at both sites, highlighting the huge impact the drier situation had on lake status and regional water balance.

The proxy data from Nar Lake and Eski Acıgöl, in combination, provide reasonable evidence to suggest that the early Holocene experienced a very different climate regime to the later Holocene, and in comparison to present day. Climate became progressively drier as precipitation levels fell and evaporation increased. Drought frequencies would have risen and water resources would have shrunk in response, providing greatly diminished moisture levels after 6500 yrs. B.P.

5.6.2.2. Comparison to the Tecer Lake proxy records

The mineralogy and grain size distribution of sediments from Tecer Lake provide another set of proxy records to compare to the Nar Lake data. Tecer Lake (figure 5.16) sits to the north-east of Nar Gölü (1393msal: 39°25’52.80’’N, 37°05’00.79’’E) (Kuzucuoğlu *et al.*, 2011) situated within the Sivas basin at the foot of Tecer Dağ. This lake site makes a suitable comparison to the Nar geochemical record because laboratory analyses have focused on very similar lines of evidence to those investigated within this study including changes in total carbon and carbonate production. The Tecer Lake chronology is based on 13 AMS dates and is not varved like Nar and Eski Lakes and the sediment record only spans the last 6000 years of the Holocene (Kuzucuoğlu *et al.*, 2011).

In Tecer, climate conditions between 5850 and 5250 cal. yrs. B.P. are inferred as humid and supposedly relate to enhanced winter-rainfall levels. It may be possible that the mid-Holocene drying trend at Nar Lake is punctuated sometime around 5800-5300 vys. B.P. by a wetting phase as identified by slightly heightened Ca/Sr but unfortunately the dating inaccuracies for this part of the Nar core sequence make it impossible to be certain as to the timing of this shift.

By 5000 cal. yrs. B.P., the Tecer Lake record shows increasingly depleted humidity and increasing dryness. A rise in gypsum and a high sand input are suggested to represent a period of lake level drop and soil instability. Increasing aridity and low lake levels are also inferred at Nar for this time period, with arid conditions worsening by ca. 4000 vys. B.P. At Tecer Lake, worsening aridity may have culminated in what is assumed to be a long lasting drought event starting around 4300 cal. yrs. B.P. shown by a hiatus in sedimentation and a low sedimentation rate. From 3850-2800 cal. yrs. B.P., lake levels are still inferred as shallow at Tecer Lake but climatic conditions alternate between wet and dry whilst at Nar this period remains very arid and there are no indications of significant wet phases between ca.4500-2600 vys. B.P. The intensity of drought at Nar Lake could relate to its sensitivity to evaporative conditions and position in relation to prevailing air masses.

During the last 2000 years, the Tecer Lake record highlights an acceleration of alternations between wet and dry. These variations compared to the Nar 2001 and 2002 isotope data (Kuzucuoğlu *et al.*, 2011) are only similar at some points in time, particularly during the Roman climatic optimum (ca. 2020-1450 cal. yrs. B.P.) and the Medieval Climate Anomaly (ca. 1130-820 cal. yrs. B.P.). As the article by Kuzucuoglu *et al.* (2011) goes into a lot of detail about how the Tecer and Nar records correspond for the late Holocene, little discussion is needed here but a point to raise is that higher variability between wet and dry phases are evidenced at both sites for the last 2000 years. These oscillations in climate characterise the later Holocene phase and contrast significantly with the rest of the Holocene.

5.6.3. Nar Lake and Eastern Mediterranean comparisons

The geochemical record from Nar Gölü may be influenced by both climatic and non-climatic factors at the local and regional scale. It is important to investigate any problems that may persist in the climate history documented from the Nar Gölü geochemical record by investigating the NAR10 sequence alongside other well-documented climate reconstructions from the Eastern Mediterranean region. Comparisons have been made with palaeoclimate records from Eastern Mediterranean sites to identify how similar the Nar sequence is to other region-wide proxy reconstructions. For the purpose of this comparative exercise, oxygen isotope records from three sites are used. Two are lake sites situated within Turkey (Gölhisar and Van) whilst the other is a cave site and speleothem record from Israel (Soreq) (figure 5.16). A carbon isotope record from another cave site in Turkey (Sofular) (figure 5.16) has also used for comparison purposes. These four records were selected for because of their close localities to Nar Lake, their high-resolution, their dating accuracy and their reliability at recording historical shifts in regional effective moisture availability.

Stable isotope analysis of lacustrine authigenic calcites from Gölhisar Gölü documents past climatic change through the Holocene for southwest Turkey. The $\delta^{18}O$ record from Lake Gölhisar (930 m.a.s.l: 37°8'N, 29°36'E) (Eastwood *et al.*, 2007a; Eastwood *et al.*, 1998a; Eastwood *et al.*, 1999; Jones *et al.*, 2002) (figure 5.18) shows a significantly wet early Holocene from ca.10150 to 8900 cal. yrs. B.P. For most of the mid-Holocene at Gölhisar (8900-6750 and 4700-3700 cal. yrs. B.P.), isotope-inferred water balance suggests generally decreased precipitation and reduced moisture availability but with large-scale switches in precipitation-evaporation balance. For the upper part of the core sequence (post 3700 cal. yrs. B.P. to present day) the isotope proxy record suggests a period of relative hydro-climate stability and principally dry climatic conditions. Wetter conditions persisted during Classical and Byzantine times (c. 2250-1600 cal. yrs. B.P.) though, punctuating a period of sustained aridity.

The oxygen isotope record from Gölhisar records a similar climate history at times to that witnessed at Nar Lake. The most noticeable similarities are witnessed during the early Holocene and during the late Holocene. The wet early Holocene documented between ca.11225 and 9400 cal. yrs. B.P. at Gölhisar is also evidenced at Nar Lake by substantially increased Ca/Sr values from 1890-1625cm (estimated to date between ca.11214 to 9292 cal. yrs. B.P.). The partial difference in timing may be due to differences between the estimated Nar varve age model and the Gölhisar radiocarbon dated record, which both contain dating errors. The oldest radiocarbon 14 date for Gölhisar is also only 9522 cal. yrs. B.P. which means that dates have been extrapolated beyond this adding further to the dating uncertainties. The close similarity in end date (~9300 cal. yrs. B.P.) for a sustained wet period though gives confidence that the timing of events is a least replicable along parts of the core sequence and suggests a clear climate shift from wet to drier around 9300 years ago. Another period of higher moisture availability is seen in the Nar record from 375-290cm (estimated to date between ca. 1552-1132 cal. yrs. B.P.), which is not too dissimilar in nature from a wet phase identified at Gölhisar from 2250-1600 cal. yrs. B.P. Again the similarity in the isotope curves between the two sites suggest that this event is the same but chronological discrepancies suggests that the shifts to negative isotope values may also relate to different climate histories.

The biggest difference between the Nar and Gölhisar records is that the Nar data suggest a major transition to arid conditions around 6500 years ago, whereas the $\delta^{18}O$ record from Gölhisar documents a transition to extremely humid conditions and high precipitation levels at this time. For this mid-Holocene phase, the climate histories at the two sites are remarkably different and may relate to the influences from different teleconnection systems. Spatial variation in climate systems would have generated differences in the timing and magnitude of precipitation and temperature changes, and thus climate oscillations may not have coincided with each other at different sites. It has been suggested by Kuzucuoğlu *et al.* (2011) that humid conditions in the Eastern Mediterranean region, for this time, are driven primarily by increased winter precipitation levels whilst summers became drier. The increased seasonality is not evidenced at Nar as very thin and indistinct winter varve deposits suggest a possible reduction in winter precipitation levels.

Lake Van in Eastern Anatolia (figure 5.16) (Landmann *et al.*, 1996a; Lemcke and Sturm, 1996; Litt *et al.*, 2009; Reimer *et al.*, 2009; Van Zeist and Woldring, 1978; Wick *et al.*, 2003) is one of the deepest lakes in the world (460m) and is much larger than Nar Lake (Roberts *et al.*, 2001). It is however situated at a similar altitude (1648 m.a.s.l), responds to similar climate patterns during modern times and is continuously laminated throughout the Late Pleistocene and Holocene (Wick *et al.*, 2003) making it suitable for comparison.

A non-floating varve record for Lake Van covering the last 14,000 years (Landmann *et al.*, 1996b; Lemcke, 1996), and recently revised by Litt *et al.* (2009), provides a unique opportunity to relate the Nar record to proxy studies with a very good annual time scale.

From ca.12750-11300 cal. yrs. B.P., the oxygen isotope record from Lake Van (figure 5.18) shows an extremely pronounced dry phase which likely relates to the Younger Dryas cooling event. The most positive isotope values are centred around 11650 cal. yrs. B.P., compared to estimated ages of ca.11500 cal. yrs. B.P. for other regional records (Roberts *et al.*, 2001). This arid phase at Lake Van is not too dissimilar in terms of timing from the Nar record which documents extreme drying from ca.12900-11700 cal. yrs. B.P., with the end of the pronounced arid period placed at 11700 varve years B.P.

Similarities between the Van and Nar datasets are also witnessed during the period following the Younger Dryas cooling event. A shift towards more negative isotopic values around 11000 cal. yrs. B.P. at Van Lake suggests increasing availability of water and an associated rise in precipitation levels, which is sustained until sometime after 10000 cal. yrs. B.P. Sustained and high levels of water availability are also documented at Nar Lake for this time period identified from Ca/Sr increases and a shift to negative isotopic values (figure 5.18). In this case, the timing of increased moisture levels at both sites is reasonably similar with wet conditions dated from ca.11214 to 9292 cal. yrs. B.P. at Nar. Whilst the dates may be marginally difference, the resemblance between the two records gives confidence that the climatic interpretation of the geochemical record at Nar is a least in part substantiated by proxies from other sites within Turkey.

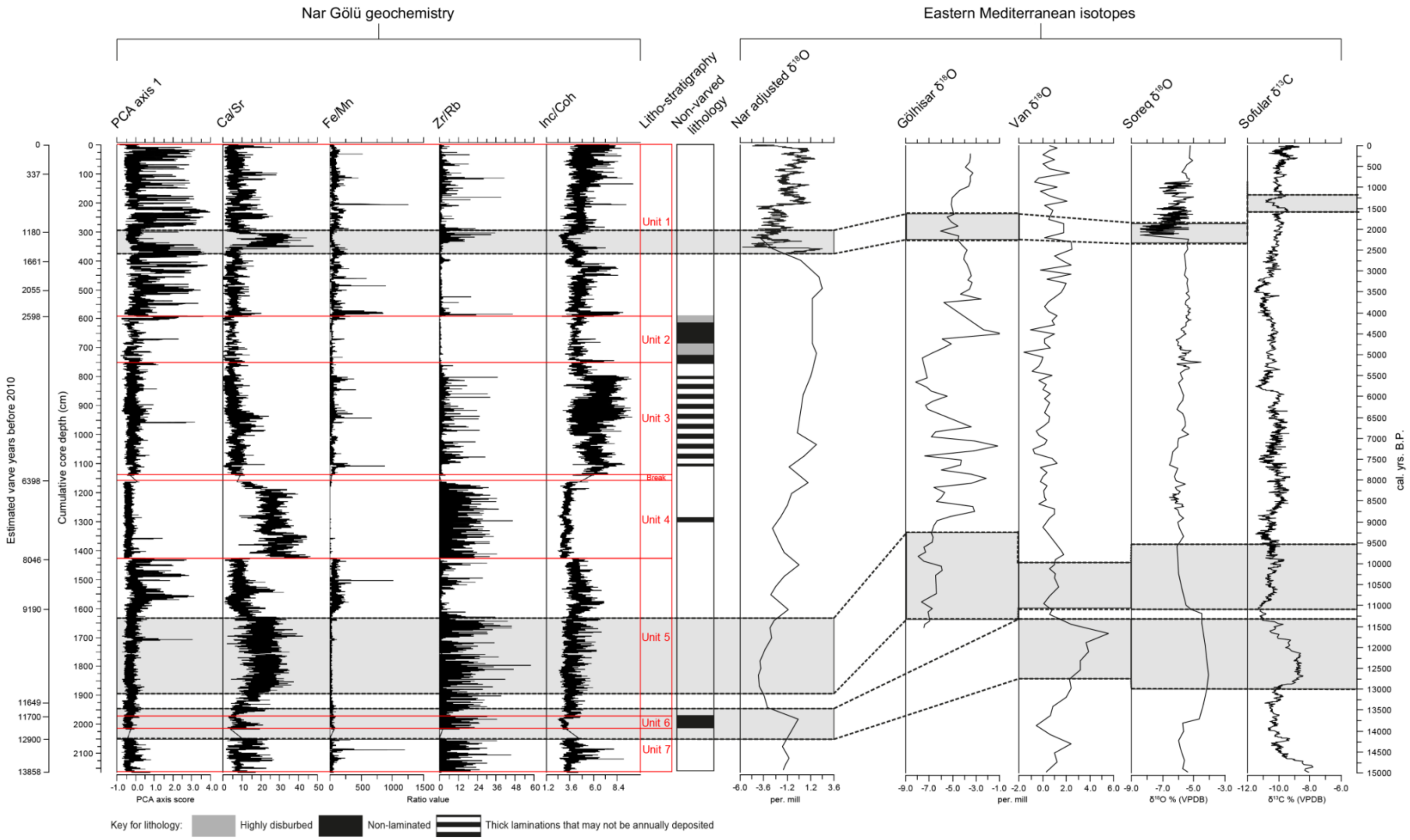


Figure 5.18: Comparative proxy data from Nar Lake and oxygen isotope data from other Eastern Mediterranean climate records. For sources see text. $\delta^{18}O$ profiles chart shifts between wet (more negative values) and dry (more positive values) climate states, and may signify changes in effective moisture levels.

For the mid and late-Holocene, the records from Nar and Van Lakes are not in as close agreement as in the Pleistocene/Holocene transition and early Holocene mainly due to the relative stability of the Van isotope record which fluctuates only subtly along the core sequence. This relates to the fact that Van's size prevents it from establishing very low lake levels so that its isotopic values vary significantly less than a crater-lake like Nar where lake waters can become highly reduced. The gradual shift to more positive isotope values during the last 4500 years though imply that Lake Van also experienced increasing aridity in the later Holocene as Nar does.

The speleothem carbon and oxygen isotope record from Soreq Cave (31°45.35'N, 35°1.35'E) (figure 5.16) (Bar-Matthews and Ayalon, 2011; Bar-Matthews *et al.*, 1997; Bar-Matthews *et al.*, 1998, 2004; Bar-Matthews *et al.*, 1999; Matthews *et al.*, 2000; Orland *et al.*, 2012; Orland *et al.*, 2009) offers another high resolution climate record in the Eastern Mediterranean and offers an alternative climate history for the region. The period from ca. 15000-11000 cal. yrs. B.P. saw speleothem δ^{18}O values drop progressively (figure 5.18), supposedly correlated to increases in precipitation. This period is punctuated by the Younger Dryas cooling event, with the driest episode documented between ca. 13000-11300 cal. yrs. B.P. (figure 5.18) (but initiated around 13750 cal. yrs. B.P.). The speleothem record for ca. 11000-9500 cal. yrs. B.P. has the lowest δ^{18}O on record and signifies a period of sustained wetting (figure 5.18). From ca. 7000-1000 cal. yrs. B.P. conditions become closer to those of today in Israel with many low amplitude oscillations and less water availability. An excursion to wet conditions is evidence in the sub-annual resolution data available for ca. 2300-1800 cal. yrs. B.P. (figure 5.18).

The Soreq record highlights three key periods of change which are also identifiable in the Nar Lake sequence. These are the Younger Dryas arid phase, the moist and humid early Holocene and the punctuated wet phase of the late Holocene (figure 5.18). There are also similarities between the two records with Nar Lake data showing an arid phase dating to ca.12900-11700 cal. yrs. B.P. and an early Holocene moist phase dating to ca.11214 to 9929 cal. yrs. B.P. The moist phase during the late Holocene is not so well matched in terms of dating though which Nar Lake data details as persisting from ca.1552-1132 cal. yrs. B.P. This period has a later start date at Nar then it does at both Gölhisar and Soreq which may suggest that it took a long time for Nar Lake waters to respond to increasing moisture balance, or that climate changes were out of phase between central Anatolia, south-west Anatolia (Gölhisar) and the southern Levant (Soreq). Given that the differences in timing for a pronounced wet phase are reasonably large, Nar Lake's locality within central Anatolia likely played a large role in its climate history for this time.

In contrast to the above three records, the speleothem record from Sofular cave (41°25'N, 31°57'E; 440masl) (figure 5.16) (Fleitmann *et al.*, 2009; Göktürk *et al.*, 2011) forms a good comparison to the Nar records because its proximity to the Black Sea coast produces different climatic characteristics to those experienced in central Anatolia, noticeably a lack of dry summers. The question therefore is whether the climates of these two areas of Turkey have ever been coupled and therefore whether the influence of Black Sea climate has been weakened, and thus influence from the Atlantic has been stronger.

The Younger Dryas interstadial is clearly reflected in the Sofular record (figure 5.18), here depicted by higher $\delta^{13}C$ values. $\delta^{13}C$ in stalagmites is often related to changes in vegetation and therefore levels of precipitation and changes in available moisture. Higher $\delta^{13}C$ values and therefore drier conditions between ca. 13000-11300 cal. yrs. B.P. indicate a period of decreased moisture availability and is surprisingly consistent with the Nar record of change, especially considering it would be expected to see a lag between vegetation response and changes in precipitation. A humid, wet summer period was established soon after the Younger Dryas as $\delta^{13}C$ values return to negative. It has been suggested by Göktürk *et al.* (2011) that $\delta^{13}C$ values for this period do not support the idea of a humid period after ca.11000 years ago but visually there does appear to be subtle changes that indicate a prolonged wet period. The mid-Holocene is represented by fluctuating conditions, with values generally indicating similar precipitation levels to those seen during the early Holocene. The late Holocene is punctuated by a short wet phase from ca. 1600-1200 cal. yrs. B.P.

Once again there are clear similarities to the Nar record, principally a strong arid Younger Dryas period and a moist and humid early Holocene. The short wet phase identified during the late Holocene is also noticeable in both records and dates to around the same period (ca. 1152-1132 cal. yrs. B.P. at Nar). It suggests that to some degree, these two sites were likely responding to similar climatic conditions but that during the mid-Holocene different processes were affecting the climate history recorded at Nar Lake compared to Sofular Cave. This is most evident in the Sofular Cave record at ca. 5750 cal. yrs. B.P. where $\delta^{13}C$ values suggest a shift towards wetter conditions until ca. 3250 cal. yrs. B.P. which is in direct opposition to the record from Nar which shows a drying trend at this time. This may suggest that during the mid-Holocene, a different climate state was being experienced within central Anatolia compared to some other parts of Turkey.

5.6.4. Summary of Eastern Mediterranean proxy comparisons

Comparisons made between the Nar geochemical data and other Eastern Mediterranean proxy records suggests that on the whole, the Nar Lake climate history can be replicated at other sites in the same region. This gives confidence in the interpretations given to the geochemical data and highlights interesting similarities across the region. Time periods which are most similar across the area are the Younger Dryas cooling event, the moist early Holocene and the period of abrupt wetting which punctuates a largely drier late Holocene. It is the mid-Holocene period which is recorded differently at each individual site, with the Sofular record for instance showing a very wet phase just as Nar is becoming extremely dry. Differences in the climate patterns witnessed may relate to local factors including lake morphology and different water chemistries but they may also relate to the influence from different teleconnection systems across the region. It is likely that Nar's unique location within central Anatolia, which is relatively protected by mountainous zones, renders it to respond differently to the influencing weather systems compared to other regions in Turkey. There are also spatial variations in the dominant forcing weather systems, which encourage regionally different humidity levels. Any contrasting climate histories are therefore likely explained by geographic specificities. The fact that there is also a large chronological uncertainty on mid-Holocene dates (from 6398-2589 cal. yrs. B.P.) at Nar Lake means that events and switches in climate cannot be well dated, thus making comparisons to other datasets imprecise. Comparisons made for the mid-Holocene period must by approached with caution as off-sets in the timing of climate changes may relate to dating inaccuracies only.

5.7. Chapter summary

The sedimentary and XRF derived geochemical records from Nar Gölü have provided various insights into changing lake status throughout the Late Pleistocene and Holocene, linked into climatic and/or environmental changes. Specific elemental components and ratios e.g. Ca/Sr have been useful in determining changes in moisture availability and lake condition, and changes in the surrounding Nar Lake catchment through, for example, Ti changes. The biggest driver of elemental change is clearly allochthonous material delivery to the lake; this is evidence by a strong PCA axis 1 which consists only of detrital indicators. Changes in carbonate mineralogy and precipitation are also important factors of elemental variation which appear to be driven by changes in water availability and biogenic activity. The Nar Gölü geochemical record therefore potentially provides detailed information about both climatic and environmental change.

Key interpretations from the Nar palaeo-record include a very pronounced and extremely arid Younger Dryas event between ca. 12900-11790 cal. yrs. B.P which is followed by a very moist and substantially wetter early Holocene phase which ends around 9292 cal. yrs. B.P. Following this wet period during sub-units 5b-d there is another pronounced dry phase, this time coinciding with increased erosional input during sub-unit 5a. The earlier mid-Holocene dating to around 8046-6393 cal. yrs. B.P. reveals heightened Ca/Sr values and very low Fe/Mn values which has been interpreted here as representing a period of even yearly rainfall and less seasonal variation in moisture availability. Low levels of Ti and Fe also suggests very little influence of catchment derived material at this time and therefore fairly pristine and clear lake waters can be envisaged. A change between 6500-6000 cal. yrs. B.P. to much lower Ca/Sr demonstrates a return to arid conditions. Optimum aridity is reached by unit 2 as high peaks in Mg and Sr suggest substitution of precipitated carbonate during drier lake conditions. From 2589 cal. yrs. B.P. until present day elemental profiles fluctuate greatly in relation to shifts between wet and dry. Of significance though is the control of geochemical variation by external forces as this top phase is dominated by detrital indicators like Ti.

In comparison to other Nar Lake proxy data, the changes evidenced in the geochemical and total carbon records match well. Suggestions that geochemical variability relates to switches between wet and dry conditions are substantiated by the Nar isotopic record. Changes in catchment material influxes are also confirmed by pollen and diatom data. The Nar Gölü palaeo-record presented here is also comparable to other regional records revealing that a wetter first half of the Holocene was replaced by a drier second half. Other periods of climatic variability such as a wet phase evident in the late Holocene are also identifiable in the Nar record and in regional comparisons. The similarities between datasets give confidence in the interpretations given to the geochemical data and highlights interesting similarities across the region and within the same lake core sequence.

6. The settlement history of Cappadocia

Results and discussion

6.1. Chapter introduction

This chapter describes systematic archaeological survey work conducted in Cappadocia, central Anatolia and collated by the author. The collation of survey data focuses on three large scale, multi-period surveys conducted in the selected region, including the Kaman-Kalehöyük Regional Survey in Kirşehir province (Mikami and Omura, 1991a; Omura, 1989-2008), the Central Anatolian Survey (CAS) in the southern Cappadocia Plains (Todd, 1998) and the Türkiye Arkeolojik Yerleşmeleri Project (TAY project) designed to build a chronological inventory of cultural heritage information for Turkey. Of the modern day provinces of Turkey, survey data were collected from the Kirşehir, Kayseri, Nevşehir, Aksaray, Niğde and Ankara (Şereflikoçhisar) provinces to encompass as much of the wider Cappadocia area as possible. Also included is a summary of the key excavated sites for the Cappadocia region to support survey data with information that potentially has stricter chronological certainty and a closer examination of settlement changes.

The primary objective of work presented here is to establish a picture of changing human occupation for the chosen Cappadocian provinces, to address objectives 4 and 5 of the thesis (chapter 1). These objectives target the accurate documentation of long-term settlement histories and analysis of artefactual research in the context of the Holocene. The use of survey data aimed to accomplish two tasks here: to capture spatial aspects of land use and the function of individual sites, and to look at habitation patterns over the longer term which is not possible from excavation data alone. Its results serve as a way of identifying change events associated with certain occupational time periods within which patterns of continuity and abandonment can be identified. Ultimately, it outlines the study of population dynamics and interactions between past people and their landscape with a specific time and regional frame. A focus at the landscape scale allows for information acquisition applicable to most human-climate-environment interactions and is a common unit of analysis to both the natural and human sciences (Crumley, 2000). Survey and excavation data presented are pertinent to subsequent chapters for comparisons with laboratory analyses and other archaeological archives.

6.2. Site survey data: limitations

Whilst archaeological excavation data can provide information about past behaviours in neat time windows, archaeological surveys are equally valuable because of their ability to document change over longer time spans and at greater spatial scales. Although providing unique insights into changes in human history over the *longue-durée*, it must be mentioned that survey data can provide only a basic understanding of changing settlement patterns and must thus be interpreted with some caution.

Limitations of site-based surveys are widely documented (Dunnell, 1992; Dunnell and Dancey, 1983; Foley, 1981; Thomas, 1975). The temporal resolution of survey results is in the order of centuries and is often a palimpsest of reconstructed events, leading to issues of contemporaneity. Combining archaeological survey and excavation data can improve our understanding of the way people used to live from these snapshots. Inferences from surveys are dependent on the type and accuracy of sample collection (Wandsnider and Camilli, 1992), and can be influenced by taphonomic histories and investigator bias. Nevertheless, spatial patterning of settlement data can still be a key source of information regarding past human behaviour and demography.

6.3. Definition of terms

Due to the recurring use of time-dependent nomenclature and special terms within this chapter, it is necessary to clarify the meaning of certain terminologies to avoid possible ambiguity and misinterpretation. The term **‘site’** is used here to mean the physical location of human activity. A site can be any size and range from a few individual objects to a structure with associated objects and finds. Site finds do not necessarily have to be primary deposits. The term **'settlement'** on the other hand is used to define and area where people lived. This could be permanent or temporary but must be a congregated space for population habitation. The use of the term **'settlement'**, for this purpose, does not include individual constructed features such as a monastery or areas of aggregated archaeological artefacts.

The periodization framework which will be used within this thesis is set out in table 6.1. The named periods help categorise data into defined blocks of time based upon common characteristics and promotes consistency in discussions.

Table 6.1: Table detailing the dates assigned to each time period addressed in this chapter. Dates are given in years BC/AD – before and after the beginning of Christian era respectively, as this is the standard system employed for discussing archaeological material in Turkey.

Time period	**Assigned date**	**Further information**
Pre-Neolithic (Pre-Neo)	Pre-8500 BC	Has no specific start date. It is likely that investigators e.g. Todd (1998) took this to principally mean Epipalaeolithic.
Neolithic (Neo)	8500-6000 BC	Encompasses two sub-phases: the Aceramic Neolithic (8500-7000 BC) and the Ceramic Neolithic (7000-6000 BC).
Chalcolithic (Chalco)	6000-3000 BC	Encompasses three sub-phases: the Early (6000-5500 BC), Middle (5500-4000 BC) and Late (4000-3000 BC) Chalcolithic.
Early Bronze Age (EBA)	3000-2000 BC	Encompasses three sub-phases: the EBA I (3000-2600 BC), EBA II (2600-2300 BC) and EBA III (2300-2000 BC). Also overlaps with the Assyrian Trade Colonies period (3000-1750 BC).

Middle Bronze Age (MBA)	2000-1450 BC	Includes Early Hittite occupations (2000-1750 BC) and the Old Hittite Kingdom (1750-1450).
Late Bronze Age (LBA)	1450-1200 BC	Hittite Empire (1450-1200 BC).
Iron Age (IA)	1200-331 BC	Encompasses three sub-phases: the Early (1200-900 BC), Middle (900-585 BC) and Late (585-332/331 BC) Iron Age. Also includes a Dark Age (1200-700 BC), Phrygian (900-585 BC) and Persian (585-332/331 BC) occupations.
Hellenistic and Roman (Hell & Rom)	331 BC – 395 AD	These two phases have been grouped together as it is hard to identify chronological changes in material for sites termed more generically as ‘Classical’.
‘Late’	585 BC – 395 AD	A period classification used during the Central Anatolian Survey (Todd, 1998) to assign sites to a phase encompassing the Late Iron Age, Hellenistic and Roman periods.
Roman-Byzantine (Rom-Byzan)	395-1071 AD	Consists mainly of Byzantine sites - yet due to dating issues some sites cannot be allotted solely to Roman or Byzantine phases and have therefore been classified together here.
Medieval-Modern (Med-Mod)	1071 AD - present	The period includes the dominant political changes of the time, including: Seljuk (1071-1299 AD) and Ottoman (1299-1923 AD), although the Ottoman Empire did not take hold here until the 15th century.

6.4. Settlement trends and patterns in Cappadocia

6.4.1. An overview of survey data collection

Site survey results collated from three major sources (I. Todd (1998), S. Omura (Mikami and Omura, 1991a) and TAY (http://tayproject.org)), recorded a total of 857 archaeological locations of which 578 can be classified as 'settlement' type sites. A synopsis of the changes in archaeological site numbers, according to individual time periods identified in the three surveys, can be seen in figure 6.1. There are however clear investigator biases related to classifying sites by time period; most authors preferring to document sites by typical and more general archaeological time period nomenclature like 'Early Bronze Age', whilst some, the Kaman-Kalehöyük survey in particular, prefer to document sites by very specific and localised chronologies. In this regard, the archaeological survey results have also been plotted in consolidated time periods (figure 6.2) to avoid totalling raw site counts by minor sub-divisions that are not comparable to other site surveys (which assigned survey material to more commonly used periodizations and archaeological terminology (Matthews and Glatz, 2009b)). Figure 6.2 also includes total raw site count data weighted by the duration of the associated time period to account for the differing temporal spans of the cultural and historical phases used for classification. A weighted count of archaeological sites thus provides an estimate of the numbers of sites occupied during one century at a particular point in time (Matthews and Glatz, 2009b).

Unfortunately, whilst some site size information could be retrieved, the discrepancies between values assigned by different investigators and the complete lack of data in other instances means that site data cannot be studied in terms of aggregated site area or magnitude. Due to the inherent problems with site size data, no attempt has been made to study the trends and patterns in size attributes through time. Where site numbers appear to decrease in the raw data, it has therefore been necessary to consider the potential impact of consolidation or agglomeration of smaller sites into larger sites on the total number of sites recorded, even if such data may not be obtainable.

6.4.2. Settlement trends and patterns

6.4.2.1. Raw site counts

Changes in site numbers for all periods identified in the Cappadocian surveys can be seen in figure 6.1. The overall pattern of change through time is not clear due to the large number of sub-divisions of phases, resulting in a highly fluctuating dataset. At the broad scale, Pre-Neolithic and Neolithic site numbers are relatively low (11 & 70 sites) but increased occupation of Cappadocia is observed from the Chalcolithic onwards. In comparison to other times, site numbers during the Chalcolithic (163 sites) are also moderately low but notably increase towards the end of the period and into the Early Bronze Age. The EBA experienced a significant peak in site numbers, totalling 340, with the EBA II period indicated as the most distinctive period of growth. Following the EBA, there is a 41% loss in occupational sites by the MBA (201 sites) and a further 52% loss in sites by the LBA (97 sites), revealing dramatically reduced site numbers by the end of the LBA. Most noticeable is the 220% increase in the number of sites thereafter. Site numbers throughout the Iron Age (310 sites) appear to rise, with the later Iron Age showing relatively high numbers in comparison to the early Iron Age as a result of Phrygian and Persian occupations. This change in the second half of the Iron Age is also documented by the sizable value recorded for ‘Late’ (195 sites) which encompasses final phase Iron Age sites. The higher values for ‘Late’, as well as for Hellenistic & Roman (Classical) times (187 sites) suggest that site numbers remained elevated for the periods succeeding the Iron Age. By Byzantine times, numbers begin to decrease again (97 sites), a pattern which continues throughout the Medieval, Seljuk and Ottoman periods (41, 2 & 16 sites respectively).

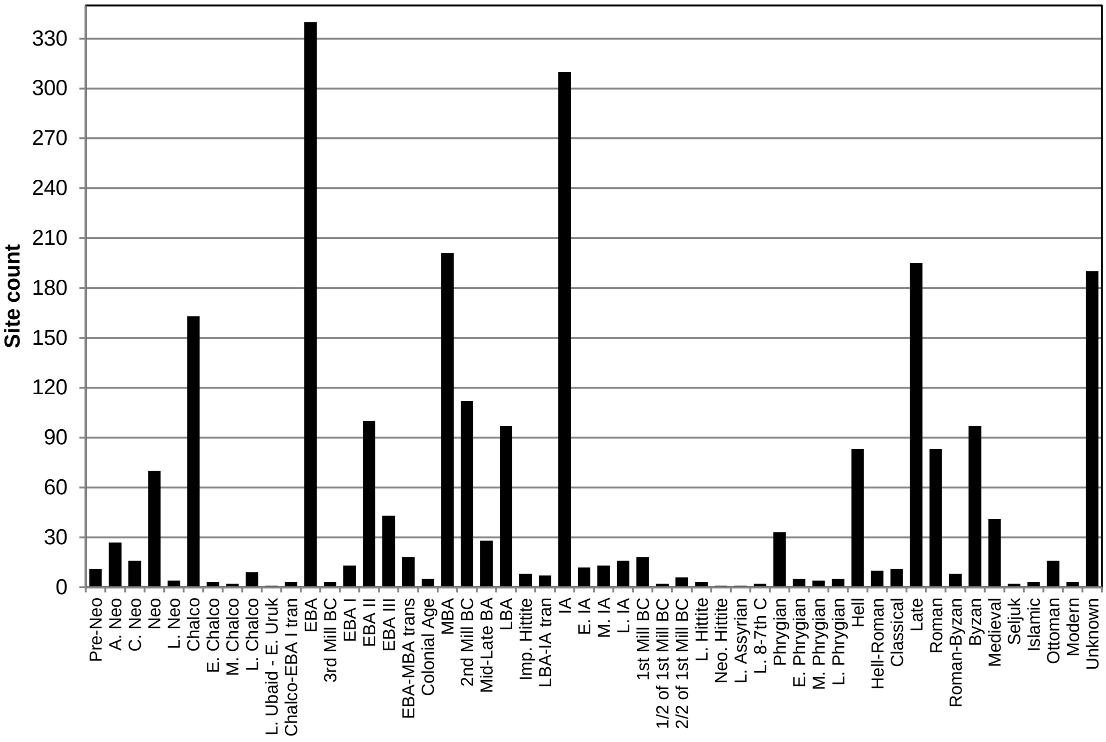


Figure 6.1: Raw archaeological site counts by phase and sub-division (all periods documented).

Unfortunately, more than 20% of survey sites have no date recorded (figure 6.1) and thus cannot be plotted by time period; most of these are tumuli sites but some are large settlement sites where chronologies are currently inaccurate and cannot be used with any confidence. The majority of settlement sites have been assigned to a specific time period and can be included within the histogram. See figure 6.5 for further details of sites with no known age.

6.4.2.2. Grouping of phases and adjusted raw counts

By documenting changes in site number using broader time periods (figure 6.2), the overall pattern of change can be seen with more ease, and the high variability of values witnessed using smaller time classifications becomes less of an issue. Through plotting site amounts in this way, the expansion in site numbers during the EBA (522 sites), the Iron Age (431 sites), and Hellenistic and Roman (382 sites) times becomes especially noticeable. The earliest major period of settlement increase and denser occupation of the Cappadocia region, as suggested by the raw count data, therefore seems to occur during the EBA. However, looking at the change in site numbers by weighted values (figure 6.2) we see a different pattern to that documented by the broad period groupings. It is in fact the MBA period which seems to have the highest density of occupation, with 62 sites recorded per century, closely followed by the EBA and Hellenistic & Roman periods (52 sites per century). Following weighting data transformation, the number of Iron Age sites becomes deflated and no longer represents the second largest phase of settlement expansion. The Iron Age records 49 sites per century, indicating a strong presence of sites at this time but on a less sizable scale than is suggested by the raw site count data.

In relation to neighbouring periods, the LBA shows a less than thriving settlement tally (112 sites) and generally reduced levels of occupation (figure 6.2). The Byzantine and post-Byzantine world evidence similarly diminished site numbers (105 and 65 sites respectively) (figure 6.2). The biggest declines in raw site number are therefore observed during the LBA and following the Arab invasions of the Eastern Roman Empire (7-9th centuries). Weighted counts for these time periods (Figure 6.2) portray a different picture however, with the LBA phase showing evidence for relatively substantial occupation (45 sites per century). The weighted count for the LBA brings occupation levels in line with those seen during the preceding MBA and proceeding IA periods. Site numbers in the Byzantine period are also partially inflated through the weighting method (16 sites per century) but comparatively remain reduced. The Medieval-Modern phase is represented by a reduction in weighted values (8 sites per century) from Byzantine times suggesting a substantial lack of site data for this time period.

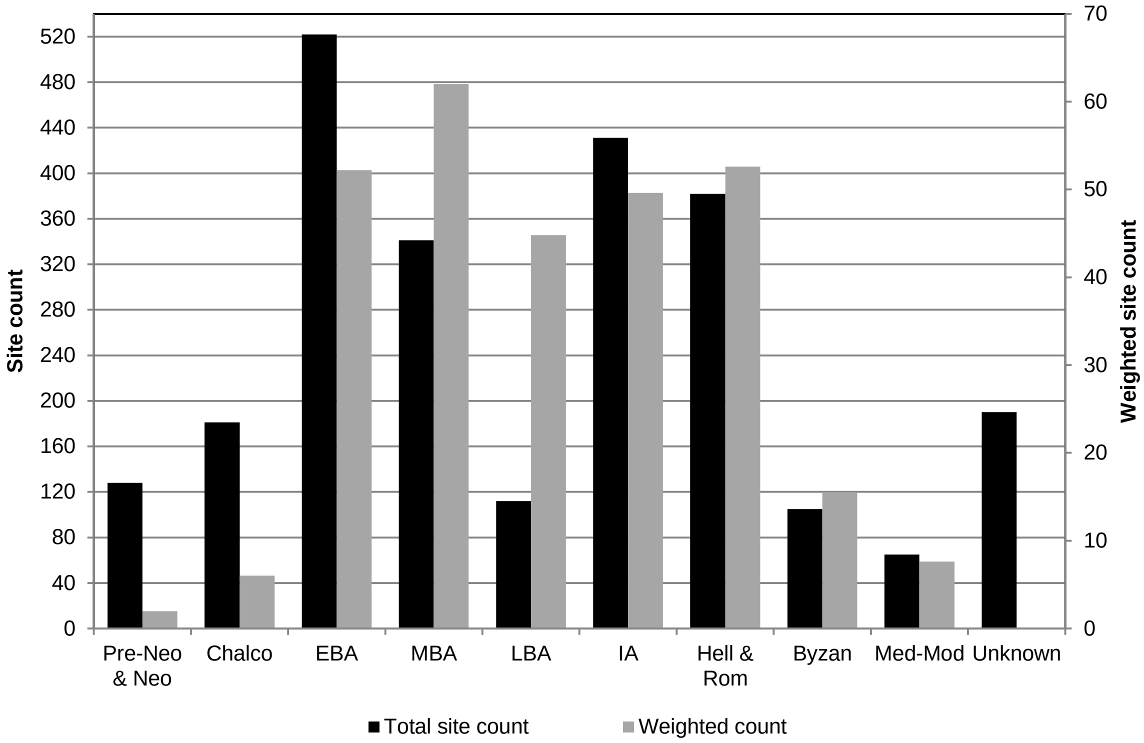


Figure 6.2: Long-term trends in site number for Cappadocia (raw site counts per combined phase and counts weighted by the temporal length of each chronological phase).

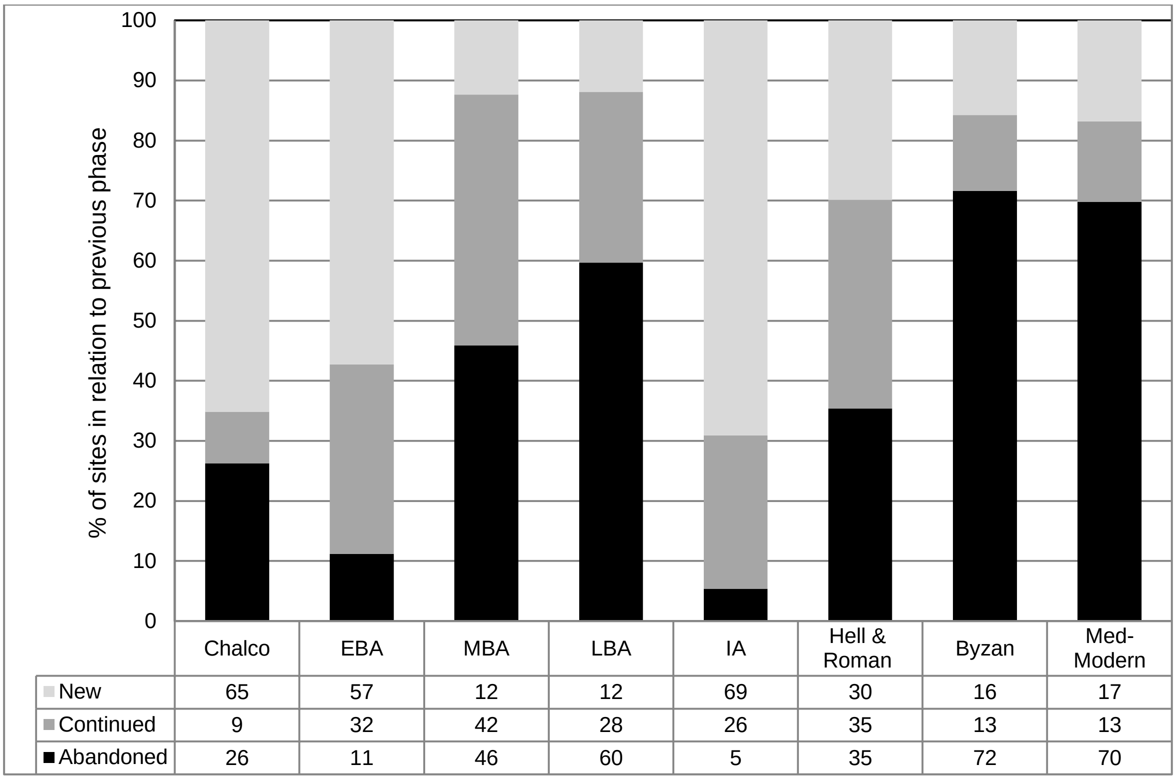
On the whole, the broad pattern of change identified using weighted counts (figure 6.2) shows increasing settlement occupation after the Chalcolithic period, which remains high until the end of the Roman period where site numbers begin to decline. This pattern of change is similarly reflected in the categorised data (figure 6.2). The biggest changes in settlement history and the most prolific occupation of the Cappadocian region are therefore indicated during the mid-late Holocene (~3000 BC – 647 AD).

6.4.2.3. Periods of abandonment and continuity

Plotting change in site numbers alone provides only a basic overview of the key fluctuations that occur between phases and it is virtually impossible to detect if changes are related to site abandonments, agglomerations, or other processes. By breaking down each periodic shift into levels of abandonment and continuity it becomes easier to identify the changes happening at each transition and how those changes are manifested in settlement preferences. Figure 6.3 highlights the extent to which sites are abandoned, occupation was sustained and new sites were established during a specific phase in relation to its previous period, calculated as a percentage difference.

The earliest form of substantial settlement in Cappadocia is witnessed during the Neolithic, as 117 sites have been recorded (figure 6.1). Following this early phase of occupation, settlement begins to increase significantly with many new sites forming. As indicated by figure 6.3, during the Chalcolithic, 65% of sites were documented as new establishments, 52% of which continued to be in existence during the EBA, a time which also saw another dramatic increase in the formation of new occupation localities (57% of sites were newly formed). The first biggest abandonment phase is observed in the MBA with a significant number of EBA sites not showing any evidence of MBA occupation (46% abandoned). Some new settlements are established but in far fewer number than had been seen previously. The MBA also witnesses some settlement continuity implying that the period cannot be defined solely by shifts in settlement organisation. The pattern of increased abandonment of sites continues throughout the LBA which sees a 60% reduction in site numbers from the period before. A clear change in settlement preferences occurs thereafter during the Iron Age as 69% of sites are new establishments, with very few LBA sites being abandoned.

Settlement continuity is a common trait for Cappadocia from the Iron Age into the Hellenistic and Roman periods. However, just as many sites are abandoned as are established in post Iron Age times suggesting that during this Classical cultural phase, settlement strategies are somewhat different from preceding periods as no single change event dominates. Following Roman dominance in Cappadocia, there appears to be a dramatic decrease and abandonment of sites. The first sign of this discontinuity is seen during Byzantine times (72% abandonment) but is further evidenced in the Medieval and Ottoman periods (further 70% abandonment). The apparent lack of settlement formation in Medieval and Ottoman times cannot be taken at face value due to the heavy focus of surveys on early occupation periods; this will be discussed in more detail shortly.



	Chalco	EBA	MBA	LBA	IA	Hell & Roman	Byzan	Med-Modern
▫ New	65	57	12	12	69	30	16	17
▪ Continued	9	32	42	28	26	35	13	13
■ Abandoned	26	11	46	60	5	35	72	70

Figure 6.3: Site continuity, establishment and abandonment for grouped phases.

On the whole, it seems as though there are many sites which have their roots embedded in previous periods but there are some significant temporal changes that reveal time specific settlement preferences or necessities, ultimately resulting in the demise or development of specific locations.

6.4.2.4. Settlement type and spatial patterning

Another interesting way of looking at settlement data is to look at time specific changes in site type to better understand how occupations are organised and how people envisaged their use of space and landscape. Figure 6.4 and figure 6.5 identify changes in site type by period and highlight the shifts in spatial patterning of sites through time at both the regional scale and around the Nar Lake study site. There are many different scales at which archaeological data can be compared to palaeoenvironmental data, including both regional and local scales, which is why spatial changes within Cappadocia and the Nar Lake area need to be identified here.

Neolithic settlement sites (figure 6.4) appear to be predominately mound or tell formations (locally known in Turkish as ‘Höyüks’), but other settlement types are recorded in smaller numbers. Atelier sites and/or obsidian and lithic scatters are also common which may indicate a preference for economically orientated locales during the Neolithic as these site types possibly suggest some form of quarrying activity or lithic production in the area. Neolithic sites on the whole are generally more dominant in southern Cappadocia, particularly in selected upland regions and on alluvial plains, and highlight the point that Neolithic occupations may have been selective in nature. Of importance are the proximity of Neolithic occupations (24 sites in total (table 6.2)) to the Nar Lake study site (figure 6.4) and the dominance of ateliers or ‘workshops’ within a 30 kilometre radius of the lake catchment. It is likely that Nar and the surrounding area formed a significant habitation spot and/or seasonal residence for Neolithic people linked to obsidian quarrying, as is evidenced in the Nenezi Dağ area (Carter *et al.*, 2006).

The Chalcolithic period (figure 6.4) in contrast sees an overall reduction in atelier sites and artefact scatters, and the establishment of many new höyük type sites. Some preference for other settlement types remain but the appearance of more mound sites is a strong characteristic of this time. Also noticeable is the occurrence of more sites to the north and around Tüz (Salt) Lake indicating the occupation of new spatial locations. Issues with investigator bias may have led to an under-representation of Neolithic sites in the north, and an under-representation of later sites in the south so this pattern of change may be an artefact of sampling strategy alone and not an indication of settlement patterning. The type of sites recorded in the vicinity of Nar Lake (figure 6.4) also changes during the Chalcolithic with much more emphasis on mound type sites and the establishment of ‘settlements’, although site numbers decrease (table 6.2). Workshop sites are no longer evidenced but some artefact scatters remain; the lack of workshop sites being testament to changing settlement choices and landscape use at the time.

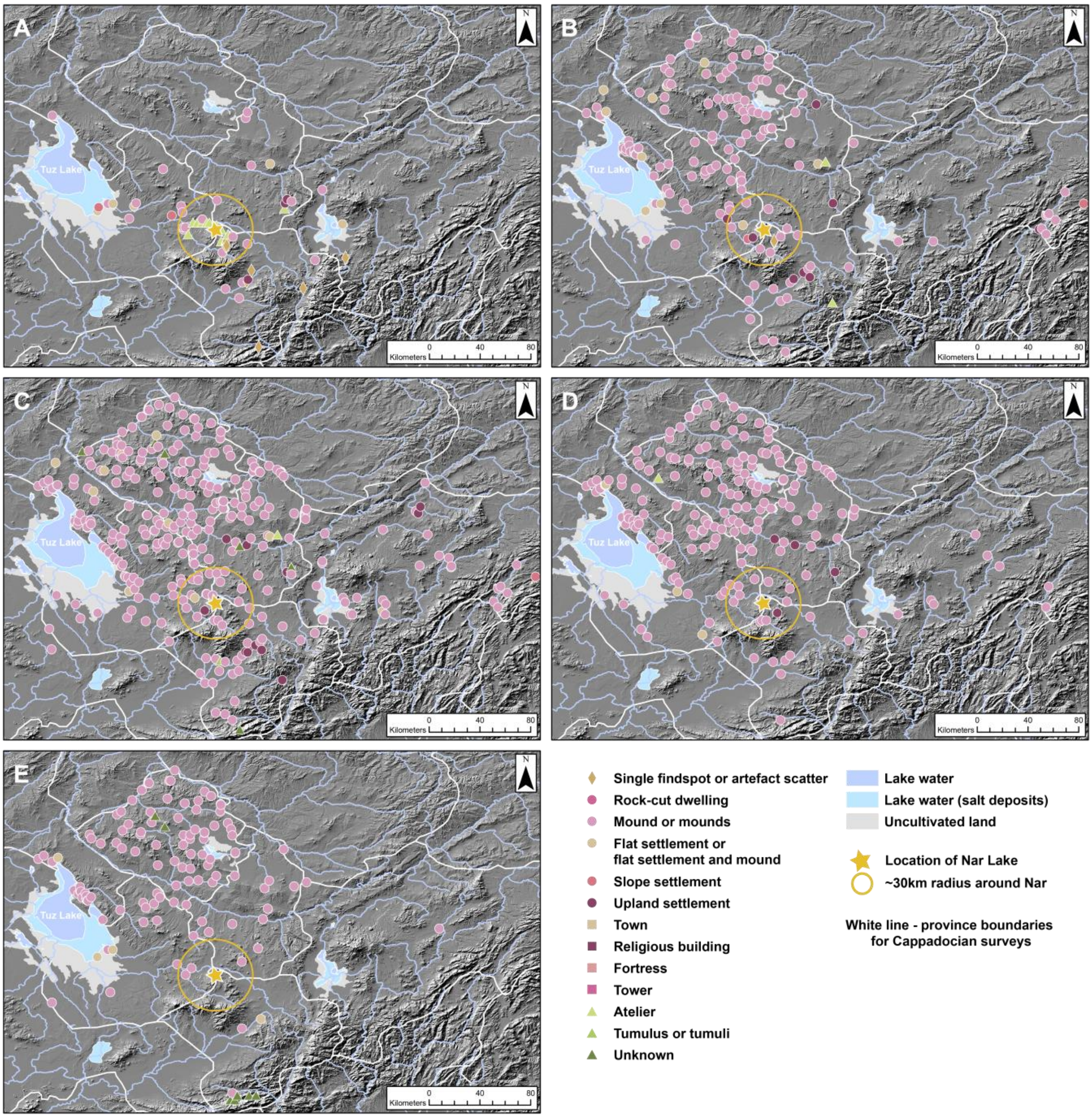


Figure 6.4: Map of Cappadocia with site survey data by period and site type. A) Prehistoric and Neolithic, B) Chalcolithic, C) Early Bronze Age, D) Middle Bronze Age, E) Late Bronze Age.

The significant rise in settlement numbers seen during the Early Bronze Age (figure 6.2) does not appear to affect the choice of site type (figure 6.4). Both the EBA and MBA show a preference for mound sites and settlement of lower lying plains as witnessed by a decrease in upland settlement types. The few unknown site types recorded for the EBA do not significantly alter this view point. The lack of artefact scatters and single find spots for both periods suggests that settlement remains for this time were generally large and noticeable and therefore a better representation of settlement sites may have been obtained if features were clearer to the investigator. It also underlines the unique nature of workshops during the Neolithic as only two such sites were found during the entire Bronze Age. A similar pattern is witnessed for the LBA (figure 6.4) with mound sites dominating, albeit with a slightly reduced number of sites.

Table 6.2: Table showing the number of sites located within a ~30km radius of Nar Lake by period.

Period	Number of sites
Neolithic	24
Chalcolithic	12
EBA	22
MBA	12
LBA	3
Iron Age	17
Hellenistic-Roman	17
Byzantine	5
Medieval-Modern	3
Unknown	2

The majority of LBA sites are located in the Kirşehir province to the north but it is hard to infer whether this change is the result of shifting settlement practices or due to investigator bias. Around Nar Lake mound sites dominate during the EBA and MBA, with only the occasional upland site recorded (figure 6.4). As may be expected given the raw site count data (figure 6.1) there are more sites within 30 kilometres of the lake during the EBA than in the two proceeding periods (22 sites during the EBA (table 6.2)). This is in contrast to the LBA where only three sites are found in close proximity to the lake, further reiterating the point that many sites appear to be located in northern Cappadocia at this time.

During the Iron Age (figure 6.5) the first clear indication of a move away from mound type locations is witnessed and new architectural types appear, including fortress sites and burial mounds (tumuli). It is possible that the increased use of the area allows for these features to be more easily seen but considering high numbers of sites are documented for the EBA also and very few non-mound sites are recorded, it is likely that this signifies a significant shift in occupational strategies.

By Classical times (figure 6.5), the building of fortress sites has increased and we begin to see a noteworthy change in the function and role of sites, in this case for control and defence of the landscape. This may imply a significant investment in new architectural forms following the Bronze Age and a new importance placed on non-residential sites. Also interesting to note is that no Classical site is documented on the widest zone of the Tüz Lake, even though occupation in the locality of the lake increases substantially. Whilst they cannot be addressed here, questions therefore arise as to why this may be. Perhaps sites closer to the lake centre are hidden by alluvium deposits or there were human selective processes that prevented people from occupying these areas.

Settlement around Nar Lake during the Iron Age and Classical times (figure 6.5) is relatively abundant (table 6.2) and stable in terms of site numbers and site type. Due to Nar Lake’s proximity to high plateaus, there is some evidence of upland settlement, but generally mound and fortress sites are recorded; a pattern that is typically reflected elsewhere in Cappadocia at this time.

The post-Roman decline in site numbers (figure 6.2) coincides with a change in settlement preferences with the establishment of rock-cut underground settlement systems (figure 6.5). Fortresses still play a dominant role, as do other monumental features classes like towers, especially in higher localities. The area surrounding Nar Lake during the Byzantine period (figure 6.5) shows little in the way of settlement history as very few sites are documented (table 6.2). Of the five sites which are recorded, all are mound occupations, for example the site of Nazianzos (modern day Bekârlar) located 12km from Nar (England *et al.*, 2008). This may in fact be a skewed vision of the true occupational history of the area as it is known from personal observations that there are rock-cut dwellings (created by Christian monks) within the lake catchment that are not recorded within the Cappadocian surveys. Of significance during Byzantine times therefore are the rock-cut habitation sites which seem to prevail in southern Cappadocia.

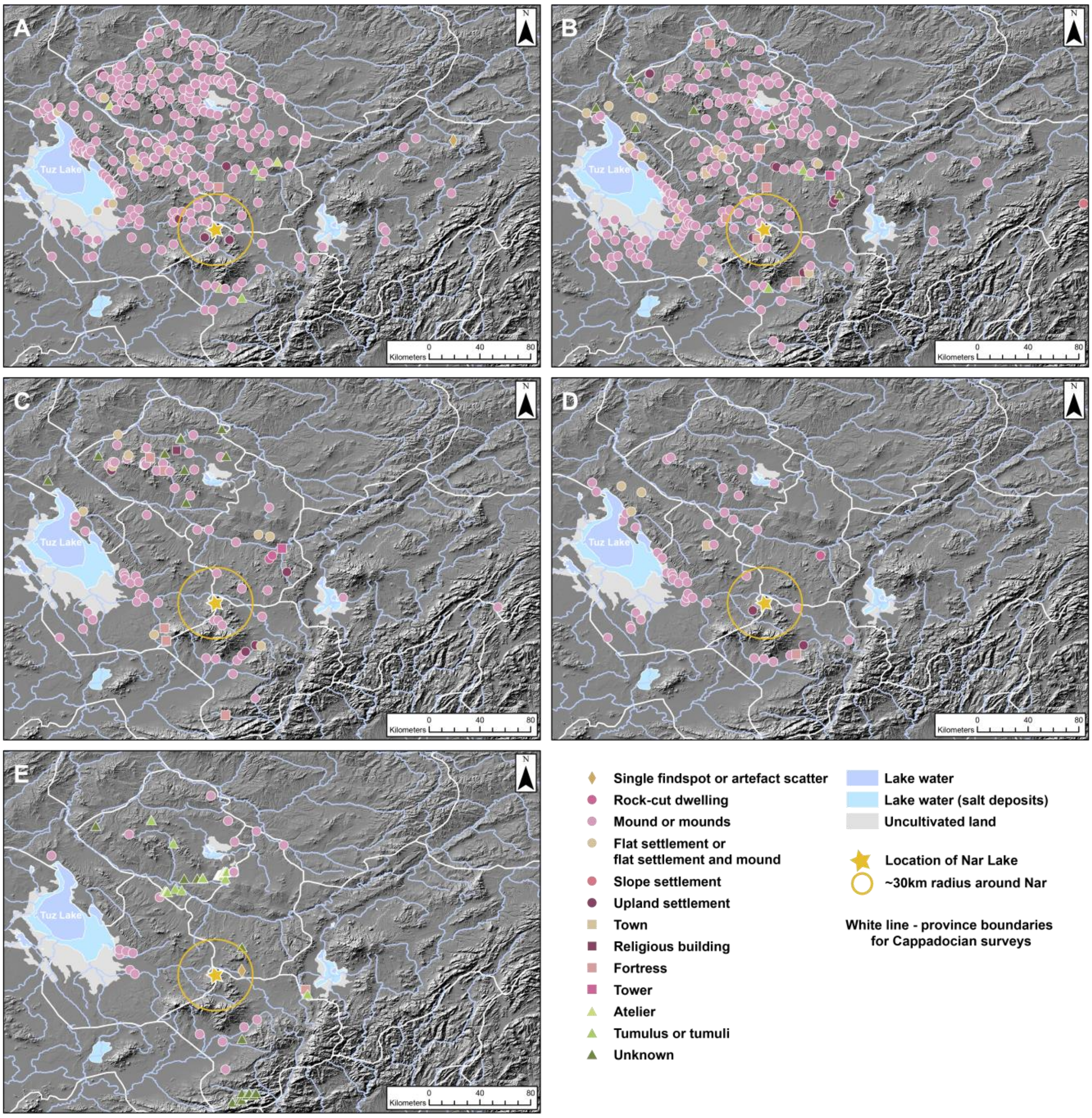


Figure 6.5: Map of Cappadocia with site survey data by period and site type. A) Iron Age, B) Hellenistic and Roman (Classical), C) Byzantine, D) Medieval-Modern, E) Unknown.

By the Medieval period, the number of monumental and rock-cut dwelling type sites is reduced with mainly mound type sites documented (figure 6.5). The northern regions also become less heavily populated in comparison to preceding periods and may imply shifting landscape preferences and/or lack of visible sites. There is some evidence of continuity of sites, particularly to the south-east of Tüz Lake where 10 sites remain in use from post-Roman times. Settlement around Nar Lake is also diminished at this time (figure 6.5) with only three sites recorded (table 6.2), none of which are situated in the lake catchment itself. Of particular importance is that those sites around Nar and elsewhere within Cappadocia seem spatially placed closed to riverine, lake or in upland locations which may highlight human selection for water-based or defensive locales.

Sites where chronologies cannot be confirmed or where datable material is unavailable seem to principally be tumuli sites where perhaps artefactual evidence is lacking. Many more tumuli sites with assigned ages could have been included within the study if suitable co-ordinate data were obtainable. Similarly high is the number of mound sites which likely results from damage and the removal of datable material by processes like ploughing. There is no particular region where unknown site ages dominate suggesting that the lack of datable material does not depend on location. The atelier site of unknown age close to Nar Lake is likely to be Neolithic in age given the dominance of workshops in the area during this time.

6.4.3. Excavated sites located in Cappadocia

Based on information available from published sources, a list of the key sites excavated within Cappadocia has been complied for the Holocene to add to the survey database (table 6.3). The documentation of excavated material sought to provide information about settlement changes and site activities which would not only help substantiate and help to refine the chronology of the survey data but which could be used to construct a more in-depth understanding of the factors which shaped settlement patterns. The most promising possibility in this regard was the chance to study transition periods and phases where survey data was limited. Excavation data provided much-needed comparative material within which to situate sometimes fragmentary and bias survey data. Several of these sites and their documented histories are referred to at relative points in the sections that follow.

For the Neolithic, the mound site of Aşıklı Höyük (Esin and Harmankaya, 1999) is uniquely informative due to its close location to Nar Lake and the fact that it provides a continued history of change from the onset of sedentism, including patterns of settlement construction. For the Chalcolithic, excavations at Tepecik-Çiftlik (Cutler, 2004) are of value as it was occupied during several transition phases. The site of Kaman-Kalehöyük (Hongo, 2004) provides the best overview of changes during the Bronze and Iron Ages, and the major cultural transformations that took place during these periods. Of importance are the profound changes in crop storage practices that relate to the long-term stability of communities and provide a direct means of piecing together dynamical changes in socio-political systems. For later periods, assorted information from various sites provides a degree of comparative background as there is limited excavation data which can be extracted from just one site.

Other central Anatolian sites which are not located within Cappadocia but which are also considered appropriate for further understanding include Pınarbaşı (Baird, 2005b) (Pre-Neolithic), Boncuklu (Baird, 2010a), Çatalhöyük East (Hodder, 2005), Can Hasan 3 (French *et al.*, 1972) (Neolithic), Can Hasan 1 (French, 1962), Çatalhöyük West (Mellaart, 1965) (Chalcolithic), Çadir Höyük (Steadman *et al.*, 2008), Alaca Höyük (Koşay, 1951) and Alişar Höyük (Gorny, 1995) (Bronze Age & Iron Age). The quantity and quality of data available for the prehistoric period in central Anatolia is considerable in comparison to historic periods. It is clear that each archaeological phase is significantly different but gaps in knowledge still remain, particularly for very early (Pre-Neolithic) and very late (post-Medieval) phases. Neolithic and urban changes are mainly studied using excavation techniques and thus such changes are generally well understood, but for other periods such as the Chalcolithic, there is less information available regarding lifestyles and economies. In this instance, discussions of certain periods like the EBA within this thesis are better informed from excavation data.

Table 6.3: Table identifying key excavated archaeological sites per time period for Cappadocia.

Time period	**Excavated archaeological sites**
Pre-Neolithic (Pre-Neo)	Kaletepe Deresi 3 (Early & Middle Palaeolithic)
Neolithic (Neo)	Aşikli Höyük, Fertek, Kayırlı-Bitlikeler, Kömürcü-Kaletepe, Kösk Pinar Höyük, Musular, Pinarbaşi-Bor, Tepecik-Çiftlik
Chalcolithic (Chalco)	Fırakin, Gelveri, Güvercinkayası, Has Höyük, Kösk Pinar Höyük, Sarioğlan, Tepecik-Çiftlik
Early Bronze Age (EBA)	Acemhöyük, Demircihöyük, Gelveri, Göltepe-Kestel, Has Höyük, Kaman-Kalehöyük, Kanlica, Kültepe, Pinarbaşi-Bor
Middle Bronze Age (MBA)	Has Höyük, Kaman-Kalehöyük, Porsuk Höyük, Zank Höyük
Late Bronze Age (LBA)	Kaman-Kalehöyük, Kirsehir Höyük, Topakli
Iron Age (IA)	Göllü Dağ, Kaman-Kalehöyük, Kaynarca, Kerkenes Dağ, Kınık Höyük
Hellenistic and Roman (Hell & Rom)	Fertek, Karahüyük – Hacibektaş, Topakli
Roman-Byzantine (Rom-Byzan)	Byzantine underground cities and rock-cut churchs (e.g. Selime Kalesi), Çanlı Kilise, Fertek, Kemerhisar-Tyana, Topakli
Medieval-Modern (Med-Mod)	Various Seljuk and Ottoman hans, mosques and other standing structures.

6.4.4. Survey summary and comparison with other surveys

6.4.4.1. Survey summary and comparison, an overview

To understand if the habitation changes presented here are representative and whether the documented settlement history is localised in nature or more specific to the central Anatolia region, it is useful to relate the trends and patterns recognised to other known archaeological surveys conducted in the area. Survey results presented for Cappadocia will be considered in relation to two well documented and extensive site surveys conducted in neighbouring regions, the Konya Plain survey to the west (Baird, 2001a, 2002, 2004b) (figure 6.6) and the Paphlagonia survey to the north (Matthews and Glatz, 2009a) (figure 6.7). Using these two adjacent surveys should provide comparable links to sites surveyed in both north and south Cappadocia.

These two multi-period site surveys are excellent at documenting settlement shifts throughout the Holocene time span and allow for period specific contrasts to be made. On the whole, the Konya Plain and Paphlagonia surveys generally fail to provide a substantial overview of post Roman/Byzantine sites but considering the Cappadocia survey is also lacking information for the historical period, there are already some useful cross-overs which suggest comparisons can be made.

The Konya and Paphlagonia surveys have similar settlement histories to those witnessed in Cappadocia but their different geographic locations and environmental settings lead to some localised variations. All three surveys show growth of Early Bronze Age communities from a somewhat smaller scale of occupation during the Neolithic and Chalcolithic, with a steady continuation of increased settlement into the latter Bronze and Iron Ages. The major distinctions are the higher settlement densities of the Konya Plain during Byzantine times (figure 6.6) and the high values recorded for LBA occupations and lack of Neolithic remains in Paphlagonia (figure 6.7).

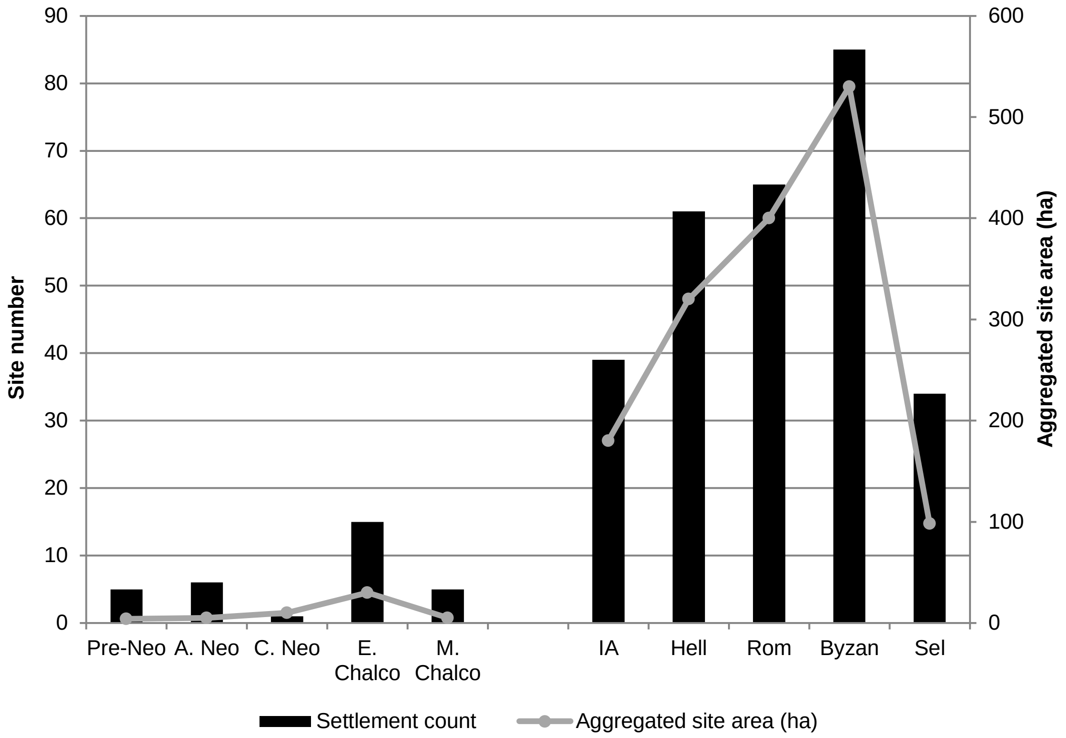


Figure 6.6: Long-term trends in site number and aggregated site area (ha) for the Konya Plain. Data as understood from Baird (2004b, 2005a). Data could not be obtained for the Late Chalcolithic-Bronze Age period.

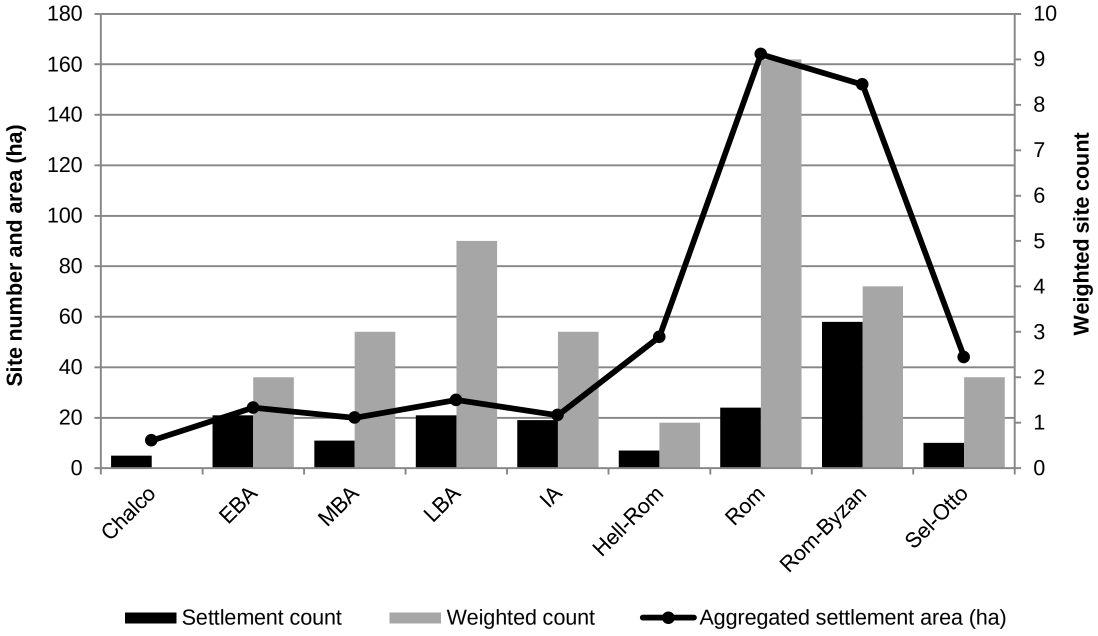


Figure 6.7: Long-term trends in site-number, weighted site counts and aggregated site size (ha) for the Paphlagonia survey. Data as understood from Matthews & Glatz (2009b).

6.4.4.2. Pre-Neolithic

The Pre-Neolithic period, as it is defined here, is not well documented by any of the surveys discussed in this chapter (figures 6.1, 6.6 & 6.7). There is a strong focus in the Cappadocian and Konya surveys on the Neolithic period but virtually no indication of settlement prior to this time which may be the result of dating confidence, lack of ‘settlement’ type locations and/or visibility of non-permanent sites. In total, the Cappadocia survey identified only 11 sites that were not classified as cave dwellings (45 Pre-Neolithic cave sites were omitted due to lack of chronological certainty); most sites documented are lithic artefact scatters and are dated by regional typologies. The limited number of sites recorded for the Pre-Neolithic period does not necessarily suggest only low populations and occupation prior to 8500 cal. yrs. BC, but the lack of sites is also testament to the strategy employed by investigators and related to the unclear nature of evidence in comparison to later periods (i.e. the visual dominance of Höyük type sites). The fact that Epipalaeolithic occupations can be traced on the Anatolian Plateau and that occupations persisted into the Holocene (Düring, 2011) suggests that sites dating to this time should be distinguishable. However, only a handful of Epipalaeolithic sites have actually been documented in central Anatolia, demonstrating a clear under-representation of sites for this period.

A similar pattern of Pre-Neolithic occupation as witnessed in Cappadocia can be seen in the south-west Konya Basin where 5-6 sites date to before 8000 BC (Baird, 2005a) (figure 6.6); the most famous of these being Pınarbaşı (Asouti, 2003; Baird, 2003, 2004a, 2005b). The sites recorded as ‘pre 8th millennium BC’ (Pre-Neolithic) in the Konya Basin are documented to be mound type sites indicating some sedentary behaviour, even if it may be periodic in nature. In comparison to survey results presented here, no mound sites were identified. To any archaeologist, mounds are certainly the most obvious feature class of this time and it is interesting to note the lack of lithic scatters recorded by the Konya survey and the lack of mound sites recorded for the Cappadocian survey. This may suggest a number of things including preservation bias, investigator bias and/or a different use of landscape.

Location plays an important role in the prehistoric settlement histories of parts of central Anatolia. It seems likely, given site type data (figure 6.4), that human presence in parts of Cappadocia was encouraged by resource availability, with people particularly being drawn to the area by the presence of obsidian outcrops and the accessibility to exchange routes (Baird, 2012; Chataigner *et al.*, 1998). The area would have been home to highly mobile groups (Baird, 2012) who took advantage of the proximity to materials and developed settlement strategies in line with the significance of the area, in this case resource abundance. Sedentary lifestyles were not of importance to Cappadocian groups but lithic technologies and interaction were (Baird, 2012). The lack of mining activity on the Konya Plain and documentation of mainly mound sites only reiterates the point that Cappadocia formed an important locale for landscape exploitation. The zonation of the wider landscape into areas of exploitation and settlement was principally determined by resource availability during Pre-Neolithic times.

6.4.4.3. Neolithic

The Neolithic period, as documented by Düring (2011), is represented by an increase in settlement numbers and more noticeable population levels which are encouraged through shared social-ideological factors like the importance of community living. In Cappadocia, settlement numbers increase to 106, but the biggest perceptible change is the appearance of mound type sites (figure 6.4). The most renowned mound site in Cappadocia is Aşıklı Höyük (~20km from Nar Lake) (Buitenhuis, 1997; Esin *et al.*, 1991; Todd, 1966; Van Zeist and de Roller, 1995), which indicates a level of permanence to occupation as inferred by site size and investment in housing and architectural planning. Included within the social landscape of Aşıklı is another site called Musular (400m southwest) which is believe to be related to domestic expansion by the people of Aşıklı themselves (Duru and Özaşaran, 2005). The increase in larger and permanent settlement sites is encouraged at this time by processes of agglomeration and sedentism (Düring, 2011). The increase in the size of sites and the formation of many new occupational locales also suggests an increase in regional population levels at this time.

From site type data presented here (figure 6.4) and other studies (Balkan-Atli, 2010; Carter *et al.*, 2006; Pernicka *et al.*, 1997) it is inferred that Cappadocia was heavily exploited during Neolithic times, a result of an expansion in obsidian resource exploitation. The area likely had great resource potential to inhabitants which may explain the rise in site numbers during the Neolithic. Surveyed sites like Aciyer, Alva Dağ, Bitlikeler, Göllü Dağ and Nenezi Dağ, which are all in close proximity to Nar Lake, are testament to the links between occupation and resource abstraction because of their primary use as mining localities. The similarity of sites between the Pre-Neolithic and Neolithic phases may suggest some form of conservatism in settlement preferences and continuity in resource exploitation practices.

The Neolithic evidence in Cappadocia, on the whole, is not similar to the Neolithic survey results from other studies. The uniqueness of the area at this time for the establishment of mining and mound sites is reiterated by the complete lack of Neolithic finds found during the Paphlagonia survey (Matthews and Glatz, 2009b) (figure 6.7) (only three sites are documented for the whole of north-central Anatolia (Düring, 2008)) and only a marginal increase in Neolithic site numbers on the Konya Plain (Baird, 2001b, 2002, 2005a) (figure 6.6). The Aceramic Neolithic of the Konya Plain witnesses more substantial settlement sites in comparison to earlier phases (e.g. Boncuklu Höyük) but site numbers remain small and there is no indication of a population shift at this time (Baird, 2005a). Similarly, during the Ceramic Neolithic, there is a lack of permanent and well established village sites (Baird, 2002, 2005a). The presence of Çatalhöyük (Hodder, 2000, 2005), a massive agglomeration site, is the only exception to this pattern. It is argued that Çatalhöyük thrived at the expense of smaller communities resulting in a lack of sites recorded for this time period (Baird, 2005a). The dominance of one settlement site forms a real difference from earlier periods and is in contrast to the wider Cappadocian region where there is a preference for smaller “village” sites.

From the limited information available, it seems that settlement in Cappadocia during the Neolithic was relatively prolific in terms of site number and heterogeneous with respect to site type and function in relation to neighbouring regions. Sites were located close to or at sources of obsidian and were involved heavily with exchange routes across the Near East region. It is likely that inhabitants’ participation in the extraction and exchange of materials encouraged increased settlement expansion during the Neolithic and the greater accumulation of people in the area.

6.4.4.4. Chalcolithic

With the onset of the Chalcolithic, regional differences are still identifiable. In Cappadocia, there is an overall reduction in mining sites and a new focus on mound occupations and the expansion of settlement into more northern regions (figure 6.4). This is in contrast to the Konya Basin where the proliferation of mound sites begins in earnest during the Early Neolithic (Baird, 2005a). The excavations of sites like Tepecik-Çiftlik, Güvercinkayasi and Köşk Höyük reveal a strong and dynamic Early-Middle Chalcolithic phase in Cappadocia, and a predominantly small-scale domestic nature of sites (Cutting, 2005). Previous work (Baird, 2012; Marciniak and Czerniak, 2007) has suggested that Early Chalcolithic sites are still economically tied to the exploitation of Cappadocian obsidian and that their nature relates heavily to their proximity to exchange routes (Marciniak and Czerniak, 2007). By the latter half of the Chalcolithic however, the importance of raw materials decreases and this is said to have manifested itself in a decline in settlement numbers (Marciniak and Czerniak, 2007), a pattern which cannot be supported by the survey data presented here (figure 6.1).

The increase in site numbers during the Chalcolithic (figure 6.2) is related, in part, to the results of the Kaman-Kalehöyük (Mikami and Omura, 1991a) survey which identifies a high number of Chalcolithic sites in northern Cappadocia. The lack of Chalcolithic remains documented by Ian Todd (1998) in the southern Cappadocian Plains gives strength to the idea that occupation became denser in northern areas. Marciniak & Czerniak (2007) comment that the Chalcolithic of Cappadocia is characterised by the occupation of new areas which would fit with the survey results presented here. The location of new Chalcolithic sites may have been structured by the development of sedentary agricultural lifestyles, region wide links in exploitation strategies and a new focus on the autonomy of households (Marciniak and Czerniak, 2007). The fact that the Cappadocian survey poorly records sites by sub-period (figure 6.1) means that it cannot be stated with confident as to when these spatial changes occurred but its seems reasonable to suggest they happened in the first half of the Chalcolithic period given the lack of site data available for the later Chalcolithic (Düring, 2011).

The lack of continuity between sites (figure 6.3) and the increase in site numbers (figure 6.2) between the Neolithic and Chalcolithic is also evidenced by the Konya Plain survey (figure 6.6). Whilst occupation at the large site of Çatalhöyük continues, there is a growth of smaller dispersed sites in the vicinity which were not witnessed in the Ceramic Neolithic (Baird, 2010b). This dispersal of population and lack of aggregation relates in part to the diminished suppression of communities by the presence of Çatalhöyük and procurement in other activities (Baird, 2010b). The Middle Chalcolithic on the Konya Plain in contrast shows a noticeable reduction in site numbers and continuation in site locations and type, with some consistency in community based relationships (Baird, 2005a). By the Late Chalcolithic, many sites disappear from the Konya Basin, including the Çatalhöyük site (Baird, 2001b). The growth of settlement during the Early Chalcolithic and fall in settlement numbers by the end of the Chalcolithic indicates considerable temporal change in settlement dynamics for the Konya Plain.

In Paphlagonia, the Chalcolithic time period is poorly represented with only 5 mound sites documented (Matthews and Glatz, 2009b) (figure 6.7). Population levels in comparison to Cappadocia and the Konya Plain are low and sites are only evidenced along resource seams or exchange networks. Middle Chalcolithic sites are dispersed and heterogeneous in nature but some sites like Maltepe reveal considerable continuity in occupation (Matthews and Glatz, 2009b) which is not too dissimilar from the stability in sites documented by the Konya survey (Baird, 2005a). Survey data suggests that the settlement preferences of inhabitants of Paphlagonia differed from the more southerly regions during the Chalcolithic, with their concern for resource extraction matching more equally to the Neolithic occupations in Cappadocia.

6.4.4.5. Early Bronze Age

A sharp rise in settlement numbers and a relative abundance of data is recorded in the Cappadocia survey for the Early Bronze Age (figure 6.2). The number of new settlements rises to a level not seen previously and whilst some sites are abandoned (figure 6.3) there is strong continuity in site location and type from the Chalcolithic into the EBA (figure 6.4). For example, Tepecik-Çiftlik (Bıçakçi *et al.*, 2007) is one of the sites that witnesses settlement continuity during the Chalcolithic-EBA transition. Due to the lack of data assigned to sub-divisions in the original Cappadocian surveys, it is difficult to known exactly when the key changes in settlement occurred but site numbers (figure 6.1) indicate that perhaps the increase is found around the EBII period, a time when town planning and urbanisation took hold (Yakar, 1985).

Settlement during the EBA seems to be structured by the need for resources and the exploitation of local deposits (i.e. metal ore) and trade routes (Düring, 2011; Yener, 2000) in a similar fashion to that witnessed in and prior to the Neolithic. Not only are settlement increases linked in with exchange but also the adjustment in community living and the erosion of trust with outsiders, likely brought about by the new economic environment

(Steadman, 2011). People were beginning to prefer occupying sites at the household level and avoiding community lifestyles, resulting in the need for more space.

Broadly, the patterns witnessed in Cappadocia match those documented for Paphlagonia. In Paphlagonia, site numbers and population levels increase dramatically (Matthews and Glatz, 2009b) (figure 6.7), as they do across the Near East region (Wilkinson, 2003). Metal ore was indicated as a key contributor to the establishment of new and fortified sites (Matthews and Glatz, 2009b), for whilst resources offer the potential of regional networks, they lead to a greater concern for security and protection in the landscape (Matthews and Glatz, 2009b). Multi-period mound sites are another common feature in both the Cappadocian and Paphlagonia surveys with the majority of these showing some stability in the landscape. New sites in comparison tend to be associated more with previously uninhabited areas.

In the Konya Plain (Baird, 2001b) too there was significant increases in the frequency and rank of settlement sites, brought about by the development of urban living and population growth. Settlement took the form of large centre sites and smaller peripheral localities, situated within close proximity to exchange pathways or areas of agricultural potential (Baird, 2001b). Whilst such a pattern cannot be delineated from the Cappadocian survey, the Konya survey also highlights a significant drop in site numbers following the EBII period, and following a period of prolific settlement development. If this is an accurate representation of change, it suggests that the boom in EBA settlement occurs at the start of the EBA period in the Konya region. The strong continuity between sites dating to the EBI and EBII, and not of EBIII in the Cappadocian survey may suggest that a change event also occurred towards the end of the EBA period within this study. What form that change event took though is not discernible from the data presented.

6.4.4.6. Middle Bronze Age

Archaeological survey evidence for the Middle Bronze Age in Cappadocia suggests similar settlement patterns to those witnessed in the Early Bronze Age, with significant levels of occupation and a clear dominance of mound type sites (figures 6.2 & 6.4). Weighted site counts (figure 6.2) suggest that this period saw the highest levels of occupation per century in relation to all other phases (figure 6.2) which is in contradiction to the high level of abandonment also implied by the survey data (figure 6.3). The major difference between the EBA and MBA is that there are very few new sites being established during the Middle Bronze Age (figure 6.3); which if viewed alongside the abandonment data suggests that occupation could not have been as prolific throughout the period as a whole as is implied by the weighted counts. Sites which continue to exist in both periods show a strong sense of settlement continuity and stability. This can be seen at major occupational sites like Kaman-Kalehöyük (Mikami and Omura, 1991b; Mori and Omura, 1995) in the north of the region.

Of importance to inhabitants and a reason for settlement stability during the MBA may have been the integration of sites into key trade routes and the new system of political power established by the trading Assyrian colonies and later by the Indo-Europeans (Crossland, 1957; Darga, 2000; Larsen, 1974; Orlin, 1970). Stability in settlement is therefore suggested to relate to increased expenditure by local authorities on settlement systems (i.e. increase political control of food distribution (Fairbairn and Omura, 2005)) and the new dependence on urban interaction. Increased social relations through trade and urbanisation allowed for increased security for a time and a productive system of food storage and distribution which enabled secure living (Fairbairn and Omura, 2005).

The security in habitation sites at this time and the link with urban-based polities may have manifested itself in the number of archaeological sites recorded in the Cappadocian survey as “Middle-Late Bronze Age” (figure 6.1), indicating the special importance of socio-economic stability across a period of time. To identify which proportion of these sites relate to the MBA, a simple percentage equation was used to spilt to the Middle-Late Bronze Age sites into two figures based upon existing counts for the MBA and LBA. As can be seen in figure 6.8, this added an extra 19 sites to the inventory for the MBA. When viewed alongside proceeding periods (figure 6.8), this new site count records a substantial level of occupation in relation to the LBA and LBA-IA transition phase.

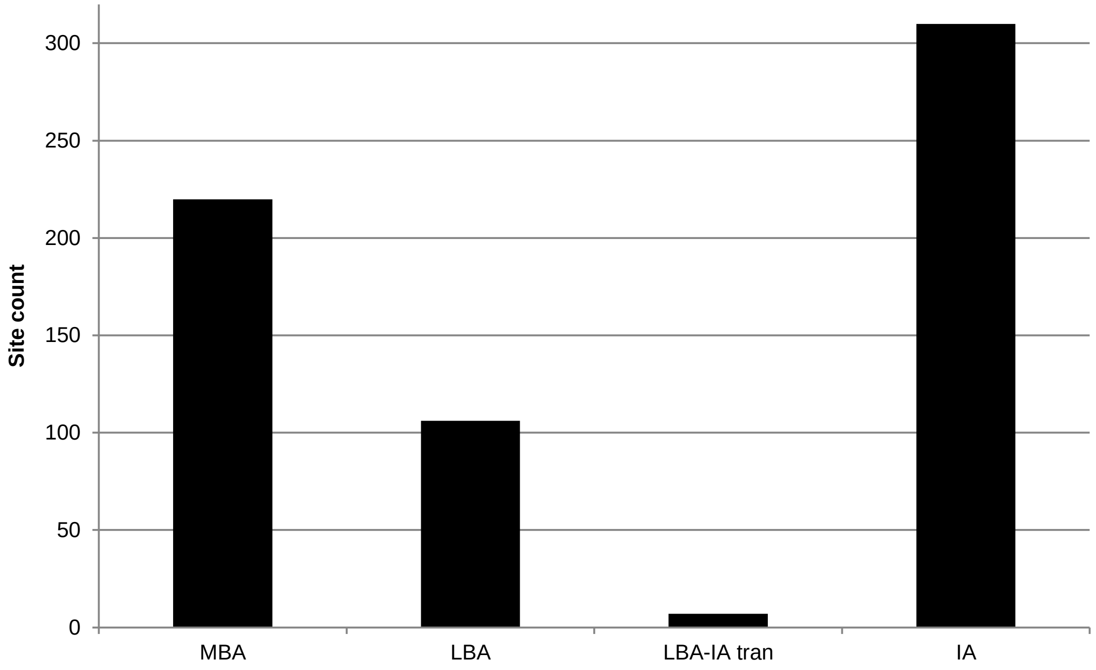


Figure 6.8: Cappadocian site count data for selected periods, adjusted using counts from the Middle-Late Bronze Age phase.

In Cappadocia, it seems that the MBA is important in terms of settlement steadiness and investiture, and points to some individual sites having strong cultural links with earlier times, as well as links with the new commercial future. The MBA as documented in Paphlagonia (figure 6.7) in comparison is likewise outlined as a significant settlement change period due to the changing context of the political and economic world. In Paphlagonia, there is a strong aspect of settlement continuity and a large increase in site numbers. Only 21 substantial sites have clear evidence for MBA occupation though

(Matthews and Glatz, 2009b) and it can be argued whether this represents a true record of settlement endurance and establishment in Paphlagonia. In Cappadocia, especially if we look at site numbers by century (figure 6.2) we see a number almost double that seen for the entire period in Paphlagonia. Survey size likely has some part to play in the numbers recorded, and whilst the pattern of MBA growth is similar, the site numbers detailed in the Cappadocian survey give greater confidence to the patterns observed.

In the Konya Plain, the Middle Bronze Age is also characterised by increases in the frequency of sites and in the aggregate site area (Baird, 2001b). In contrast to the Cappadocian and Paphlagonia surveys however, the Konya survey documents less stability in the settlement record with sites shifting in location and occupying previously unoccupied locales. Resident differences in environment and agricultural potential have been accredited for the variability in settlement preferences seen on the Konya Plain and therefore make comparisons to the data presented here difficult. Nevertheless, some broad similarities are witnessed, including the increased intensity of settlement.

6.4.4.7. Late Bronze Age

The LBA period in Cappadocia is contradictory. There is evidence for both settlement continuity from the MBA (figure 6.3) and evidence for dramatically reduced settlement numbers (figure 6.3). Overall though, occupational sites which had existed with some stability during the MBA are abandoned during the LBA. Weighted counts (figure 6.2) provide a more accurate indication as to the level of occupation at the time and indicate that the decreases were not as extreme as they first appear from the site count data alone (figure 6.1). Nevertheless, these changes do occur to some extent and certainly many MBA sites appear to be uninhibited during the LBA.

Of those sites documented to be LBA in age, most appear to congregate in the north of the region whilst southern parts of Cappadocia appear to be less extensively inhabited (figure 6.4). This could relate in part to investigator bias but considering LBA sites elsewhere are documented to have been unstable (Dönmez, 1999; Yakar, 1980), it suggests that this pattern of landscape abandonment may be a region wide phenomenon. Campaigns on Hittite communities by Kasha tribes from the north (Yakar, 2006) have been suggested as a reason for the demise in permanent settlement and the lack of settlement stability during the LBA (Matthews, 2004). The apparent presence of more sites in north Cappadocia though is intriguing as this is where territories would have been most under threat. The dominance of the ruling Hittites in the north however had a strong pull on communities, encouraging settlement in and around the source of political power. The advantage held by locating near to sources of power but far enough away from fortified borders would have been a deciding factor in settlement histories of the time.

The Paphlagonia survey in comparison documents many new sites forming by the end of the LBA (Matthews and Glatz, 2009b) (figure 6.7) which may be linked into the building of new fortification sites for security. The spatial placement of sites is also intriguing as they seem to be located in strategic defensive areas like along river systems and in high localities (Glatz *et al.*, 2009; Matthews and Glatz, 2009b). This is in contrast to the Cappadocian survey which sees an overall decline in site numbers and little change from 'Höyük' type occupations. The presence of a strong LBA in Paphlagonia is not matched by data here and indicates a prominence of northern areas of LBA populations or a preference for diminished aggregation of populations. At the regional level there is a general decline in LBA settlement and the abandonment of many MBA sites in the Central Anatolian Plateau (Glatz, 2009). Survey data for the Konya Plain during the LBA is not readily accessible due to minimal publication but from the data available, a decline phase is not documented (Baird, 2001b), indicating some similarity to the Paphlagonia results. Therefore whilst the results presented here are aligned with the regional pattern of change, the downwards shift in settlement is not apparent in neighbouring locations.

6.4.4.8. Iron Age

The Iron Age (IA) period in Cappadocia forms the next big notable shift in settlement figures following the EBA settlement boom. Site numbers dramatically increase and the intensity of settlement seems remarkably high (figure 6.1). Whilst there is some continuity from the LBA, generally sites are new establishments (figure 6.3) showing a change in settlement preferences from settlement maintenance to settlement creation. The LBA-IA transition phase includes very few documented sites (figure 6.8) which may suggest a massive drop in settlement prior to the IA increase, although archaeological data from sites like Kaman-Kalehöyük imply that several substantial occupations did continue on from the LBA (Mora and d'Alfonso, 2012). Important to note is that weighted counts (figure 6.3) suggest that IA occupation levels may not have been as high as is evidenced by the site count data. The noted importance of Phrygian (900-585 BC) occupations in Cappadocia (Summers, 2006; Voigt and Henrickson, 2000) though may suggest that averaging the site count data by centuries is not suitable for this time where occupation was likely more dominant at one point in time and not throughout the IA period as a whole.

Site numbers by sub-period (figure 6.1) in Cappadocia are too poorly recorded to notice a significant shift in numbers immediately following the LBA but the higher proportions of sites document for later IA periods suggests that at these times, Cappadocia was a key area for Phrygian and Persian (585-331 BC) populations. The preference for new sites (figure 6.3) and settlement locations (figure 6.5) may suggest new people moving into the area with new ideas of spatial planning and site formation. Due to the number of sites recorded as ‘Late’ it has been necessary to divide these data across the late Iron Age, Hellenistic and Roman times as this is what ‘Late’ implies. The resultant settlement count can be seen in figure 6.9 and shows that late Iron Age sites are of some importance. The increase in site numbers identified in the IA is witnessed right across central Anatolia with a clear differentiation to the Bronze Age (Glatz, 2009). This phenomenon seems directly related to the changing political situation and the re-colonisation of the area following decline during the end of the LBA.

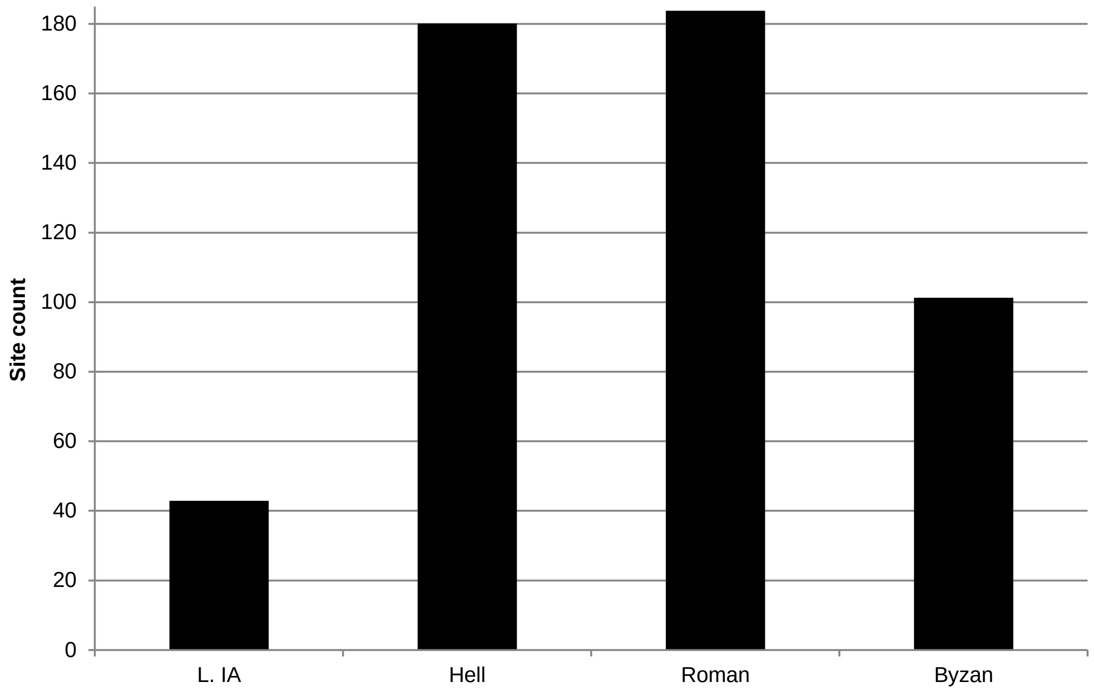


Figure 6.9: Cappadocian site count data for selected periods, adjusted using counts from Late, Hell-Roman and Roman-Byzantine phases.

This is in contrast to the results observed in Paphlagonia (figure 6.7) where following the collapse of the Hittite state there is a significant drop in settlement numbers and a meagre spread of sites (Matthews and Glatz, 2009b). It seems likely that there was an initial hiatus to permanent and recognisable settlement sites, sometime around the decline in site numbers documented here. The Paphlagonia survey includes some IA sites dating to the Phrygian time period (Matthews and Glatz, 2009b) which may indicate a recovery in occupation levels towards the latter half of the IA. The presence of these sites on top of defensive structures of the LBA suggests a need to continue with security and use of defensive locations. Paphlagonia at this time formed a somewhat border zone between the Phrygian state and its northern neighbours (Matthews and Glatz, 2009b), likely resulting in the much localised pattern of settlement change witnessed.

The localised pattern of change in Paphlagonia is made more apparent in relation to the Konya Plain survey (figure 6.6) which, similar to the Cappadocian survey, indicates increased site numbers and the recolonisation of the Plains by small sedentary communities (Baird, 2001b). In the Konya Basin, IA sites are documented as variable in size and non-hierarchical in nature, and the position of a site does not seem to relate to any one urban centre. This is in contrast to preceeding periods and suggests that much of the settlement distibution is new, similar to the pattern of change outlined in this study.

6.4.4.9. Hellenistic and Roman (Classical)

Due to the problems of distinguishing between Hellenistic and Roman sites as a result of their similarity, the two time periods will be dealt with together here. In some cases (166 out of 382), sites can be attributed to one particular time period and in these instances, site numbers for both periods are the same (83 sites each) (figure 6.1). Even when the ‘Late’, ‘Hell-Rom’, ‘Classical’ and ‘Rom-Byzan’ sites (figure 6.1) are incorporated into the settlement count, we see similar site numbers for the two periods (180 & 184 respectively) (figure 6.9). Typically, this Classical phase is represented by an aspect of settlement continuity and continuation in settlement preferences, with relatively high numbers recorded. The political changes that occurred post Iron Age do not seem to have affected much of the settlement distribution. There is however growth in the number of fortress type sites being built during the Hellenistic-Roman period (figure 6.5), which is in contrast to other areas which saw the prolific introduction of defensive structures during the LBA. This is likely the result of Cappadocia’s location on the eastern borders of empire (Van-Dam, 2002) where previously it had not been part of any border zone.

The increase in site numbers at this time (figure 6.2) may be the result of two processes. It seems reasonable to first suggest that the security and agricultural prosperity that developed under elite rule would have encouraged population growth or at least movement into the area, and thus resulting in settlement expansion. Secondly however, as Cappadocia is only described as a ‘backwater’ of empire (Van-Dam, 2003), and the fact that only two sites (Tyana and Caesarea) become major regional hubs, it is reasonable to suggest that the appearance of amplified settlement may relate to the establishment of many smaller agricultural ‘village’ sites.

In Paphlagonia, Hellenistic times were typical of a decline phase with a 63% reduction in site numbers from the preceding phase (Matthews and Glatz, 2009b) (figure 6.7); there may be some evidence for agglomeration which could explain the lack of noticeable site locations. The process of settlement agglomeration occurs after Hellenistic times on the Konya Plain (Baird, 2001b). In relation to the Hellenistic pattern of change, the Roman period in Paphlagonia witnesses the area flourish, with settlement spreading and increasing in intensity (Matthews and Glatz, 2009b). The site survey results from Cappadocia are more comparable to those from the Konya Plain (figure 6.6) as these suggest a steady rise in site number and aggregate size from the late Iron Age through to Roman times and do not hint at any discontinuity within the Hellenistic period. It seems that during Hellenistic-Roman phases, Cappadocia has more in common with events occurring on the Konya Plain as both indicate the establishment of permanent towns and agricultural villages.

6.4.4.10. Byzantine

After the decline of the Roman Empire (~AD 395) and particularly after administrative instability from ~AD 670, site numbers fall by 72% and reach low values (105 sites) not recorded since the LBA (112 sites) (figure 6.2). It is likely that short-lived periods of socio-political dislocation and landscape abandonment influence the figure recorded by the Cappadocian survey (England *et al.*, 2008). The physical invisibility of remains is a problem for this phase and it is difficult to know if this truly is the result of minimal Byzantine occupation. Considering the lack of site survey work for the Byzantine period, and the fact that most sites are probably buried under modern town developments, it is likely that this number is under-represented. This lack of clear Byzantine information is emphasised by Cooper & Decker (2012) who outline that settlement surveys of the time are often limited in scope.

The most prominent, and well documented shift in settlement during Byzantine times is the expansion of cave dwelling sites (Erdem and Erdem, 2005; Ousterhout, 2005) (figure 6.5) and cave monasteries (which are not documented here) (Cooper and Decker, 2012; Rodley, 1985). This shift in habitation is picked up only partially in the Cappadocian survey but is expressed in more detail in Ousterhout (2005). The building of underground settlement sites and the expansion of subterranean features shows a clear divergence in the architectural vision of populations and a need for new habitation practices. The use of these sites as defensive locations is suggested (Bertini, 2010; Kalas, 2007) and reflects an instability in residential populations that was not evident during Roman times. A period of insecurity is evident in the area from the mid-7th century onwards when Arab invasions begun and Christian lifestyles were threatened (England *et al.*, 2008). Cave life (including the sanctuaries for monks seen around Nar Lake) was made obligatory by the frequent changes occurring in the political realm (Çorakbaş, 2012), but ultimately höyük architecture is still evident (figure 6.5) and signifies a heterogeneity to settlement choice.

Whilst Byzantine Cappadocia is poorly explored within the three surveys outlined here, Paphlagonia and the Konya Plain have been surveyed more extensively and provide a much more reliable picture of Byzantine settlement change (figures 6.6 & 6.7). In contrast to Cappadocia, Byzantine settlement on the Konya Plain flourished, particularly during the 5th-7th centuries and appears to witness a kind of settlement boom (Baird, 2004b). This is the largest number of sites recorded since the Iron Age in the area and probably relates to increased human presence in the vicinity. The sites indicate a strong sense of continuity from Roman times but also the presence of many new sites indicates some growth. The location of settlement sites also shows some continuity, with the same area repeatedly being selected for occupation. Extensive settlement is recorded near and on alluvial fan areas which is in contrast to Cappadocia which sees settlement off the Tüz Lake fan edge and in potentially more predictable landscapes which are not subjected to regular sedimentary deposition.

During mid-Byzantine times, Cappadocia found itself at the limits of empire, as did the inhabitants of Paphlagonia as witnessed by the reduction in site numbers moving into the Arab phase (Matthews and Glatz, 2009b). As with Paphlagonia, the typical urban centres were being replaced by more specific building types like religious buildings and fortresses particularly as conflict ensued towards the end of the period. Konya too begins to see collapse and abandonment after the 7th and 8th centuries (Baird, 2004b) suggesting a region-wide upheaval of settlement practices and habitation.

6.4.4.11. Medieval – Modern

It is difficult to infer much from the survey data regarding this time period but here and elsewhere it is likely that site numbers fell with the advent of Arab (7th-9th century) invasions and the unstable political and military situation that occurred as a result of these incursions (Cooper and Decker, 2012). The fact that there was little construction and development in site locations (figure 6.3) suggests a reduced period of growth as the region was passed through the hands of Seljuk and Ottoman rulers. ‘The ebb and flow of Byzantine-Arab warfare’ (Cooper and Decker, 2012 pg. 21) would have put considerable stress on populations as attack threatened everyday living but it remains uncertain as to whether settlement changes were driven by imposing policy or a communal response to the upheavals (Cooper and Decker, 2012). The major Roman/Byzantine urban city of Tyana is said to have been sacked many times due to its strategic importance in terms of position (Cooper and Decker, 2012), placing its’ inhabitants on a constant state of alert. With respect to other villages and towns, it is likely therefore that significant population shifts occurred as people sought to avoid the pursuing conflict and as the role of settlement also changed.

Whilst the full trends in settlement distribution and density for periods following the 10th century AD cannot adequately be identified here, it can be concluded from other survey work (Baird, 2001b; Matthews and Glatz, 2009b) and published work (England *et al.*, 2008) that settlement numbers in central Anatolia remained relatively low and that habitation was relatively stable. Cooper and Decker (2012) suggest that settlement had been greatly affected, resulting in the intensification and fortification of strategic urban centres and a move back to Cappadocia's ruralised past. Occupation during the Medieval and Ottoman periods relied heavily on agricultural prosperity which helped to maintain a steady cultural landscape for a time (Eastwood *et al.*, 2007b). Life was ultimately administered through village living and cereal based agriculture (Eastwood *et al.*, 2007b), with a mix of Christian and Muslim populations (Ballian, 2010).

6.5. Chapter summary

The various selected results for the three Cappadocian surveys covered here demonstrate a varied settlement history that is only in part comparable to changes documented in neighbouring regions. The evidence is such that it is possible to detail large scale changes in settlement distribution and the role of the Cappadocian landscape in habitation preferences. A major factor in the constructed settlement culture seems to be the location of Cappadocia and its placement between often opposing political entities. Local populations would have certainly played a role in shaping settlement histories but ultimately it appears to be the larger scale socio-political/economic changes that affected site number and type for the region.

Given the problems associated with investigator biases and identifying certain material culture types, historical data are only a partial representation of the actual trends and patterns that had occurred. The similarities to other known survey results are encouraging and we can be sure that the spatial and chronological changes that were evidence are at least somewhat valid.

The pattern of change witnessed sees small-scale non-sedentary communities mould themselves into urban and complex communities, often alongside developments in economic strategy and political administration. The Cappadocian surveys identified, in the form of mainly lithic scatters, a clear Pre-Neolithic phase prior to a well-developed and substantial Neolithic occupation built around access to raw materials and exchange networks. The first substantial phase of intensified occupation however did not begin until the Chalcolithic when settlement numbers increase, and continue to increase well into the Middle Bronze Age period. Mound sites are the most dominant site type at this time, some of which continued to be occupied over many thousands of years showing incredible continuity and a conservative approach to settlement. The MBA period was one of relative stability and growth, anchored into the continuous economic prosperity of the area. Settlement numbers from the end of the MBA period through into the Iron Age are more changeable and for the first time a clear decline phase is evidenced. Also noticeable is a significant shift in the location of settlements, with evidence pointing towards a preference for more northern localities.

The Iron Age period sees considerable settlement expansion and growth but settlement strategies appear altered in comparison to previous phases with the establishment of more fortification site types. By the Roman period there is a substantial shift towards investiture in non-settlement type sites and a greater concern for security and defence. Settlement numbers in Classical times remain high and very few sites are altered or reconstructed from the late Iron Age onwards, suggesting strong settlement continuity. Another fundamental change is evidenced post Roman, and more particularly between this and Medieval times where settlement numbers decline in light of political instability. The apparent decline in occupation must be approached with caution however due to the lack of survey investigation for these historical phases. During Medieval and Ottoman times, the pattern of settlement change stabilises as communities re-establish their agricultural heritage and the threat of attack diminishes.

In and around Nar Lake there too have been significant shifts in settlement. The most prolific occupation of the area was seen during Neolithic times when a number of workshop type sites were recorded. Given the popularity of Cappadocia during EBA and IA-Roman times, Nar Lake was also heavily populated during these periods, consisting predominately of multi-period mound occupations. Two major decline phases are noticed in the survey data. Very few sites are recorded within ~30km of Nar Lake during LBA and Byzantine-Ottoman times, although some rock-cut dwellings are known about within the lake catchment. This signifies a dynamic settlement history for Nar Lake and suggests that the area was particularly favourable during certain periods of the Holocene.

Each phase and change in site number witnessed by the Cappadocian survey appears to have its own characteristics, which in most cases seem rooted to preceding periods. Despite period specific peculiarities, settlement organisation and fluctuation, and location do not alter too significantly between the Neolithic and Bronze Ages. Any disruptions to settlement planning are often small and short-lived, and appear to result from shifting political situations. Four major periods of change are identifiable, including: the dominance of workshops during the Neolithic, the prevalence and growth of höyük type sites in the EBA, the introduction of defensive architecture types by the IA and the decline in settlement during the 7-8th centuries. Geography also likely played some part in the changes witnessed and is what distinguishes these survey results from neighbouring investigations. Cappadocia’s abundance of raw material, particularly obsidian, and its dynamic landscape of plains and highlands encouraged targeted settlement for reasons including resource abstraction and fortification boundaries. Ultimately the patterns of settlement change documented here reflect the shift from small-scale resource gathering communities to a fully urbanised integrated system.

7. Palaeoclimatic, palaeoenvironmental and archaeological change

7.1. Chapter introduction

Palaeoclimatic and environmental information identifiable from geochemical and sedimentological changes allows these records to be applied to archaeological data to provide information about the links between natural change and cultural change. The inferred palaeoclimatic and environmental changes at Nar Gölü coincide with considerable shifts in past human practices and habitation and indicate possible associations between the two systems. Past climatic and environmental variability may therefore have a significant relationship with the pattern of human change witnessed in Cappadocia, central Anatolia. This chapter combines archaeological survey data collated in this thesis (chapter 6) with inferred palaeoclimatic and palaeoenvironmental changes (chapter 5) to investigate how social systems developed alongside changes in variability as per the thesis aims.

7.2. Change in palaeoclimatic, palaeoenvironmental and cultural relationships

7.2.1. An overview to past climate-environment-culture relationships

The Nar Gölü geochemical record indicates considerable environmental and climatic variability in central Anatolia for the late Pleistocene and Holocene. Itrax derived XRF data show pronounced shifts between wet and dry, changes in lake level and highly fluctuating levels of detrital influx linked into changing climate systems and localised environmental dynamics (including human impact). A key aspect of this project is to link the geochemical record with archaeological data over the longer-term perspective (*longue durée*) to understand the integration between past environmental/climatic change and human response within central Anatolia. Lacustrine sediments in central Anatolia have already been used as archives to address the effects of climate on human development (England *et al.*, 2008) but only for selected time periods. The Nar Gölü record, covering the last ca. 14000 years offers the chance to reconstruct climate forcing on societal evolution for longer time duration than has previously been attempted. Due to the fact that archaeological evidence may only show selected response to climatic change, the focus of this study is on change at the largest chrono-cultural scale to make sure that the overall pattern of human action can be summarised.

Societies will often adjust with little difficulty to most natural changes, however some changes are of such magnitude or rarity that societies can be deeply affected by them (Sheets and Cooper, 2012). Vulnerability or post climatic/environmental event stress can be witnessed in the archaeological record and thus through comparisons of archaeological site survey data and Itrax derived geochemistry it is possible to highlight links between the natural and human worlds. Many of the conceivable human responses to climatic stress will not be detectable in the archaeological record. The most visible one that is considered within this study is the change in settlement population and site numbers brought about by human dominance in the landscape.

7.2.2. Matching of archaeological periods to Itrax derived XRF data

The study of human response in relation to climatic and environmental history must first identify which archaeological periods occur with climatic phases in the geochemical and sedimentary record. As already stated, it is important to observe the whole historical trajectory in order to see over-arching links between the two systems. With this in mind, figure 7.1 shows the long term view of archaeological cultures against the Nar Gölü geochemical data. Details of the site survey data have also been added to show where the periods of densest occupation lie in relation to the geochemical profiles. A discussion of this figure and the implications it has for understanding the interaction between past populations and natural change will be dealt with in the following sections.

7.2.3. Archaeological periods and Nar Gölü inferred palaeoclimate

The linking of archaeological periods to the Nar Gölü geochemical record (figure 7.1) highlights significant shifts in habitation and human activity coinciding with periods of pronounced climate change in central Anatolia. A discussion of climate and cultural change prior to the Holocene will not be made due to the lack of archaeological data for the late Pleistocene but here follows an overview of the comparisons from 10,000 years B.P. to present day.

Early Holocene climate (sediment units 5b, 5c & 5d), as inferred from the Ca/Sr and Zr/Rb geochemical ratios was moist and precipitation levels were high; this pattern of climate is also witnessed in other records from Turkey and the Eastern Mediterranean (figures 5.17 & 5.18). This period of enhanced moisture availability and favourable climate coincides with the development of the first sedentary Neolithic communities in central Anatolia, shown in figure 7.1 by the establishment of Aceramic Neolithic populations. It is interesting to note that the ‘Neolithic’ way of life developed later in central Anatolia than in Eastern parts of Turkey and the Levant (Schoop, 2005b), despite the establishment of climate conditions more than suitable for the adoption of the agricultural package promoted by other Near Eastern Neolithic populations. It is therefore possible to postulate a localised tradition of cultural change that has limited direct relation to climate, because climate amelioration (wet and warm) would have provided a perfect backdrop for testing agricultural subsistence practices.

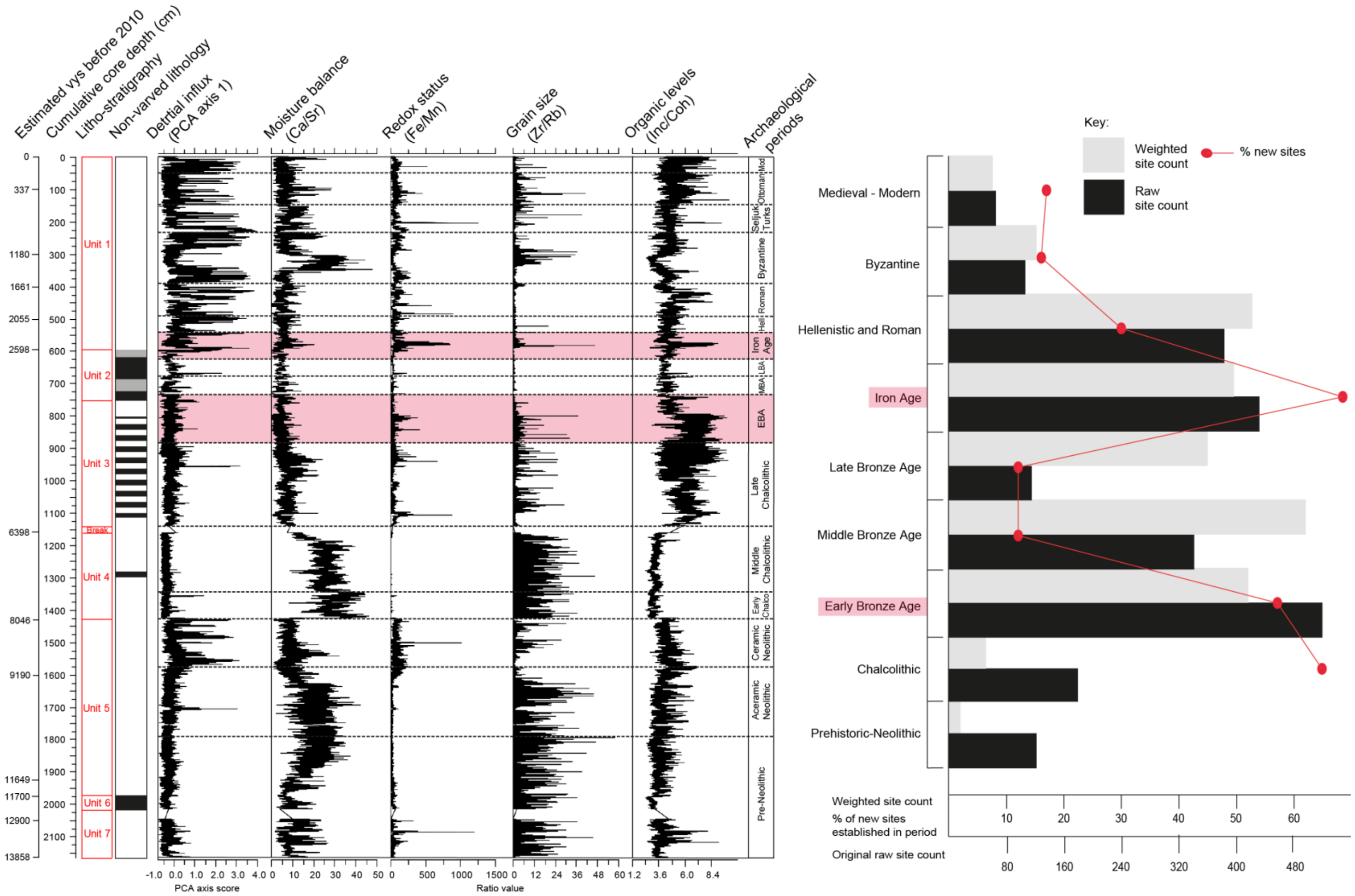


Figure 7.1: Long-term perspective of archaeological and climatic/environmental change. Archaeological periods for central Anatolia have been placed alongside the Itrax derived XRF geochemical record to show links between cultural and natural change. Archaeological site survey data suggests that the most prolific periods of occupation occur during the EBA and IA which are highlighted by pink. Boundaries for the late Chalcolithic and Bronze Age are provisional given the chronological uncertainty here.

On the other hand, however, climatic amelioration would have encouraged new ecosystems to develop, which were advantageous to a range of wildlife and thus would have allowed proficient exploitation of local animal resources. With an abundant and high density of possible food sources, hunter-gatherer populations would have been less likely to alter their subsistence strategies if times were ‘good’. Hunter-gatherer populations would have sustained more traditional subsistence practices as they could cross new environmental thresholds due to the higher water availability. Perhaps the process of ‘Neolithisation’ was postponed due to ability to build equally as complex societies from the use of only ‘natural’ resources; an argument favoured by Schoop (2005b). Aşıklı Höyük, an Aceramic settlement in Cappadocia, and close to Nar Lake, witnessed advanced hunter-gather subsistence practices continuing for more than 1000 years without clear reliance on cultivated plants (Esin and Harmankaya, 1999), which likely relates to the stability in agreeable climate conditions. Of course, an absence of plant or animal domesticates does not entirely imply that they were not manipulated for consumption purposes but the fact that at many sites across central Anatolia there is a heavy reliance on ‘wild’ food sources for the Aceramic Neolithic suggests that domesticates played a minor role in subsistence practices.

As Schoop (2005b) suggests, it is likely that the Aceramic Neolithic semi-mobile communities were dependent and thrived on the new grassland habitat that emerged due to the wetter and moister climate conditions that prevailed during the early Holocene. Turner *et al.* (2010) agree that the early Holocene is marked by the rapid expansion of grassland across the Anatolian plateau but relates the change to wetter but seasonally dry climate which increased the occurrence of dry-season burning of landscapes. The main stimulus to sustain hunter-gather ways of life may have been the rich and varied environmental possibilities brought about by a favourable climate state but possible restrictions did exist in the form of increased seasonal extremes and burning frequencies that may have made the shift to agriculture more difficult. It is difficult to partition the role of humans from increased fire frequencies, but during the earliest Neolithic, it is likely that climate was the principle ‘pacemaker’ for fire activity (Turner *et al.*, 2010). Fe/Mn ratios from Nar Lake for this period however signify that lake conditions were primarily oxic. The growth of oxygenated conditions at the lake bottom has been inferred as representing a phase of reduced seasonal extremes (chapter 5) and is in contrast to Turner’s assumptions. Perhaps the role of humans on the fire activity of the early Holocene has been under-stressed.

Interestingly, during the Ceramic Neolithic where there is a reduction in moisture levels as indicated by reduced Ca/Sr values (figure 7.1) we also see new cultural patterns emerging in the archaeological record (sediment unit 5a), namely increased ritual activity and household autonomy (Düring and Marciniak, 2006). The Ceramic Neolithic in the area may represent a period of emerging domestic production and consumption but it is also associated with the development of the household and the breakdown of conservative lifestyles (Marciniak and Czerniak, 2007). The question therefore remains as to whether reduced moisture levels impacted upon the more ’traditional’ lifestyles that had been the case in the earlier Neolithic, forcing later Neolithic populations to seek new subsistence modes and form new relationships within the community. Boyer *et al.* (2006) suggest that increased flooding and alluviation of the Konya Basin, perhaps partially driven by more seasonal climatic conditions and therefore increased soil erosion had little effect on human occupation at the time. In fact, communities responded well to the spring floods which may have been an advantage to the mixed-farming communities.

Drier and less encouraging conditions nevertheless would have meant that the grasslands which had sustained populations until the late Neolithic would have altered in character and thus would have altered the availability of abundant ‘wild’ resources. The scale of this social change is most evident in the settlement data for Cappadocia for the late Neolithic/early Chalcolithic which witnesses considerable changes. Sites appear in completely new areas and are much smaller in size than those that had previously been established. Settlements such as Tepecik-Çiflik, Köşk Höyük and Pınarbaşı-Bor show a less permanent nature to habitation (Düring, 2011) in comparison to early Neolithic occupations and it is speculated whether these changes were influenced by the shifting climate system of the time or whether driven by social practices alone. The hypothesis that deterioration of ecological conditions as the result of climate lead to an environment that could no longer support populations (Özdoğan, 1997) in the way it had previously is likely given figure 7.1

The shifts in cultural practices seen during the late Neolithic are also driven by new economic practices and the presence of obsidian trade routes through the central Anatolian plains (Balkan-Atli *et al.*, 1999), and cannot be solely determined by shifts in moisture availability. This helps explain way settlement sites shift in character and why populations become less communal in nature if the construction of society was becoming more driven by economic processes. However it has to be considered that a decrease in precipitation would have put strain on populations dependent upon natural ecosystem services for prosperity, likely encouraging them to adopt new measures, which in this case may have resulted in an increased reliance on obsidian exchange and farming lifestyles. A straightforward link between technological development and climate is not proposed but it is possible to envisage the effects a drier climate may have had on the shared traditions of the earlier Neolithic and facilitated the movement of people away from hunter-gatherer lifestyles.

Another point to mention regarding Neolithic lifestyles is that some authors (Weninger *et al.*, 2006; Weninger *et al.*, 2009) have discussed Neolithic reactions to the 8.2 ka cal. yrs. B.P. event and the potential implications climatic drying had on the Neolithisation process. Major disruptions to Neolithic cultures in central Anatolia are believed to be driven by aridity around 8200 cal. yrs. B.P., and it is speculated that this climate event led to settlement abandonment and cultivation failures (Weninger *et al.*, 2006) towards the end of the Ceramic Neolithic. The Nar Lake record shows two peaks in detrital elements ca. 8303 and 8169 vys. B.P. which may be related to increased arid conditions but comparisons to the archaeological record (figure 7.1) reveals that similar detrital peaks prior this had no relation to Neolithic development so there is no obvious link between aridity and societal change in this instance.

By the early Chalcolithic we see communities based around farming practices and economies which were dependent on the exploitation of local resources (Düring, 2011). Archaeological survey data suggest that site numbers increase, as do the number of new locations being exploited (chapter 6). This is against a backdrop of enhanced moisture levels as indicated by the geochemical proxies at Nar Lake (figure 7.1). The primary cause of settlement change at the time was likely the result of economic prosperity (Marciniak and Czerniak, 2007) but a developing favourable climate may have also promoted the stability and growth of early Chalcolithic communities, particularly if dependent on the growth of crops for food. An increase in regional moisture levels would have also allowed new areas to be agriculturally sustained thus allowing for settlement expansion and increased use of landscape. Thus it appears that the enhanced levels of precipitation may have affected population distributions in terms of increasing the ability to grow and expand. Agricultural development and associated societal development benefitted from higher levels of humidity, both in terms of climate and water availability.

It has been noted that in Cappadocia, the middle Chalcolithic witnesses an abandonment and collapse of permanent occupation in comparison to the early Chalcolithic (Marciniak and Czerniak, 2007). One of the reasons postulated for settlement collapse is believed to be the breakdown of obsidian exploitation and a decrease in the availability of raw materials (Thissen, 2002). There is no significant evidence for a major change in climate during the middle Chalcolithic at Nar Lake (figure 7.1); stable and consistent climate conditions therefore corroborate claims that the middle Chalcolithic cultural decline was human led. The end of the middle Chalcolithic phase however coincides with the biggest shift in lake state witnessed for the entire Nar profile, which sees the start of an extreme reduction in available moisture levels and a decrease in precipitation levels (figure 7.1). By the middle Chalcolithic/ late Chalcolithic transition we see the onset of aridity which would have likely caused major challenges for human populations. Perhaps the parallel changes witnessed in the archaeological record, although not witnessed to such extend here due to poor survey coverage and the collation of all Chalcolithic sites into one time category (chapter 6), relate partially to the mid-Holocene climate degradation initiated during the 6th Millennium B.P. which would have certainly impacted upon the agricultural lifestyles developed during the early-mid Chalcolithic.

Coincident with and partly stimulated by this climatic downturn, complex societies developed within the Eastern Mediterranean during the late Chalcolithic and Bronze Age (Roberts *et al.*, 2011a). Rather than having a ‘negative’ effect, the climate shift corresponds to the start of EBA city dominance (Rosen, 2007) and the start of metal manipulation in central Anatolia, and would suggest a clear ‘positive’ relationship to the climatic stimulus (Roberts *et al.*, 2011b). The move to a drier climate may have initiated a response in human populations to agglomerate and live in close proximity to each to combat the effects that the change in climate may have had, particularly the establishment of a typically ‘Mediterranean’ ecology favourable to shrub vegetation and lacking in woodland habitats (Roberts *et al.*, 2011a). Interestingly, we see the biggest period of settlement growth and prolific occupation occurring in central Anatolia during the EBA at a time of highly reduced water availability (figure 7.1) and associated landscape evolution (Roberts *et al.*, 2011a). It is also possible that settlement increase began earlier during the late Chalcolithic but because site survey data fails to classify Chalcolithic sites by sub-period they have had to be grouped together (chapter 6) and thus this limits the interpretation of late Chalcolithic habitation practices.

Whilst the climate regime may have seemed unfavourable, EBA settlements prospered (chapter 6) which likely related primarily to social and political factors, but these emerging centralised powers (Rosen, 2007) may have also been encouraged through the necessity to protect growing populations from the occurrence of drought and unpredictable climates. The fact that people lived well during these times may suggest a unique way of coping during what should have been a harsh time for those reliant on subsistence agriculture. Living under administrative rule and within urban centres (Rosen, 2007) may have been a way of dealing with climatic risk and depletion in humidity.

Settlement numbers during the MBA remain relatively unchanged even though many sites witness abandonment and very few new sites are inhabited (chapter 6); this is during what is interpreted to be a continuation in arid conditions. In fact, by sediment unit 2 we see arid conditions worsen at Nar Lake with lake waters becoming exceptionally low and precipitation levels significantly decreasing as indicated by low Ca/Sr levels and the absence of varve formations (figure 7.1). It is also interesting to note that the start of the MBA and the end of EBA coincides with the development of what Nar Lake data suggests to be the most arid phase in central Anatolia (although there is a large dating uncertainty here). This transition period is renowned for being a period of collapse in the archaeological record (Mellaart, 1958) (see Roberts (2011b) for further information). It may be likely that social disarray and settlement abandonment resulted from both increasing drought frequency and a change in the political system encouraged by drought weakened communities (Roberts *et al.*, 2011b). The role of a 4.2 ka cal. yrs. B.P. abrupt aridity event in the demise of EBA populations has been the subject of lively debate (Algaze and Pournelle, 2003; Cullen *et al.*, 2000; Kuzucuoğlu, 2007; Lemcke and Sturm, 1997; Rosen, 2007; Weiss *et al.*, 1993) but evidence in the Nar data for shifts in aridity are not well constrained chronologically. In reality, Cappadocia experienced a longer-term trend in drying that was not sudden in nature.

The change in occupational growth from the EBA to the MBA (chapter 6) was likely brought about an overall sensitivity to a drier climate which ruptured local traditions and trade links, and was worsened by ill-effective response mechanisms. Despite the dry climate challenge faced by MBA populations, settlement data outlined here would suggest that many societies coped reasonably successfully, as 42% of sites showed no change between the EBA and MBA periods (chapter 6). Societies faced the climatic challenge and developed well during the MBA until the LBA where there is once again evidence for cultural instability.

LBA site data suggests another fall in settlement numbers and a shift in occupational practices, with a further 60% of sites becoming abandoned (chapter 6). There are three competing perspectives for the decline in Bronze Age societies. Firstly that the widespread settlement collapse reported for the LBA and evident in the settlement data here (chapter 6) is linked to the collapse of the Hittite Empire and the associated gap in political power that was filled by incoming ‘Sea People’ (Kealhofer *et al.*, 2009; Roberts *et al.*, 2011b; Voigt and Henrickson, 2000). Secondly that there were internal conflicts brought about by a reduction in urbanisation, population, trade, literacy and centralised authorities and thus sustainability (Kealhofer *et al.*, 2009; Riehl *et al.*, 2012). Thirdly that a phase of significant aridity and drought (figure 7.1) events hastened socio-economic problems (Kealhofer *et al.*, 2009). Sustained arid periods and reduced water levels would have only added to the problems already created by foreign raids and increasingly would have put human populations under intense internal stress.

The impact that the shift in climate may have had on populations can be seen in pollen diagrams from the Eastern Mediterranean (Boyer *et al.*, 2006; Eastwood *et al.*, 1998b). The LBA phase witnesses decreased forest cover and land clearance which may relate to human populations trying to cope with the ever changing climate conditions, and tree species declining in light of the drier climate. Arboreal pollen levels at Eski Acıgöl reach their lowest during the LBA (figure 5.17) which may relate to increased aridity and human impact during the Beyşehir Occupation phase (Eastwood *et al.*, 1998b). Much of the effects of drier conditions on the environment were exacerbated by the actions of people in response to the downturn in climate and would have certainly further influenced the sustainability of subsistence strategies and LBA lifestyles. Mid-Holocene human populations were transformed by the complex interactions between climate forcing events and human activities (Roberts *et al.*, 2011b).

It took some time before societies successfully managed to cope again with problematic climate changes. It is not until the late Iron Age where we begin to see another phase of settlement growth (chapter 6) likely encouraged by new economic and political affinities. In fact, the IA period demonstrates a time were cultures blossomed in the face of an unstable but improving climate (figure 7.1) as seen by increasing urban development and the inter-connectedness of tribal kingdoms (Gunter, 2012). During the later IA, settlement dramatically increases, and corresponds to a time of increasing precipitation levels after 2600 cal. yrs. B.P. (figure 7.1). It could be of some significance that the height of IA settlement coincides with an improvement in climate and there is a remarkably close correspondence between a wet phase and establishment of late Iron Age, particularly Persian, rule after 2500 cal. yrs. B.P.

Archaeological survey data suggest little change in settlement from the IA through into Hellenistic and Roman times which is a similar pattern evidenced in the climate record (figure 7.1) as moisture levels stabilise for these Classical archaeological periods. The shift away from extreme aridity though would have been beneficial to populations of Classical times and may relate to Cappadocia becoming an agricultural production zone for which evidence exists from the late Iron Age (Balatti and Balza, 2012). Other studies suggest that the Eastern Roman Empire was generally wet and warm for a sustained period (McCormick *et al.*, 2012) which may have played some role in Cappadocia re-establishing itself as an area of economic and strategic importance, particularly in Roman times.

It is noteworthy to suggest that the best represented period of Byzantine rule, the early Byzantine period corresponds to a period of higher precipitation, and therefore a decreased frequency of drought (figure 7.1), making climate conditions more suitable for greater agricultural prosperity. The numerous Arab raids that likely passed through Cappadocia at the end of the early Byzantine period likely put stress on Byzantine communities (England *et al.*, 2008).

With the onset of modern climatic conditions, we see short term fluctuations between wet and dry, with drier periods coinciding with the start of Seljuk and Ottoman rule respectively (figure 7.1). It is likely that settlement changes (chapter 6) during this time were driven by political changes but an unstable climate would have certainly put pressure on populations who were already under threat from instabilities in agricultural practices and disturbances brought about by raids and warfare. A study by White (2011) is important in understanding the possible linked between the environmental and climate history of Anatolia alongside the political, economic and social changes in the early modern Ottoman Empire. The focus of the study is on the Little Ice Age (LIA) climate event and how it triggers the *Celalî* rebellions that nearly brought an end to the Ottoman Empire during the 17th century AD. Ultimately, agricultural prosperity was delayed, in his opinion, by climatic crisis. In the Nar geochemical record (figure 7.1), there is little evidence for a major cooling trend as generally proxies do not respond to temperature directly but a peak in Ca/Sr around AD 1650 may relate not to heightened rainfall but moisture availability from increased snow-melt (a cause of the riots). On the whole, the Nar data suggests reduced water availability during Ottoman occupations (figure 7.1) and seasonal data from Nar diatoms (Dean *et al*., 2012) suggests reduced seasonal conditions implying that winters were on the whole dry. Drier conditions during the LIA (Roberts *et al.*, 2012) may have coincided with cooler conditions and therefore bad winters.

7.2.4. Summary of archaeological and proxy record comparisons

The Nar Gölü palaeoclimatic and Cappadocian archaeological data are on the whole complementary. At times of past human change we see variations in the climate record, thus detailing possible connections between socio-economic and political changes in the Holocene with the climatic changes that deeply marked the region. The Nar Gölü data indicate three major periods of climatic discontinuities that appear to at least characterise the archaeological record. Firstly is a wet early Holocene which coincides with substantial conservatism in the archaeological record and economic prosperity. Secondly, the trend to more arid conditions during the mid-Holocene coincides with increasing complexity and the development of urban lifestyles during the Early Bronze Age. This is interesting considering it would have been expected to see increasing social stress in the archaeological record during worsening climate. Thirdly, drier climatic conditions that persisted thereafter coincided with the height of late Holocene occupation.

7.3. Variability in the Nar Gölü geochemical record and its relationship with cultural change

7.3.1. Nar Gölü sediments as an archive of climatic variability

When trying to understand cultural transformations in the context of shifting climate states it is necessary to go beyond comparing patterns of change, and focus more heavily on the causation of change. Of course the relations between culture, climate and environment are complex and causation can be difficult to demonstrate. One way of looking at causation over scales of centuries-millennia is to examine patterns of stability and instability in the climate record. This approach can be a more productive way of examining climatic events with cultural actions as it avoids having to directly match records with differing temporal resolutions (Rosen, 2007). It is not proposed here that cultural changes are principally related to stability in climate but that variability in climate may influence or affect the way that natural change is experienced and that in turn could result in different socio-cultural factors or in the case of this thesis, settlement patterns.

Climate change happens over different lengths of time, including millennia, centuries and decades but it is the change that happens at the smallest scale, for example year-to-year that people will experience most readily (Biehl, 2012). Human societies and individuals will remember most clearly changes in the natural world that have happened within life spans and those which happened to be most abrupt or different. Short-term fluctuations also have a more significant impact on human systems if the system is already weakened by longer-term climate patterns (Parry, 1978). It is therefore necessary to understand all climate ‘triggers’ as year-to-year fluctuations are the means through which longer-term change is experienced (Parry, 1978).

From a human perspective, a shift from what is normal and expected (stable) has the potential to initiate a shock within the social system. People can respond to predictable climate changes or invariable conditions but are less likely to formulate successful response mechanisms in the face of discontinuity in climate. As Sandweiss and Quilter (2012) state, it is the ‘unknown unknowns’ that create the most problems and challenges to cultural prosperity if the unknowns are potentially unfavourable.

The view considered here takes into consideration Marek Zvelebil’s (2005) idea that human agency and human decisions, as represented in the archaeological record, can be structured by present and past knowledge of the natural world. If people’s constructs of climate are promoters of cultural transformation then an unstable climate or sudden event that had not been socially or individually understood previously may represent a larger ‘negative’ factor within cultural frameworks. Climate which was stable and ‘understood’, even that which was extremely dry or wet, could be incorporated into human habits and practices as has been argued by Feynman and Ruzmaikin (2007) regarding the adoption of agricultural practices. Vulnerability of past people to climate change is not a straightforward relationship with exposure, it also relates to people's perception of the climatic risk (Berkes, 2007). If that climatic risk was characterised by surprises then it would be hard to build effective perceptions of what that risk entails, especially without any other cultural memory of the risk. Only if the climate risk is understood can people become resilient to uncertain times and thus periods of unstable climate, if sudden and unprecedented may likely cause societal adaptation problems.

With this in mind, the Nar Gölü geochemical proxy record, which records climatic change at yearly scales, can be examined in terms of climatic stability to see how periods of more predictable climate relate to the archaeological history of central Anatolia. Holocene climatic and environmental variability, as recorded in the Nar record, have been analysed in 'time windows' or selected temporal intervals along the core sequence to identify periods of stable and unstable conditions. The time windows selected for investigation represent 500 varve year intervals, and have been constrained by non-varved and un-dated sections. Table 7.1 shows the mean value, standard deviation and coefficient of variance computed for ten 500 varve year time windows using the Ca/Sr and PCA axis 1 Itrax XRF data. The Ca/Sr profile has been used because the ratio proxy represents effective moisture balance within Nar Lake and is thus most likely to relate to changing climatic conditions. PCA axis 1, as an indicator of clastic input into the lake has also been used as it may relate to changing environmental condition, including catchment disturbance. In order to quantify variability in the geochemical proxies, the coefficient of variance (CV) for Ca/Sr and PCA axis 1 was calculated; a larger CV value means greater dispersion in the dataset and therefore is used to show the extent of variability in relation to the mean. The standard deviation of each dataset was divided by the mean in order to calculate the coefficient of variance; this allows for comparisons of time windows with vastly different units of measure and means, and allows for a discussion regarding the level of variation for each time window. CV requires positive values to avoid being misleading therefore PCA scores were adjusted by adding a constant of 1 to circumvent using negative numbers.

Table 7.1 and figure 7.2 highlight changes in variability in the Ca/Sr and PCA records as inferred from the coefficient of variance values and show changes in the mean state. High average values for the PCA axis 1 data are evident during the Ceramic Neolithic (1.03) and from the late Iron Age up until Ottoman times (above 1.39), indicating high clastic in-wash during these periods. High average values for the Ca/Sr data are documented for the Aceramic Neolithic (22.03) and middle Chalcolithic (25.54) suggesting that these periods were the wettest on record. The calculation of variance (CV %) for each proxy record suggests that the most stable and therefore least variable phase coincides with sediment unit 4 (1161.2-1428.2cm) – variance of 15% (PCA) and 13% (Ca/Sr). Highest variability and therefore unstable conditions are most evident for the top two time windows associated with sediment unit 1 (0-592.7cm). Variance increases significantly within the late Byzantine, Seljuk and Ottoman time window to 72% (PCA) and 59% (Ca/Sr) which are the highest values for the entire record for both proxies. An increase in variability to this degree would be expected during times of acute climatic fluctuations and heightened terrestrial disturbance.

Table 7.1: Mean value, standard deviation (std) and coefficient of variance (CV) for Ca/Sr and PCA axis 1 selected time windows. Grey cells highlight intervals with higher variability. Std and CV values have not been computed for unit 2 because the sediment is not varved here and dates are uncertain.

				PCA axis 1 (proxy for clastic in-wash)			Ca/Sr ratio (proxy for moisture balance)		
500 varve year time window (vys)	**Associated depth interval (cm)**	**Associated sedimentary stratigraphic unit**	**Associated cultural phase(s)**	**Average value (PCA score)**	**Standard deviation (std)**	**Coefficient of variance (%)**	**Average value (Ratio value)**	**Standard deviation (std)**	**Coefficient of variance (%)**
500-1000	135-260	1	Late Byzantine, Seljuk and Ottoman	1.73	1.24	72	7.97	4.72	59
1500-2000	366-490	1	Roman and Early Byzantine	1.71	0.98	57	5.22	2.54	49
2100-2600	499-596	1	Late Iron Age and Hellenistic	1.39	0.77	55	5.71	2.09	37
2700-3200	613-720	2	Mainly LBA. Possibly also MBA and Early & Mid Iron Age depending on dating	0.86	-	-	4.67	-	-
4500-5000	750-871	3	EBA	0.84	0.17	21	4.18	1.95	47
5500-6000	1000-1061	3	Late Chalcolithic	0.81	0.14	17	6.99	1.99	28
6700-7200	1211-1294	4	Middle Chalcolithic	0.61	0.09	15	25.54	3.33	13
8200-8700	1454-1514	5a	Ceramic Neolithic	1.03	0.54	52	8.47	1.84	22
10000-10500	1713-1785	5b	Aceramic Neolithic	0.71	0.13	18	22.03	4.45	20
13000-13500	2064-2122	7	Pre-Neolithic	0.67	0.14	21	10.20	4.64	45

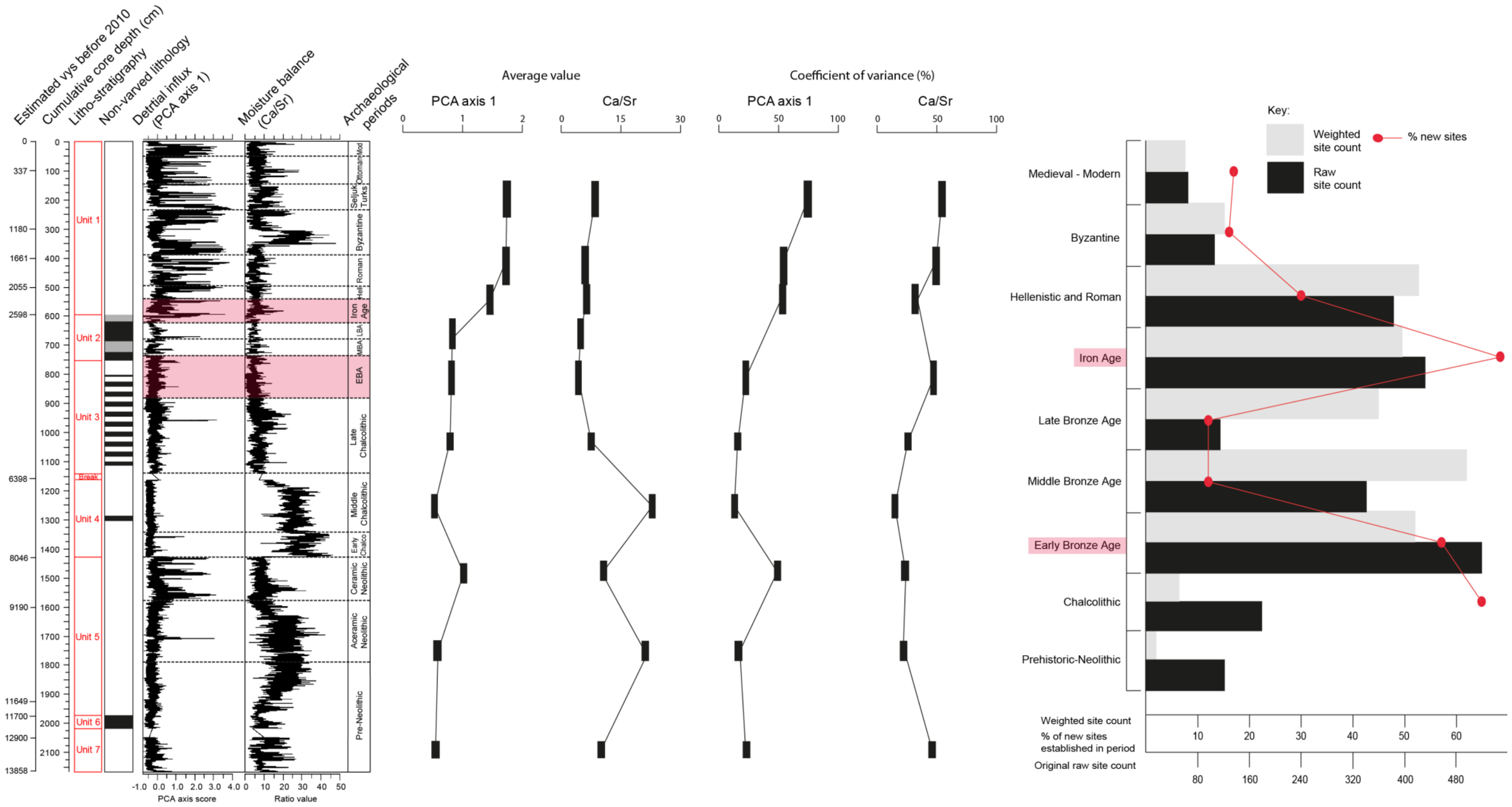


Figure 7.2: Average values and CV (%) per time window plotted alongside archaeological survey data and periodisations. Higher variability as inferred from the CV data for PCA axis 1 is evident during Ceramic Neolithic and Iron Age-Ottoman times. Higher variability for Ca/Sr is evident during Pre-Neolithic, EBA, and Roman-Ottoman time.

There is little doubt that the calculations of variance for each time window suggest that at least four of the ten time slices have experienced relatively instable climate conditions. Changes in the Ca/Sr ratio through the sedimentary record at Nar principally reflects changes between wet and dry and therefore increased variability relates to higher amplitudinal shifts in climate state and regional moisture balance. Higher climatic variability is evident during the Late Glacial period (45%) (figure 7.2) which is likely the result of the interplay between interstadial and stadial periods (see Abrantes *et al.*, 2012 for summary). Higher climatic variability is also evident during the Early Bronze Age which has a coefficient of variance value of 47% (figure 7.2). The highest CV percentages are associated with Roman and post-Roman cultural periods (49 and 59%). The relatively drier climate state for EBA and post Roman times, and heightened variability suggests a very challenging climate state during these periods. Not only were conditions arid but they were unpredictable and could change quite significantly in a short space of time.

Higher variability levels for the Ca/Sr record for the EBA may have some relation to the type of laminae formation witnessed, which at this time may not be annual in nature and are dominated heavily by thick organic rich deposits. A rise in organic matter within laminated sections could signify deposition by more intensive flooding (Martín-Puertas *et al.*, 2009) in the locality of Nar Lake which may explain why the EBA is associated with a more variable Ca/Sr record if certain periods experienced higher-energy water influxes. A higher Ca/Sr CV% during the EBA though is surprising given the lack of visual fluctuations in the Ca/Sr profile for this time (figure 7.2). A small shift in the mean state during the associated time window could be one likely explanation for the pattern witnessed. Whilst attempts were made to avoid time windows that covered significantly different mean states or peaks in the data, the length of the time window (500 vys) and dating problems, in this case, resulted in the need to overlap the time segment with a small adjustment in mean state. Therefore, high variability levels for the EBA may be deceptive.

The relationship between climatic variability and archaeology is of interest during unit 1 where we see the biggest amplitudinal shifts in Ca/Sr ratio. Higher variability levels during Roman and early Byzantine phases coincide with a generally high level of occupation in Cappadocia (chapter 6) and a flourishing agrarian community (England *et al.*, 2008) suggesting that greater shifts between wet and dry were relatively irrelevant to the prosperity of human populations. During increased climatic variability from late Byzantine times we see considerable changes in site number which show an overall decline in habitation after the Byzantine period (chapter 6). It is likely that habitation changes related primarily to the impact of multiple invasions and internal religious reform known as Iconoclasm (Ousterhout, 2005). However, due to the unpredictable nature of climate during late and post Byzantine times it is easy to envisage communities put further under stress by the prevailing climatic conditions. Given the political upheavals of the time it is likely that such climatic conditions only exacerbated social instability.

The following two periods of Seljuk Turk and Ottoman rule saw central Anatolia move between the hands of various political leaders and it is likely that the Arab Muslims who were used to drier climates took advantage of periods of aridity by making consistent attacks upon Byzantium with the hope of taking control. It is witnessed in pollen records from the area (England *et al.*, 2008) that agrarian land was abandoned sometime around the start of incursions from Arab populations and it may be that both changes in the variability in climate and warfare resulted in this fatal damage to subsistence practices. Economic disruption, enslavement of populations and interruptions to agricultural life (England *et al.*, 2008) are commonly assumed consequences of the Arab incursions but little has been discussed relating to the impact of increasing climatic variability.

Increasing variability seems to have had less of an impact on later Medieval and Ottoman populations who may have been discernible to the unstable nature of climate. By this time, communities would have been aware of the issues faced during unpredictable climate conditions and built strategies to deal with this. Agricultural prosperity during the centralised and westernised Ottoman state (England *et al.*, 2008) suggests that populations were well adapted to the unstable climate regime. White (2011) however argues that agricultural prosperity and intensification was delayed as a result of unfavourable climatic conditions therefore it is interesting to consider the role of increasing climatic variability on landscape ecology and land-use. Agricultural strategies may have been affected by the less stable climate regime, particularly if the level of instability related to increased seasonal variation. The role of seasonality cannot be discussed in detail without finer detail investigation of the varve deposits but seasonality may have certainly played a large role in determining fluctuations between wet and dry, and thus impacted upon agricultural production. Well defined summer and winter laminae during unit 1 imply a clear distinction between a cooler wet and warmer dry season and therefore marked distinctions in yearly moisture availability. It is also possible that larger amplitudinal shifts were more noticeable against a back-drop of generally dry climate (7.97 Ca/Sr average) which increased the effects of an unstable climate, particularly if water availability decreased.

7.3.2. Nar Gölü sediments as an archive of human impact during the Holocene

Changes in the rate of sediment influx through the sedimentary record at Nar Lake reflect changes in climatic and/or land-use forcing mechanisms. The observed changes in PCA axis variability likely derive from increased catchment sediment supply or from within-lake redistribution processes. Periods of increased clastic variability during sedimentary sub-unit 5a (1428.2-1606.2cm) (52%) and unit 1 (0-592.7cm) (above 55%)

(figure 7.2) coincide with the development of Ceramic Neolithic and late Byzantine-Ottoman populations; with the whole duration of unit 1 also corresponding with Persian, Hellenistic, Roman and early & mid-Byzantine rule. During these cultural periods, archaeological survey data (chapter 6) suggest substantial expansion in human occupation and activity at and around Nar Lake. The role of anthropogenic factors on increased detrital input is therefore possible given the coincidence of heightened human activity close to Nar Lake and the proliferation of sediment influx instability. Here, the sediment variability data may therefore be used to evaluate the role of human presence in changing the sediment dynamics of the lake and catchment over the Holocene.

The level of sediment influx variability during sub-unit 5a (9190-8046vys) and unit 1 (2589-0vys) is unprecedented and may reflect the impact of amplified disturbance from human populations who potentially affected landscape stability and the sensitivity of soils to climatic changes. Increased land use by human populations during sub-unit 5a and the Ceramic Neolithic relates primarily to mining and obsidian resource abstraction activities conducted within very close proximity to Nar Lake (chapter 6) where lithic resources were exploited for the purpose of exchange (Balkan-Atli and Binder, 2012). Neolithic activities such as sedentary behaviour, agriculture and animal husbandry (Düring, 2011) also likely led to increased environmental instability at the time. In the late Holocene (here associated with sediment unit 1), catchment disturbance may have been influenced heavily by human factors rather than climatic or natural agencies as landscape change is believed to be largely driven by cultural actions (England *et al.*, 2008). Catchment changes at this time are said to relate to increased agricultural production from Hellenistic times onwards in central Anatolia where olive plantation becomes very fashionable under Classical rule (Mitchell, 2005) and much of Cappadocia became agrarian in nature until the establishment of the Turkish Republic (England *et al.*, 2008). The presence of rock-cut features on the edge of Nar Lake (figure 7.3) is also testament to the increased use of the area by Christian populations during the late

Holocene. Times of decreased landscape instability have been suggested to relate to times of economic stress and social upheaval as seen during the Arab invasions (England *et al.*, 2008) but more generally would relate to a reduction in human disturbance processes, evidenced here during the middle Chalcolithic (figure 7.2; chapter 6).

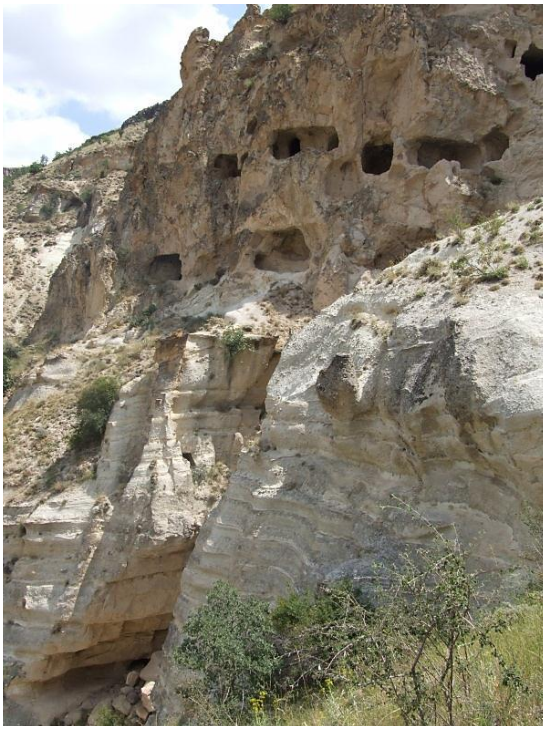


Figure 7.3: Photo of anthropogenic rock-cut features within the Nar Lake catchment.

Human-induced clearing of vegetated areas for economic and subsistence use, and as the result of population expansion may have increased the likelihood and intensity of water runoff from the catchment (e.g. Dearing, 2008) and therefore led to greater levels of terrestrial input into the lake. Climate parameters for both sub-unit 5a and unit 1 suggest relatively dry conditions on the whole (chapter 5) rather than higher precipitation levels; drier times would have also led to soil instability hazards through desiccation which may have been exacerbated by human presence and seasonal extremes. If higher clastic input is associated with generally dry and variable conditions climatically (units 5a and 1) (figure 7.2), but not heighten during increasing aridity (e.g. units 2 and 3) and high amplitudinal changes between wet and dry (e.g. units 3 and 7) (figure 7.2) then it can be hypothesized that anthropogenic effects are indeed greatly responsible for the very high allochthonous variability recorded for sediment sub-unit 5a and unit 1.

Peaks in the PCA axis 1 record (which reflects changes in both Ti & Fe) may also result from volcanic material being deposited within the lake system. The origin of increased detrital variability remains unclear as unstable conditions during sub-unit 5a also occur during a period of proposed volcanic activity in central Anatolia (Hamann *et al.*, 2010; Zanchetta *et al.*, 2011). It has been argued using Neolithic illustrations that the volcano Hasan Dağ (Mellaart, 1993) which is situated close to Nar Lake was active during Ceramic Neolithic times, and was therefore potentially erupting at a time of increased allochtonous input into Nar Lake. The presence of Göllü Dağ and Nenezi Dağ (figure 7.4) near to Nar Lake also implies that a volcanic origin for increased detrital variability is possible. Nearby Eski Acıgöl Lake documents tephra deposits dating to around 9.0 cal. yrs. B.P., as well as others between the late Pleistocene and mid-Holocene (Roberts *et al.*, 2001) suggesting noticeable volcanic activity within Cappadocia during enhanced early Holocene clastic in-wash at Nar Lake. Unfortunately, no definite tephra horizons have been identifiable in the Nar record to date but micro-faulting and disruption to laminations during unit 5 sedimentation may be linked into increased landscape movement which in turn could relate to volcanism or seismic activity, and thus greater detrital flow as a result of tectonic influences.

The abrupt subsequent stabilisation of sediment in the Nar catchment from ca. 8046-2600 varve years B.P. which likely relates to reduced human presence in the vicinity of the lake (chapter 6) and a reduction in human impact (mining, deforestation, pastoral and agrarian activities) is also of interest. Episodes of higher human occupation during mid-Holocene times (mainly EBA) (figure 7.2) show only a weak influence on sediment influxes, indicating either limited environmental impact/and or a more ‘buffered’ environmental system at this time. The mid-Holocene period is characterised by increasing aridity which does not appear to have greatly impact upon the record of environmental variability.

Figure 7.4: Photo highlighting the closeness of Nenezi Dağ volcano to Nar Gölü (volcano is situated at the back of the photo to the north of Nar Lake, photo looking north-west).

Nevertheless, despite potential volcanic and climatically induced landscape disturbances, there appears to be a relationship between past cultural actions and past catchment instability. Sediment influxes are most noticeable during sub-unit 5a and unit 1 and appear to be in response to specific human changes occurring within the lake catchment. Lacustrine response to changes in detrital input, and therefore landscape stability suggest that at times of increased human presence in the vicinity of Nar Lake during Ceramic Neolithic and post late Iron Age times, the degree of human impact increases in line with increased occupation. Erosional change explicitly associated with anthropogenic land-use practices produce a destabilised soil surface and increased erodability (e.g. Chiverrell, 2006) that is picked up within the Nar Lake geochemical record. This allows assumptions regarding the role of human impact on landscape stability and long-term environmental change within Cappadocia to be made. Detrital variability at Nar is a suitable data source for examining the magnitude of human impact on the environment during different occupational periods, with significant anthropogenic effects occurring from as early the 9th millennium B.P.

Further work at Nar Lake includes the use of faecal sterols to provide a record of human occupancy through time to help confirm the presence of past communities around Nar during heighted clastic variability. The study would be similar to that undertaken by D'Anjou *et al*., (2012) to distinguish between natural anthropogenic factors of lake geochemistry and environmental impact.

7.4. Evolutionary adaptive change, Cappadocian cultural trajectories and the Nar Gölü record

7.4.1. Theoretical framework

It is important to evaluate, within a selected spatial and chronological framework, aspects of the archaeological record (e.g. changing settlement patterns) that may offer evidence of human choice and decision making processes that arise as a reaction to climatic/environmental change (Asouti, 2009). The question of socio-economical adaptation and adjustability, as identifiable in the archaeological record, is therefore examined here in light of the variable and longer-term climatic changes documented from the Nar Lake geochemical record. A 'resilience theory' conceptual framework (Redman, 2005; Redman and Kinzig, 2003) is used to assess and characterise the changing periods of human occupation and coincident climatic changes. Concepts of panarchy and adaptive cycles (Gunderson and Holling, 2002; Vaneeckhout, 2012) will help to describe the changes in socio-economic systems. The use of this whole systems approach may be viewed with caution given concerns of resorting too heavily on Processual ideas of systemics (Weiberg, 2012) but given the positive and socially integrating nature of the resilience framework it enables a nuanced view of history in close context with developing climatic conditions as per the thesis aims.

'Resilience theory' seeks to explore the source and role of change and how it relates to systems that are resilient and adaptive (Holling and Gunderson, 2002). Further details of resilience theory can be found in chapter 2 of this thesis or in Redman (2005). Adaptation cycles are a resource for integrating observations and interpretations in a formal way. Linking archaeology and palaeolimnological records using adaptive cycles is therefore exploratory in nature but may highlight the interaction of climatic variability and environmental response with periods of human activity in Cappadocia, for the Holocene.

In a panarchical sense (Gunderson and Holling, 2002), the level of change for Cappadocia happens at two frequencies, the meso (decadal-centennial) and macro (centennial-millennial), with meso scale nested cycles articulating into four macro scale relationships. The presence of four different threshold states and shifts into steadier social systems is consistent with the ideas of adaptive cyclical behaviour and complex systems development, suggesting that the concepts of adaptation and resilience are appropriate for this study. The human socio-economic trajectory for Cappadocia, as viewed in terms of adaptive cycles can be seen in figure 7.5.

7.4.2. Macro scale adaptive behaviour in Cappadocia

The evidence from archaeological survey data (chapter 6) and climatic and environmental variability parameters (this chapter) suggest that one macro-scale adaptive cycle can be attributed to the development of Pre-Neolithic (mostly Epipalaeolithic) societies up until the Ceramic Neolithic (figure 7.5). Over this time period it can be suggested that the establishment of moist and warm climatic conditions, and relatively stable catchment systems (this chapter) following the Younger Dryas cooling event (commencement of sediment unit 5) allowed for the establishment of successful hunting and gathering strategies by Pre-Neolithic populations. This quickly led into a phase of societal development (first α stage) encouraged by the broader-based diets and mobility of Holocene hunter-gatherer lifestyles (Baird, 2005b). The flexibility brought about by ameliorating climatic and environmental conditions led to a greater potential amongst Pre-Neolithic populations to exploit the diverse range of wild resources and increase their buffering capacity or resilience to change. The low level and organisation of habitation in the Pre-Neolithic (chapter 6), is consistent with the Ω and α phases of the adaptive cycle where investiture in different food sources, the formation of new societal relations, and the growth in flexible living behaviours (Baird, 2012; Düring, 2011) allowed for movement within the cultural system and therefore increased the resilience of communities to change events.

As hunter-gather communities began to acclimatise to the shifting prosperity, this led towards more sedentism and organisation of village life (chapter 6), which was also encouraged by the abundance of obsidian outcrops within southern Cappadocia which offered a new means of capital (Balkan-Atli *et al*., 1999). This growth phase (first r stage) links into periods of expansion in resource exploitation and habitation reorganisation during the Aceramic Neolithic (Düring, 2011; Özdoğan *et al*., 2012); a time when predictable and dense resources were produced by the people themselves rather than provided for by nature. This change in social organisation occurs against a back drop of low climatic variability and relatively moist and warm climatic conditions (this chapter). During this r phase, external influences (climatic disturbances) decrease in visibility due to the high level of resilience within communities and the positive impact climate likely had on populations. Social development, for a time, was not constrained by climate parameters or human actions. Times were good and there was no climatic or social mechanism for a conscious change in subsistence practices. The postponement of ‘truly’ agricultural lifestyles within central Anatolia at the time (Schoop, 2005b) was likely the resulting factor of climatic and social stability which allowed for the continuation of successful hunter-gather subsistence practices.

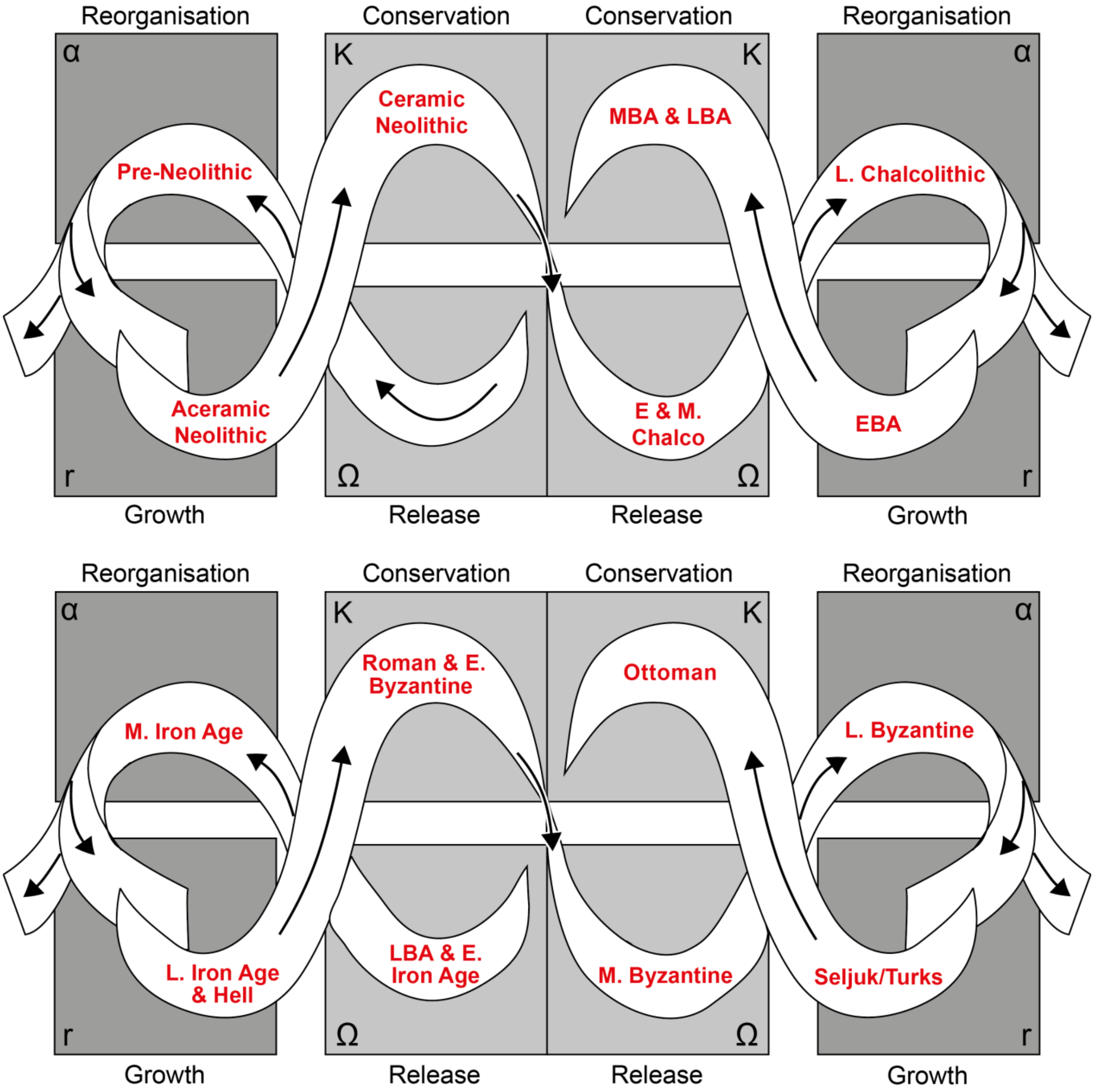


Figure 7.5: Four medium scale adaptive cycles of social and climatic relationships that can be identified from archaeological and palaeolimnological geochemical records of this thesis. Image adjusted from Rosen and Rivera-Collazo (2012).

By the early Ceramic Neolithic, there is increased sedentary behaviour, associated growth in population, intensification of the productivity of exploited sources and investiture in ritual behaviours (Özdoğan *et al.*, 2012). This rigidity in culture, conservatism and increasing expansion of resource extraction were sustainable for a time but became less sustainable as climatic conditions became drier (chapter 5) and soils were beginning to destabilise (this chapter). The change in socio-economic pressures may have also encouraged greater investiture in plant cultivation and husbandry (Marciniak and Czerniak, 2007), putting further pressures on the landscape and soil stability. The decrease in mobility, increase in landscape disturbance, pronounced exploitation, inter-connectedness of villages and growth in settlement (chapter 6 & this chapter) are all consistent with a K phase in the adaptive cycle. Conservative efforts would have been needed to maintain the level of productivity seen only a few centuries before and may explain why there is no major restructuring of cultural practices and increasing conservatism during the early Ceramic Neolithic. These efforts would have been made more fast moving in light of the increased risk and vulnerability from variable landscape conditions, and accentuated by a down-turn in climate (chapter 5). The natural pressures exerted on later Neolithic populations did not trigger a change in culture but were likely perceived more readily at a time when resilience levels were declining.

The extreme rigidity in cultural norms that had developed by the late Ceramic Neolithic meant that communities became increasingly vulnerable to the impact of a drier climate state and exerted further pressure on an already down-graded landscape (this chapter). As moisture availability decreased, hunter-gatherer type resource exploitations of a varied landscape would have been less viable and the flexibility in exploitation and subsistence strategies lessened. The pressures place on late Neolithic people may have manifested themselves with the symbolic behaviour of communities which often referred to symbols of death or violence (Erdogu, 2009). Towards the end of this cultural phase, the response of communities was to initiate new cultural practices to become more adaptable to the ‘not so normal’ climatic and environmental perturbations. In this case, it is postulated that natural change was a strong influence on social departure. Rather than investing more in social connections or fully adopting cultivation as a major subsistence strategy (a high risk option), late Ceramic Neolithic people developed new cultural trajectories like living at the household level with greater emphasis on territoriality (Marciniak and Czerniak, 2007). The heavy exploitation of obsidian though continued, as did the growth of occupation in Cappadocia (chapter 6) suggesting that land-use organisation was little effected by the change in adaptive strategy.

It is therefore possible to view a new positive phase of societal evolution initiated towards the end of the Ceramic Neolithic and developed during the early Chalcolithic which was encouraged by the need to increase societal resilience. The early Chalcolithic appears in line with the Ω stage of the adaptive cycle as there is a ‘release’ type reorganisation into a new social system which evolved around the intensification of individualism within and between communities, new symbolic expressions (Erdogu, 2009), a focus on landscape domestication through cultivation and herding practices, and a change in economics (Marciniak and Czerniak, 2007). Expansion into new settlement areas is also noticeable (chapter 6) which is likewise consistent of a release phase as significant energy was made available by new forms of settlement in previously under-occupied regions (Marciniak and Czerniak, 2007). Climatic conditions at the time were favourable (particularly wetter) and the influx of detrital components into Nar Lake decreased (chapter 5) suggesting less intensive exploitation of the Nar catchment. The amelioration in climate was advantageous for new opportunities to develop and for people to take advantage of the new system characteristics. This period of societal re-adjustment stemmed from a long period of social rigidity and connectedness that evoked a change to more individual behaviours, and at the same time towards greater social complexity and innovation.

After around 500 years of prosperity settlement numbers decline (chapter 6), and the impact of people on the Nar landscape is reduced (this chapter). This probable decline in occupation and land-use but sustained social complexity during the middle Chalcolithic (chapter 6) suggests that social reorganisation was not a stable process and that the growth of new systems was likely fragmented. A switch in climatic conditions at the end of the middle Chalcolithic towards declining moisture availability (chapter 5) would have certainly played a large factor in social development and it is possible to postulate that settlement abandonment and a slower level of growth were related in part to the worsening climate state. Most scholars (e.g. Marciniak and Czerniak, 2007) promote a lack of economic prosperity as the cause for settlement change during the mid-Chalcolithic. Economic organisation and natural influences helped to maintain a level of lower growth and prosperity which has resulted in the middle Chalcolithic being seen here as a continuation of the Ω phase.

The late Chalcolithic, which had some new cultural preferences (e.g. enclosure walls and monochrome potteries) in comparison to earlier Chalcolithic communities (Arbuckle, 2012; Düring, 2011) can be seen as the second significant period of societal reorganisation (α phase). It has been suggested that the gradual change in socio-economic status of late Chalcolithic groups was a human response to climate change of the mid-Holocene (Baird, 2012). The Nar record suggests a generally degraded and transformed climate state that was on the whole arid during the late Chalcolithic (chapter 5). This synchronism though would point to a rather positive effect on central Anatolian populations as there is a rise in settlement numbers (chapter 6) and a growth in semi-pastoralist lifestyles (Gülçur, 2008; Schoop, 2005a). By the end of the late Chalcolithic there is a new wave of flourishing urbanism, crop agriculture, metal manipulation and trade (Gülçur, 2008; Roberts *et al.*, 2011b; Yakar, 1985) that imply a renewed period of innovation and a clear trajectory of development. The late Chalcolithic in central Anatolia remains relatively poorly investigated (Düring, 2011) though and generally is only understood from a handful of archaeological excavations (e.g. Can Hasan, Haşhöyük and Firakin) making any inferences made here sceptical. However, organisational structures were definitely becoming more elaborate and economic sectors were advancing which would identify the late Chalcolithic as a clear reorganisation phase.

EBA cultures within Cappadocia are similar to the (r) stage of the adaptive cycle as we see a growth of social structures and increasing connectedness which result in agricultural intensification, internal specialisation, hierarchical organisation and nucleation (Yakar, 1985). The relationship between climatic stimulus and cultural change at this time seems to show incredible social ingenuity to cope with the degrading climatic conditions as increasing complexity in the archaeological record coincides with a reduced regional moisture balance (this chapter). It is also important to note though that climate variability at this time may have been heightened (this chapter), and seasons may have been more extreme suggesting that climate changes could have been less predictable. It is suggested here that the increased reliance on community relations, growth in trade networks and lack of individual-control (Yakar, 1985) might relate to the choice to build an integrated system that could work against the stress brought about by degrading climate in the hope of increasing consumption and capital. This was the EBA way of coping and trying to raise the standard of living against a setting of tentative unfavourable climate.

The boom that was the EBA, culminated into a well-populated, highly settled (chapter 6) and regional connected MBA during what is inferred as sustained dry climatic conditions (K stage) (this chapter) (note the chronological uncertainty here). The reduction in new settlement sites and the strong sense of settlement continuity (chapter 6) are similar to a conservation phase in the adaptive cycle where it would be expected to witnesses a reduction in growth and an attempt to preserve the prosperity that was propagated throughout the r phase. Populations were forced into lifestyles that had been initiated in the EBA and thought to be legitimate due to the wealth increases but were hard to sustain. Regional trade, urban interaction and increasing investment in productivity was directly linked to a socially driven narrowing of lifestyle options that reinforced the need for more storage and politically controlled social security (Fairbairn and Omura, 2005). The fact that food distribution strategies and greater administrative control is evidenced for the MBA period (Fairbairn and Omura, 2005) suggests that increasing effort was placed upon stability and maximisation of sub-systems, which in turn possibility related to the extreme aridity that was prevalent at the time and an attempt to mitigate the effects of drier climatic conditions.

The attempt to hold out within the K phase continued into the LBA but an inflexibility of social practices, as well as shifts in political control brought about a rigidity in lifestyles that decreased systems resilience. In light of the LBA being the driest period on record (chapter 5) (keeping in mind dating issues), it is postulated that climate pressures were greater at this time when resilience levels were at their lowest. The increase in fortified sites and a shift in settlement practices (chapter 6) principally relate to changes in the political realm but it is possible that extreme aridity was an added stress to increased internal conflicts and a weak central government (Yakar, 1993). The cumulative impact of practices and decisions, climate change, encouraged unsustainable behaviours and political disruption was systems failure towards the end of the LBA and during the early Iron Age (Dark Age). The release into a new socio-economic system at this time (third Ω phase) was a way of coping with the changes occurring in both the natural and political worlds, and related to a decrease in resilience, likely brought about by the inflexibility of MBA/LBA lifestyles and collapse of centralised state control. It is hypothesized here that that need to restructure the social system derived not from human agency but mainly from a failure of behaviours and are not consistent with resilience transformation.

Nevertheless, as is expected from the adaptive cycle principle, socio-economic systems reorganised through the establishment of Iron Age cultures. Whilst occupation levels during the early Iron Age remained relatively low (chapter 6) as communities begun to reconceptualise social directions (Ω stage), the middle Iron Age sees an increase in settlement associated with Phrygian rule and re-colonisation of areas abandoned during the LBA (chapter 6). This is consistent with a reorganisation phase in the adaptive cycle (third α stage) and highlights the extension in urban development and sedentary behaviour that stemmed from a social memory of the positivity of settlement expansion from the EBA. At the same time, a slightly increased moisture balance following the early Iron Age (this chapter) allows the tentative suggestion of an interconnectivity between social restructuring and climatic conditions. The directional change to more favourable climatic conditions and re-investiture in landscapes contributed strongly to help promote and stabilise socio-economic conditions.

The significant level of occupation reached by the late Iron Age (Persian) and Hellenistic periods (chapter 6) and the high investiture in territory linked to political control (Mieroop, 2007; Sağdıç, 1987; Van-Dam, 2002) are all consistent with a growth (third r) phase of the adaptive cycle. This investment in the landscape, combined with no major restructuring from the middle Iron Age, reflects a period of increasing exploitation and growth in social capital. The slight reduction in aridity (this chapter) would have eased the threat of climatic stress and made communities' less vulnerable to the impact of deterioration in climate forcing no energy loss as the result of climate change. The increased presence of people and a greater demand on the environment created a new situation of landscape vulnerability (this chapter) that would have put pressures on productivity and exploitation, forcing greater investiture in maintaining capital. In this case, humans may have built social systems that exacerbated rather than mitigated potential hazards by socially conditioning the landscape around them (Nelson *et al.*, 2012).

By the Roman and early Byzantine periods, exploitation reaches its maximum as people become heavily involved in agricultural production (Van-Dam, 2002) and settlement sites continue to increase in number (chapter 6). The anthropogenic impacts of agrarian subsistence strategies appear to relate heavily to increasing erodability as evidence within the Nar catchment clastic record (this chapter). The impact of growth and expansion of cultivation would have been felt most noticeable on soil stability and condition within the landscape. The potential that could be extracted from the soils would have been reduced, and therefore to increase growth, further time and investment would have been required to maintain expansion and wealth. A period of sustain intensification and landscape alteration are features of the K phase and reflect a long-period of lifestyle conservation and social investment in subsistence systems. Surprisingly, this is against a backdrop of increased climatic variability and unstable precipitation levels (this chapter). It has been suggested that winter conditions in Cappadocia at the time were ‘harsh’ and snow cover was common (Van-Dam, 2002). Despite limitations to winter productivity and a less predictable climate regime, agrarian communities flourished (Van-Dam, 2002) and the agricultural landscape appears to have been maintain at least up until AD 670 (England *et al.*, 2008). The seemingly well-ordered cultural landscape was an important aspect in economic rigidity which was not broken until raids by Arabs during mid-Byzantine times (England *et al.*, 2008).

Whilst it is difficult to relate climatic/environmental parameters and socio-economic development at a time when complexity in social systems was high, the agrarian landscape characterised during Roman and early Byzantine times was maintained until the impacts of land use and soil erosion decreased systems resilience. Landscape degradation (this chapter) likely had negative consequences on social development and the fragility of the system resulted in another ‘release phase’ (fourth Ω phase) in the adaptive cycle by the mid-Byzantine period. The influence of attacks by Arab forces likely also encouraged the move into the next adaptive cycle as communities needed to drop to a lower level of living to help combat and adapt to the changing political situation which likely brought about many disturbances in the socio-economic sub-systems. A decrease in settlement numbers (chapter 6) and damage to the agrarian economy (England *et al.*, 2008) no doubt related to the ensuing conflict and environmental instability as a shift to wetter climate conditions at the time implies that climate change was not a limiting factor. On the other hand however, the increase in climatic variability and dramatic shift between dry and wet at the time (this chapter) may have been of some significance even though conditions were generally improving.

According to the Nar Lake pollen record, it took around a century for the agricultural landscape to re-establish (England *et al.*, 2008). This is likely related to two processes; firstly that the landscape was given time to recover after extensive use during Roman and early Byzantine times and a reorganisation of the agrarian and pastoralist communities during the late Byzantine period (α phase). Once investiture in Cappadocia re-emerged under late Byzantine rule, there appears to be cultural growth and expansion under Seljuk Turk and Ottoman control. The Seljuk and Ottoman periods were phases of recovery and increasing resilience (r and K phases respectively) in the face of challenging climatic conditions which were very variable and relatively dry (this chapter). At the long-term scale, both the Seljuk and Ottoman phases appear little affected by the unpredictability in climate. Increasing expenditure in the landscape once more though continued to create unstable soil conditions as the discernible impact of long-term landscape use for agriculture resulted in increased erodability at Nar Lake (this chapter). It could be argued that by the late Ottoman period, rigidity, heightened exploitation and increasing political management of sub-systems (White, 2008) again left communities less resilience and more susceptible to risk. It is possible that a new adaptive cycle has developed following the late Ottoman period but it is too soon to look at this at the long-term scale.

7.4.3. Micro scale adaptive behaviour in Cappadocia

The trajectory of cultural evolution in Cappadocia also displays micro scale (decadal-centennial) adaptive changes, particularly within archaeologically defined cultural phases, but the usefulness of analysis at this scale is small given the aim to study regional long-term changes and interactions between climate and people. However, it is worth mentioning that the EBA period in particular may show a transformability that is potentially contemporaneous with climate disruptions. The EBA I & II can be linked to the reorganisation and growth phases (α and r stages) of the adaptive cycle and the EBA-MBA transition can be linked to the release phase (Ω stage) as evolutionary development may have been encouraged by a need to increase resilience to the worsening climate state of the 3th Millennium B.C. Minimum resilience likely developed towards the end of the EBA III phase where you get active influence from neighbours and low social mobility in terms of economic practices (Yakar, 1985); this is in line with the K phase of the adaptive cycle. It is argued here that the systems' vulnerability during the EBA was not noticeable until exposure of the system to extreme arid climatic conditions at the EBA-MBA transition suggesting heightened sensitivity to climatic stress at this time. Equally important are the lack of efforts to strengthen the system against the adverse external conditions it was exposed to, to such a level that the only effective mechanism was adaptive transformation to increase resilience.

7.4.4. Summary of the application of adaptive cycles to Cappadocian data

Adaptive cycles allow dynamical understanding of relationships rather than just how they were at one point in time. Adaptive cycles as identifiable in Cappadocia are caused by both internal social-economic and external factors such as climate or soil mismanagement. The use of these adaptive cycles helps identify specific social system components and how they related to changes in climate over the Holocene period. Different social configurations in terms of reorganisation, growth and conservation have enabled cultures to adapt to the longer-term changes in climate and environmental states and the ensuing political and economic well-being. Key points that resonate from adaptive theory are that change is to be expected and not feared and resisted (Redman, 2012), and that it is a process of stabilising socio-economic systems in un-resilient situations and is therefore a positive influence of social development and opportunity. Without adaption strategies and reorganisation there is a likelihood of collapse and damage to the system, which as it suggested here does not occur at any point in Cappadocian social history.

The trajectory of Cappadocia is characterised into four main stages of change which are used to regulate societal resilience and coping capacity. The complexity of relationships between climate and cultural become visible when looking at non-linear and cyclical change at both the large evolutionary scale and smaller sized time window. Especially interesting is that change does not seem to have been negative or detrimental, but was seen as a chance for a fresh start and important in terms of long-term social stability. Climate appears to have been a major factor for Pre-Neolithic populations and mid-Holocene urban communities but never was it the sole driving factor in social development. A transition in development needed the synchronisation of many different acting groups, either by external factors or neighbouring cultural systems or internal dynamics. Mapping the adaptive cycle onto millennial cultural changes in Cappadocia suggests that the record of land-use and erosion are typically detrimental to people after the late Iron Age where accelerated catchment disturbances are linked into an intensification of cultivation practices. The cumulative effects of increased erosion was associated with the conservation stage of the resilience mechanism suggesting that landscape instability may have been a factor in reducing resilience levels within communities.

Numerous assumptions are required in order to infer adaptive cycle changes for the Holocene. Recognising the limitations that result from these assumptions is important when considering the likelihood of inferences made. The concepts of panarchy and adaptation cycles assist in the analysis of complex systems and allow social change to be viewed alongside external climatic and environmental influences. The Cappadocian perspective on adaptation cycles though is but a general one and down-scaled because of the limited archaeological record and fragmentary chronology for the Nar Lake record. The fact that only ‘archaeological cultures’ are being studied and that the archaeological history of Cappadocian still remains ‘patchy’ means that an understanding of climate-environment-human interactions in terms of systems dynamics is limited by current understandings of change. The focus on external influences may also be, to some, questionable given that mono-causal explanations of change are seen as outdated and fail to convince in many cases. Nevertheless, multifaceted societal systems do have relations with external factors such as climate and environment and it would be unreasonable to think that these were of little importance. Varied reactions to external influences at different scales goes beyond linear relationships, and brings in an element of social individually that makes studies regarding cultural/climate interactions much less deterministic in this instance.

7.5. Chapter summary

The Nar geochemical record, which was identified as a good regional signal of climate change, was compared alongside the archaeological history for the region to identify possible interactions between shifting climate and socio-economic trajectories. Three significant periods of climate change were identified that coincided with significant shifts in the archaeological record. These were 1) a favourable and moist early Holocene phase which was associated with the growth and development of Neolithic populations and the establishment of sedentary lifestyles; 2) a dramatic drop in moisture levels and increasing salinity during the mid-Holocene coincident with the growth of urban centres and long-distance trade; and 3) a changeable and relatively arid late Holocene which prevailed during heightened agrarian activity and population of the Cappadocian plains.

In light of these long-term changes it were also useful to understand how smaller-scale shifts were responded to by past people, as it is likely that it is at this scale where climatic or environmental perturbations are most felt. The impact of higher climatic variability was different depending on the community, with later more complex communities finding it increasingly difficult to cope with shifts in climate states, especially against a backdrop of sustained aridity. Environmental variability was also shown to be a key factor in the record at Nar. In comparison to the archaeological record, it appears that highest variability coincides with higher landscape use and habitation levels during the late Neolithic and post Iron Age world. The role of volcanic activity cannot be ruled out so the record of possible human influence on the Nar catchment must be approached with caution.

In an attempt to link the proposed climate and environmental variability records to the human record of change, adaptive cycles were chosen as a framework upon which to understand the influence of external change on socio-dynamics. These proved very useful for determining possible stress indicators and the self-organising capabilities of societies. Four adaptive cycles of different system components showed that in no point of time was climate or environmental degradation the sole mover of societal change.

8. Conclusions

8.1. Introduction

This thesis project aimed to highlight the interactions between cultural developments in Cappadocia as witnessed in the archaeological record and regional long-term Holocene climate and environmental change and variability. Of particular interest were the life choices made by past people at various points in time related to the uncertainties in the natural environment and how this ultimately impacted upon socio-economic trajectories. A comparative analysis of changes in climatic/environmental stability and archaeology has provided the means to record factors relating to the adaptability and sensitivity of past communities to the different climate/environmental regimes. Three research aims and fourteen objectives were identified in chapter 1, and these are restated in a streamlined form below:

1. To analyse lake sediments as an archive of Holocene climatic/environmental change at high temporal resolution.
2. To merge these records of Holocene climatic and environmental change with the past human record as understood from archaeological materials to develop ideas relating to the inter-relatedness of natural and cultural change at a regional level.
3. To use systems models to understand the challenges that past people faced in the light of stable and unstable climate regimes and to establish whether people were effective in coping with unpredictable climatic situations.

The Eastern Mediterranean (EM) history of societal change has been particularly sensitive to drought and desiccation, due to the limited water resources available, and commonly susceptible to climatic variations between wet and dry (Weiss *et al.*, 1993). Annually deposited lake sediment data are a potential medium for providing information regarding regional climate at a scale which was recognisable to past people and could be firmly and accurately dated. Annually laminated deposits from lake settings offered a record of climate and environmental variability which was sensitive to regional hydrological balance thus allowing the successful reconstruction of high-resolution climate shifts (Brauer and Negendank, 2002; Marshall, 2010).

Nar Gölü (Lake) located in central Anatolia (chapter 3) is the source of high-resolution information on the climate history of the EM analysed in this thesis. This study site was chosen for its 1) continuous Holocene record, 2) annually-deposited sequences, 3) ability to provide a reliable chronology, and 4) existing understanding of relationships between climate proxies and particular climate variables. Lacustrine geochemical variability was investigated using XRF core scanning at sub-annual resolution to identify different temporal changes in elemental variability for the late Pleistocene and Holocene. The application of geochemical analysis has allowed a record of hydrological regimes and limnological changes to be derived, from which palaeoclimatic and palaeoenvironmental inferences could be made. For further interpretation of the geochemical proxies, other sedimentological analysis including total carbon and sediment stratigraphy were also recorded for the Nar Lake sediment sequence.

The thesis aimed to synchronise lacustrine derived palaeoclimate/environment changes with a regionally specific scale of archaeological analysis, particularly using site survey data to formulate narratives of climate-environment-people interactions. A combination of visual comparisons to the geochemical data and exploratory frameworks provided the basis for understanding relationships.

Palaeoclimate data (isotope (Jones *et al.*, 2006) and diatom (Woodbridge and Roberts, 2011)) from previous late Holocene Nar Lake proxy investigations and other regionally relevant climate histories (Bar-Matthews and Ayalon, 2011; Eastwood *et al.*, 2007a; Litt *et al.*, 2010; Roberts *et al.*, 2001) provided supplementary palaeo-information which aided the confirmation of inferences and gave a clearer understanding of the pattern of Holocene climate documented in this thesis.

Qualitatively and quantitatively, the Nar Gölü Itrax geochemical record appears to have been sensitive in its response to palaeoclimatic and palaeoenvironmental changes. The data produced using the relatively new high-resolution Itrax core scanner picked up clearly changes in allochthonous and autochthonous input along the whole core sequence. The more quantitative hand-held XRF was also used at lower sampling resolution to compare to the data produced by the Itrax machine, and corroborates many of the patterns witnessed from the first XRF spectrometry technique. This therefore provides confirmation that the method of Itrax scanning was the correct choice to obtain a high-resolution, quick and non-destructive record of elemental change. This allowed investigations into geochemical shifts in response to palaeoclimate/environment at a resolution suitable for the high temporal changes occurring along the core sequence. This technique also allowed turbidite layers to be identified providing a unique record of catchment in-wash events for the entire Holocene. The major contribution of this dataset is the high resolution data which provides an excellent record of the dynamic changes in climate and environment to help describe changes in frequency and magnitude of natural variability. The high-resolution data also provided extra information on the annual nature of varve deposition and shifting seasonal behaviours.

8.2. Reconstructions of climate and environment from XRF derived elemental variability using the Nar Gölü NAR10 sediment record

Overview

Varved lake sediments from Nar Gölü were investigated to obtain a high-resolution record of climate and environmental change for the last ~ 14,000 years (chapter 4). Geochemical and sedimentological records were obtained to extend the record from previous Nar core sequences mainly at 200 µm resolution through this time period.

Modifications and improvements to the Itrax suite of elements were also made using hand-held XRF at 8cm sampling resolution. Geochemical changes closely relate to changes in stratigraphy and show a clear coupling of elements down-core associated with their varying role within the lake system. Analysis of elemental variability through the NAR10 sediment record reveals clear shifts in seasonal deposition between Ca-rich summer deposits and Fe-rich winter deposits, with disruptions in laminae deposition from clastic in-wash events characterised by high Ti, Fe, K and Rb. Other elements of interest included the Si profile which provided information regarding biological silica content, Zr and Rb as indicators of grain size and Mn which seems to be a major guide to redox state. It has been shown that the Nar Lake sediment contains multiple climate-sensitive proxies that record changes in available moisture (Ca, Sr and Mg) and the presence of catchment material (Ti, Fe, K, Rb) related to landscape stability. The general story is one of shifting lake status linked into authigenic processes (Ca and Sr) overprinted by influxes of sediment (Ti and Fe) related to changes in precipitation-evaporation and soil erodibility.

XRF spectrometry provided some methodological difficulties in trying to fit the sediment cores within the scanning device and applying the correct scanning parameters to each individual core section. The ‘stitching’ process required the linking up of 27 individual core scans. This process highlighted some minor modifications to the NAR10 master sequence core depths and enabled the correction of the master stratigraphic sequence; thus improving the accuracy of the depth scale.

Studies relating to the total carbon content of the core sequence were carried out (chapter 4) which led to a further understanding of processes within the lake system and the Itrax derived record which may have been influenced by changes in organic levels. Unfortunately, the influence of high inorganic values meant this method was made less accurate in places by high TIC and in samples with a low mass. Organic level reconstructions therefore derive more accurately from the Inc/Coh ratio computed from the Itrax scans which are affected by the same lithological and water factors that affected the reliability of the other XRF elemental profiles.

Numerical analyses (chapter 5) were used to investigate the climate and environmental history at Nar Gölü. The general climate history from the Late Glacial period through to the modern period is very similar to that witnessed at other regional relevant sites (chapter 5) with few differences in the timing and duration of climatic events. Any differences in interpretation of this dataset and previous work are minor, usually consisting of discrepancies in the timing or magnitude of particular events, and likely stem from problems of dating reliability, differing regional expressions and diverse response mechanisms of proxy indicators.

Interpretations of the geochemical and total carbon records for the Holocene period require a number of assumptions based upon the relationships between the lake system and climatic variables, particularly assuming those which are evident today or in other studies are applicable to the Nar Lake situation. Therefore that other proxy records form the same core sequence and other regional climate accounts record the same climatically-driven hydrological changes gives weight to the accuracy of interpretations made in this thesis.

Lacustrine inferred climate/environment

Geochemical and sedimentological indicators (chapter 4 & 5) suggest that palaeoclimate fluctuated greatly during the Late Glacial period (2165.24-1974cm; ~ 14000-11700 years ago) and into the Holocene (starts around 1974cm) noticeable by fluctuations in lake level driven by switches between warm/moist and cool/dry. The lake level at Nar was very low during the period of time corresponding to the Younger Dryas (2013-1974cm) (~12.9-11.7 cal. yrs. B.P.), inferred from high carbonate precipitation, low lake productivity and the absence of varves. Low catchment runoff and erosion is also inferred from reduced input of detrital material. The early Holocene is characterised by stable climatic conditions and increasing lake water depths. A rise in detrital in-wash and biological indicators suggests increased lake productivity relating to algal growth and landscape instability, particularly during sub-unit 5a (1606.2-1428.2cm; 9190-8046vys). A subsequent rise in precipitation levels marks unit 4 (1428.3-1161.2cm; 8046-6398vys); it is possible that this change is a reflection of sustained rainfall levels throughout the year as suggested by oxic lake conditions. Most importantly there is also a long-term reduction in clastic influx inferred from a decreased supply of titanium and lithogenic elements, which suggests a clear stabilisation of the landscape.

By the mid-Holocene (~ 1200cm) there is a marked transition to a reduction in regional moisture balance, evidenced by significant drops in Ca/Sr ratio and a decrease in clay deposition. A strong relationship between organic content and thick, probably non-annual laminations exists for unit 3 (1139.7-753.7cm; 6398-~3/4500vys) but the reason for this change in lamination type is hard to decipher. The first major evidence for extreme aridity is found during unit 2 (753.7-592.7cm; ~3/4500-2589vys) which is recognised by low and stable Ca/Sr and peaks in Mg (a salinity indicator). An abundance of detrital elemental components during unit 1 (592.7-0cm; 2589-0vys) may have become more enhanced due to sustained aridity, but have also related to human-induced landscape change and instability as the result of increased anthropogenic activity. Climatic conditions over the last 2000 years have been variable with shifts between wet and dry. Changes to high precipitation and high lake stands at the beginning of sub-unit 1c (centred around 350cm; ~1440vys) have been interpreted from high Ca/Sr.

Climatic and environmental variability

As well as presenting evidence for hydrological changes in response to palaeoclimatic and palaeoenvironmental changes, it was also vital to discuss the short-term inter-annual variations as changes at this scale are most relevant to past cultural change (Biehl, 2012). The likelihood of past people responding to climatic change and for it to be registered relates to stability characteristics of the ensuing climate (Rosen, 2007). In this sense, it is the unstable and highly variable fluctuations in climate that will be most noticeable by past communities, especially against a back-drop of already degrading climate. The annual nature of Nar Gölü sedimentation and high scanning resolution of the geochemical data allowed for investigations into unstable climate periods to be made.

A significant pattern of changing climatic and environmental variability was documented from statistical analysis of time windows of geochemical data (chapter 7). The most dominant periods of high climatic variability were during units 7 (2165.24-2013cm; ~14000-12900 years ago) and 1 (592.7-0cm; 2589-0vys), and were interpreted to related to higher amplitudinal shifts between wet and dry conditions and changes in precipitation levels during the summer and winter seasons. Similarly, highest environmental variability was associated with sub-unit 5a (1606.2-1428.2cm; 9190-8046vys) and unit 1 linked into increasing erosion of catchment material into the lake environment and therefore landscape instability.

Collection of archaeological survey and excavation data (chapter 6), from Cappadocia, suggest that during sub-unit 5a and unit 1, increased landscape instability is related to the presence of people in the lake catchment and growth of agrarian lifestyles principally after the late Iron Age. More unstable landscape conditions during sub-unit 5a coincide with the growth of Neolithic populations and obsidian mining activities in the vicinity of Nar Lake but the role of volcanically-induced sediment influx cannot be dismissed. These relationships are likely to be important for understanding the impact of past people on landscape dynamics and on geochemical responses in the lacustrine environment. The relative degree of landscape sensitivity to anthropogenic factors cannot be quantified successfully without statistical models and further calculations but the likelihood is that unstable soils were dependent on numerous factors both physical and biological, externally and internally. Determining the impact of people is complex but at least there appears to a close relation between erodibility and increased land-use whether that is for agriculture or resource abstraction.

8.3. Collated archaeological survey results from Cappadocia

Archaeological site survey data

Collation of archaeological survey results for the Cappadocia area (chapter 6) show significant changes in settlement density associated with temporal changes in human habitation. Comparative analysis reveals the existence of regional differences between southern and northern Cappadocia throughout the Holocene. These differences are due to a large environmental gradient, uneven distribution of exploitable resources and changes in political territorial boundaries. During all archaeological periods, occupational preferences were strongly coupled to subsistence practices, exploitation strategies, administrative control, and environmental conditions.

The variable archaeological survey records for Cappadocia indicate a settlement history that is only partially comparable to neighbouring regions. The pattern of settlement change documented (chapter 6) sees an early occupation built around access to raw materials and exchange networks during the Neolithic, particularly in southern Cappadocia and therefore in close proximity to Nar Lake. A substantial growth in occupation occurred during the late Chalcolithic period, and continued well into the MBA phase. Occupation at this time is one of relative stability, anchored into economic prosperity and investment in sedentary lifestyles. The first pronounced significant drop in settlement numbers is evidenced for the LBA. Also evident is a significant shift in the placement of settlement sites, with northern Cappadocia being favoured perhaps for its links with political power. Re-establishment of high settlement numbers and an expansion in habitation can be seen from the middle Iron Age (900-585 BC) onwards, with a greater concern for non-settlement sites as a means of increased administration, security and defence. Another decline phase likely occurs after late Roman dominance in the area linked to political instability during the Arab period (670-900 AD) but a lack of settlement data for this time period may suggest that there is an under-representation of sites at this time.

Ultimately, the patterns of settlement change documented here reflect the shift from small-scale resource gathering communities to fully urbanised and integrated settlement systems. At no point is there a complete collapse of occupation in Cappadocia but there are two phases of decreased settlement associated with the LBA and mid-Byzantine times that suggest some disruption to habitation. Each phase of change is individually characterised but in most cases has its roots embedded in settlement organisations of preceding periods.

Limitations of linking archaeological site survey data and climatic data

One of the major considerations of this study was the use of both natural and archaeological data from a region where very little is known about the interactions between climate and culture. When these two datasets were looked at simultaneously, a great deal of information could be gathered regarding the nature of socio-evolution in light of climate or environmental events. The discussion presented in this thesis is a simplified summary of the true situation. There is still an aspect of uncertainty regarding the documented societal changes from archaeological survey data and whether the geochemical record is sufficient to provide a complete picture of regional climatic and environmental development. To solve these issues, further studies will need to be based on additional archaeological, environmental and climatic records, in which dates are firm and reliable. An interesting question is therefore whether human culture-climate interactions remain misunderstood due to limitations in data collection. The solution would require more in-depth studies which at present are problematic within Cappadocia. Issues of representation require less consideration though when cores are stratigraphically consistent across the lake basin and comparisons with other palaeoclimate reconstructions show a similar understanding of Holocene climatic change, as is the case at Nar.

8.4. An evaluation of the relationship between climate-environment-culture in Cappadocia

The changes seen in the archaeological record of Cappadocia for the Holocene are likely to result from a combination of social, political, economic, environmental and climatic stimuli. As an exploratory technique to investigate the interactions between all these components, at various spatial and temporal scales, the adaptive cycle model (Holling and Gunderson, 2002) was used to provide a comprehensive picture of the pooled data sources (chapter 7). The adaptive cycle concept provided this study with two major advances. Firstly it does not imply a separation of climate from culture as in deterministic principles and secondly the model integrates different continuous scales of change allowing patterns to be considered at various temporal levels (Widlock *et al.*, 2012).

It is unrealistic to assume that the adaptive model can provide a complete understanding of climate-environment-cultural interactions and people's response mechanisms to shifts in natural variability but it helps to distinguish those features that play an important role in shaping societies and the outcomes of potentially adaptable behaviours. In summary it is a simple tool to summarise the evidence from very different archives and will change as more information becomes available.

The adaptive model applied to the Cappadocian archaeological history of cultural change and XRF derived record of climatic and environmental variability (chapter 7) identified links at different scales of analysis. It was those changes evidenced at the macro scale that provided the best whole-systems dialogue about the challenges faced by past people and ultimately, what actions they took. In total four macro scale cycles were identified, highlighting times when cultures were ill-prepared and failed to establish effective coping mechanisms during times of societal instability.

At no point throughout the Holocene was climatic variability seen as a driver of societal change but there were periods, for instance during the Pre-Neolithic and Aceramic Neolithic, when climate (moist and warm) was important in terms of increasing resilience and economic development. There were also times, for instance towards the end of LBA, where climate (in this case sustained aridity) may have put added stress on communities at times of already dwindling resilience levels. Variability in climate seems to have only affected communities at times of decreasing resilience, for example when climatic variability is high during Roman and early Byzantine times we see a blossoming agrarian society. In contrast when climatic variability is high during the mid-Byzantine, a time when there is significant political upheaval, there seems to be a greater impact on communities from climatic changes.

The role of environmental variability in shaping the nested adaptive cycles is also interesting given the attractiveness of linking human land-use practices with increasing detrital in-wash into the lake environment. It is demonstrated in the thesis that it is often during the conservation (K) phase of the adaptive cycle that environmental instability (as determined from the Nar recorded) is greatest. One possible explanation for this is that carrying capacities had been reached and the level of growth had been reduced encouraging communities to intensify their environmental pressures. It is also possible to assume increasing environmental instability linked into the agrarian lifestyles of the later Neolithic and post Iron Age worlds. It is reasonable to accept that added agricultural activities would have weakened soil development, particularly during deteriorated climate conditions and increased the chance of catchment influx events.

8.5. Proposals for future research

The seasonal resolution and clear sedimentation changes of the NAR10 sediment sequence have resulted in an important understanding of regional climate development. Further work on the sediment cores beyond those already carried out (e.g. diatoms, isotopes, pollen, pigments, XRD) will lead to a further understanding of the limnological processes driving geochemical variability in climate change. There is potential to use the varve data, gathered from grey scale analysis, thin-section digital imagery and laminae thickness measurements, in conjunction with the geochemical understanding of varve formation to establish new climate proxies for the Nar Lake record.

As it often the case with lake data, questions still remain over the timing of these climatic events and how to further develop the depth-age scale that is currently used. Thin-section records would also be important in trying to provide a more robust chronology for the Nar sequence as laminae could be counted more precisely under microscope or distinguished from colour intensity variations. Nevertheless, this study provides a much better chronological precision than its possible from most other regional sediment records.

Also of interest is the possible relationship between increase environmental instability and volcanism during the early Holocene. Further investigation of this issue may enable a better understanding of the role of volcanic material in limnological geochemical variability and the record of environmental change established. Furthermore, it could have implications for the understanding of hazards and their role within societal development of the region. This could be achieved through tephra horizon investigations from thin-sectioning the Nar sediment sequence and microprobe analysis if tephra deposits are found.

This thesis has shown that high-resolution investigations from annually deposited sequences offer an excellent archive of past climatic and environmental change. The lack of investigations between such records of natural change and the archaeological understanding of human cultural change suggests that further work needs to be done in this area. One of the benefits of a study of this type is that it can be extended to different geographical localities and temporal scales, meaning it is not restricted to the central

Anatolian region or lake sediments. In combination with site specific excavation data and regional survey overviews, more data such as those presented here at the regional scale will allow further analysis of the characteristic properties of cultural change in light of natural change and vice versa. Consequently, the adaptive model of change presented here is a stimulus for further investigations directed at climate-culture interactions.

It would be interesting to expand this work to regions neighbouring Cappadocia which have similar patterns of settlement change (chapter 6) such as the adjacent Konya Plain. A detailed survey of the archaeological landscape and on-site palaeoenvironmental sampling may allow reconstructions to be made with specific detail at the broad regional scale from sites which are directly related.

Appendix 1

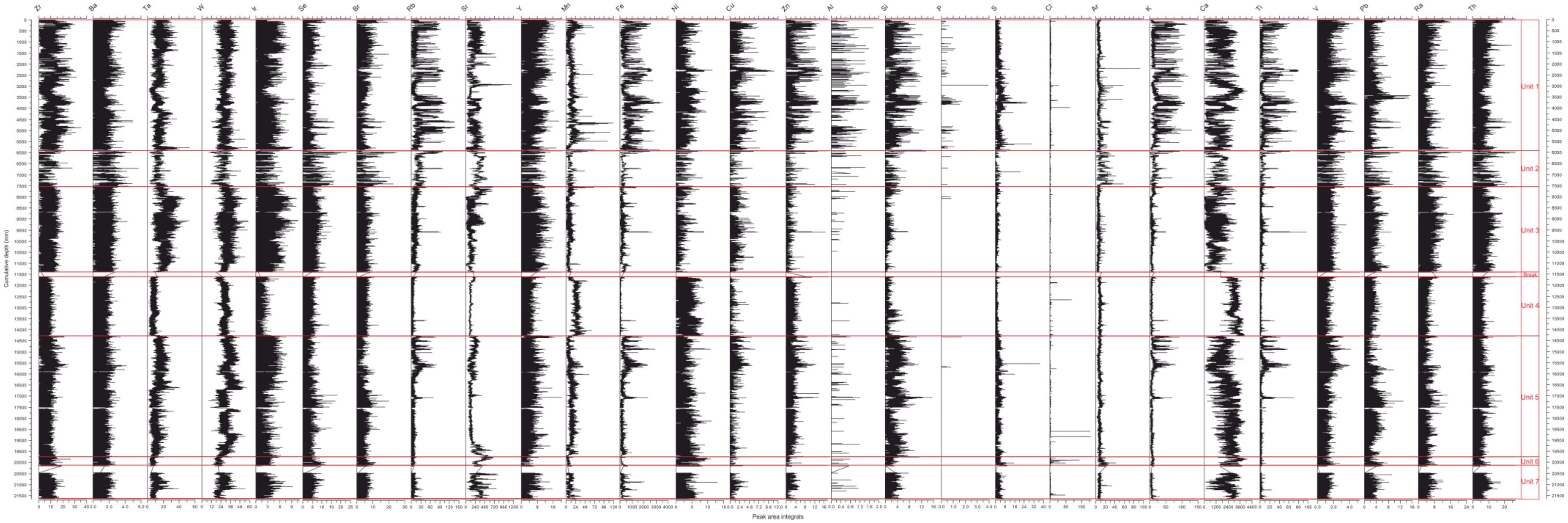
Mean annual and monthly precipitation data (presented in millimetres per month/year) for two Cappadocian weather stations, Nevşehir and Niğde, highlighting yearly variations in rainfall for the Nar Lake region. Data collected by the Turkish Meteorological Service and supplied by Murat Türkeş.

Nevşehir	**Year**	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Mean annual monthly (mm)**	**Mean annual total (mm)**
	2001	1.8	36.4	21.2	22.2	103.4	0.6	6.1	0.7	8.7	9.6	29.3	53.8	24.48333333	293.80
	2002	41.9	15.6	16.8	84.0	27.1	7.3	21.5	18.9	23.8	13.6	20.6	41.7	27.73333333	332.8
	2003	14.9	63.0	50.5	41.7	63.8	6.7	0	0	22.0	44.7	35.8	29.8	31.075	372.9
	2004	37.9	32.4	26.5	57.9	28.1	27.4	15.0	1.9	0	7.5	81.5	34.2	29.19166667	350.3
	2005	43.1	39.1	51.1	41.0	29.5	7.0	0.5	7.0	30.8	29.9	29.8	18.4	27.26666667	327.2
	2006	50.4	23.6	20.2	70.2	29.6	5.2	0.7	0.8	17.1	54.2	29.9	8.3	25.85	310.2
	2007	25.1	47.9	52.4	73.5	89.4	46.2	0.4	14.2	3.1	18.3	60.2	52.4	40.25833333	483.1
	2008	35.3	30.5	27.0	22.0	46.1	15.2	0	1.1	31.2	41.7	25.9	47.5	26.95833333	323.5
	2009	49.8	76.5	83.8	51.5	63.3	25.7	52.7	0	12.2	3.7	78.9	45.8	45.325	543.9
	2010	86.4	43.7	41.1	76.1	11.1	75.4	4.1	0.1	3.6	122.3	5.2	67.1	44.68333333	536.2

Niğde	**Year**	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Mean annual monthly (mm)**	**Mean annual total (mm)**
	2001	2.0	61.0	29.9	28.7	75.1	2.7	0.1	0.2	2.3	21.9	69.7	34.4	27.33333333	328
	2002	35.4	13.6	15.4	92.2	54.1	13.7	22.6	21.4	31.6	22.0	34.7	49.7	33.86666667	406.4
	2003	25.7	53.1	30.8	47.6	41.3	10.7	0.1	0.4	12.2	33.2	49.7	22.8	27.3	327.6
	2004	34.2	16.9	18.9	53.5	19.0	11.7	16.6	0.3	0	12.9	54.6	11.5	20.84166667	250.1
	2005	37.6	27.8	59.1	30.7	15.4	14.4	0.1	0.6	28.8	21.7	20.9	22.3	23.28333333	279.4
	2006	29.3	22.2	30.5	45.3	42.7	31.8	2.6	7.0	4.1	64.0	37.0	0.5	26.41666667	317
	2007	19.0	19.3	20.6	38.2	38.8	14.4	0.2	26.3	0.5	26.2	106.1	41.8	29.28333333	351.4
	2008	22.7	19.9	28.3	16.0	46.7	14.4	0	21.8	21.7	40.1	55.8	25.0	26.03333333	312.4
	2009	65.4	59.7	52.6	38.5	61.8	4.1	37.5	0.1	20.2	13.6	70.1	37.2	38.4	460.8
	2010	63.4	28.4	37.1	71.9	16.0	49.4	2.9	7.4	4.8	89.7	7.9	104.4	40.275	483.3

Appendix 2

Stratigraphic profiles of all the elmental components detected during Itrax XRF core scanning on lake sediments from Nar Gölü. Elements are presented as peak area integrals in no specific order, and against the Nar lithostratigraphy. The Itrax derived results have been adjusted using kilo counts per second (kcps) and erroneous peaks removed.



Appendix 3

Results from portable handheld XRF scanning of bulk modern sediment samples from Nar Gölü. This table provides a list of the samples investigated along with the elemental changes recorded as ppm (values are plotted without decimal places to enable the data to be displayed more clearly).

Sample Number	Easting	Northing	Scan mode	Mg	Si	Al	K	Fe	Zn	Cu	Pb	Zr	Ti	As	Ba	Mo
SS2a	36627087	4245017	Mining	4447	221945	42887	18559	32048	45	0	20	108	3060	0	202	0
SS3a	36627291	4245052	Mining	7783	213151	50122	14173	48540	58	49	9	109	4887	0	320	0
SS5a	36627472	4244942	Mining	9813	159897	37054	8581	42579	45	29	0	77	3644	0	290	0
SS5b	36627478	4244945	Mining	7500	227471	51991	15699	44937	52	35	9	103	4574	0	282	0
SS7a	36627471	4244051	Mining	2409	243778	45336	23087	24380	41	0	21	102	2426	0	250	0
SS8a	36627020	4243850	Mining	0	259985	38178	31372	11059	32	0	24	102	1211	0	278	4
SS8b	36627049	4243869	Mining	1488	239158	39975	27187	17826	37	0	23	101	1879	0	301	3
SS8c	36627049	4243869	Mining	0	260686	37779	31701	11749	33	0	24	101	1370	0	237	3
SS8d	36627073	4243935	Mining	1069	236253	35968	28399	15395	38	0	26	114	1778	0	313	3
SS8e	36627073	4243935	Mining	741	248992	35802	30768	12469	32	0	26	101	1321	0	267	3
SS9a	36627073	4243832	Mining	1427	246694	42192	26902	16717	36	0	21	102	1868	0	285	3
SS9b	36627077	4243839	Mining	1043	237372	38404	26077	15054	32	0	24	113	1919	0	245	3
SS9c	36627090	424892	Mining	1337	254776	41415	28720	14134	38	0	23	103	1739	0	289	3
SS9d	36627091	4243939	Mining	1220	242885	38818	28040	14451	31	0	24	95	1760	0	310	0
SS9e	36627094	4243942	Mining	1166	256208	40947	29376	14895	30	0	20	103	1739	0	312	0

SS9f	36627066	4243985	Mining	1624	256962	41731	29077	13970	32	0	22	102	1685	0	316	3
SS10a	36627043	4244139	Mining	1351	246075	37593	29178	14609	33	0	23	88	1538	0	219	3
SS10b	36627086	4244168	Mining	1331	244584	36425	26363	15322	33	0	26	99	1654	0	255	3
SS10c	36627174	4244152	Mining	936	235843	35877	26041	14889	36	0	20	95	1654	0	193	0
SS10d	36627264	4244158	Mining	569	243747	42993	27458	17288	36	0	23	98	1815	0	225	3
SS10e	36627381	4244168	Mining	1232	252083	40291	27094	16140	35	0	24	104	1712	0	282	0
SS10f	36627507	4244168	Mining	0	254256	37191	30503	12128	24	0	21	90	1191	0	252	3
SS11a	36626891	4244026	Mining	2534	234298	40415	25311	22619	39	0	20	92	2078	0	282	0
SS11b	36626901	4244049	Mining	1806	233692	38177	26644	21424	35	0	22	107	2135	0	307	0
SS12a	36626799	4244159	Mining	4691	221414	49521	16806	38591	50	28	15	102	3978	5	289	0
SS12b	36626829	4244166	Mining	3875	228012	44300	21612	31008	42	22	15	86	3050	0	289	0
SS13a	36627467	4243993	Mining	2005	238841	46908	22140	26446	36	0	21	104	2478	0	255	0
SS14a	36627367	4243949	Mining	0	270760	41124	30365	13208	28	0	22	90	1351	5	261	3
SS14b	36627365	4243955	Mining	0	255585	37576	30362	12040	29	0	23	90	1263	0	243	3
SS14c	36627361	4243956	Mining	796	265537	39593	30184	12843	26	0	21	89	1313	0	260	3
SS14d	36627360	4243955	Mining	682	253915	40434	28643	14233	27	0	23	95	1417	5	240	3
SS15a	36627656	4244262	Mining	2369	216765	40860	17604	34587	51	28	20	107	2982	0	190	0
SS16a	36627749	4244346	Mining	3673	214121	46037	18041	32465	46	0	16	102	3420	0	270	0
SS16b	36627777	4244313	Mining	4023	219617	46772	18471	34011	44	0	18	102	3425	0	293	3
SS16c	36627790	4244307	Mining	4055	231935	48222	20638	30793	45	0	18	99	3088	0	266	0
SS16d	36627803	4244272	Mining	4444	191625	50602	8547	54487	64	39	8	82	5391	0	330	0

SS17a	36627814	4244303	Mining	4749	228267	51663	17391	45101	54	27	10	94	3934	0	324	3
SS18a	36627284	4243796	Mining	0	253885	35592	30088	11664	25	0	24	80	1139	0	272	0
SS18b	36627287	4243795	Mining	612	238683	35103	27887	14280	27	0	22	100	1532	0	246	4
SS19a	36627280	4244087	Mining	5489	219595	50482	17939	38583	48	35	19	136	3694	6	268	0
SS19b	36627924	4244279	Mining	5455	233149	52046	18212	42842	53	36	11	112	4120	6	330	3
SS20a	3662707	4243757	Mining	2109	239995	41380	26290	15935	39	0	23	114	2213	0	261	0
SS20b	36627018	4243759	Mining	1794	214468	37446	22787	16942	36	0	20	103	2163	0	273	3
SS21a	36627198	4242800	Mining	1807	250738	41175	25106	19150	35	0	23	95	2280	0	238	0
SS22a	36626512	4244149	Mining	5971	197479	55807	12380	50013	58	45	12	108	5154	0	292	0
SS23a	36626596	4244649	Mining	4866	189023	49277	11580	51074	63	49	10	116	5347	0	267	0

Sample Number	**Easting**	**Northing**	**Scan mode**	**Nb**	**Sr**	**Rb**	**Bi**	**Ni**	**Mn**	**Cr**	**V**	**Ca**	**Cl**	**S**
SS2a	36627087	4245017	Mining	13	172	59.74	16.29	0	593.64	173.55	190.18	28125.82	362.3	0
SS3a	36627291	4245052	Mining	11	279	28.44	7.03	47.69	917.63	184.1	250.01	51306.55	461.11	0
SS5a	36627472	4244942	Mining	7	338	32.7	0	101.51	694.8	191.74	186.77	131342.3	300.8	1953.46
SS5b	36627478	4244945	Mining	10	248	34.01	8.68	71.91	857.01	189.99	219.78	42716.27	475.96	0
SS7a	36627471	4244051	Mining	14	107	72.67	24.6	0	455.54	99.82	168.96	11792.75	502.37	266.81
SS8a	36627020	4243850	Mining	17	63	88.24	27.95	0	299.7	0	176.32	7250.28	1013	268.54
SS8b	36627049	4243869	Mining	14	89	78.84	22.67	0	348.63	64.09	176.66	11492.41	688.99	338.94
SS8c	36627049	4243869	Mining	15	78	84.75	25.15	0	263.24	0	156.74	8308.64	975.69	0

SS8d	36627073	4243935	Mining	15	94	79.86	20.97	0	362.78	47.27	179.45	10124.14	769.85	151.44
SS8e	36627073	4243935	Mining	16	69	86.6	28.83	0	286.06	30.9	166.79	8535.87	916.81	135.76
SS9a	36627073	4243832	Mining	15	92	78.7	21.27	0	322.68	57.94	174.43	10221.34	708.08	610.14
SS9b	36627077	4243839	Mining	15	85	75.8	21.65	0	188.59	32.56	205.8	8933.95	730.46	1536.87
SS9c	36627090	424892	Mining	14	90	80.63	22.17	0	276.75	38.71	183.5	8524.06	836.63	289.35
SS9d	36627091	4243939	Mining	14	90	80.68	26.27	0	329.48	0	169.99	9946.23	773.7	415.88
SS9e	36627094	4243942	Mining	14	94	79.99	25.92	0	303.72	34.86	165.13	10035.68	855.84	284.6
SS9f	36627066	4243985	Mining	13	101	79.62	23.92	0	267.1	52.43	161.24	10959.5	811.12	225.49
SS10a	36627043	4244139	Mining	13	90	75.53	20.97	0	309.9	0	155.81	12250.19	835.8	0
SS10b	36627086	4244168	Mining	15	79	80.01	20.78	0	310.7	50.03	161.92	11413.79	750.3	591.37
SS10c	36627174	4244152	Mining	13	73	77.63	22.69	0	232.89	38.78	160.28	10605.71	721.62	992.26
SS10d	36627264	4244158	Mining	16	65	78.2	26.11	0	272.85	45.11	153.27	7824.53	675.95	658.68
SS10e	36627381	4244168	Mining	16	71	83.56	22.88	0	397.28	52.93	153.58	9268.04	642.82	0
SS10f	36627507	4244168	Mining	15	63	87.14	27.77	0	281.78	0	127.59	7870.49	736.68	0
SS11a	36626891	4244026	Mining	14	120	71.2	21.22	0	632.02	79.32	172.01	19677.66	641.16	97.49
SS11b	36626901	4244049	Mining	15	115	71.09	20.87	0	514.03	74.51	180	15482.92	674.13	0
SS12a	36626799	4244159	Mining	11	195	48.19	14.48	0	867.67	188.55	229.27	35616.23	425.34	0
SS12b	36626829	4244166	Mining	12	184	50.88	14.06	0	818.7	129.52	177.69	25100.75	507.05	0
SS13a	36627467	4243993	Mining	14	126	69.74	21.6	0	456.77	90.94	170.91	13356.59	539.6	1050.78
SS14a	36627367	4243949	Mining	16	64	85.71	26.55	0	275.06	60.22	131.01	7897.21	771.31	0
SS14b	36627365	4243955	Mining	15	59	86.88	25.73	0	284.7	0	132.77	8098.96	749.62	0
SS14c	36627361	4243956	Mining	15	60	87.98	28.84	0	275.72	36.78	133.36	7245.29	750.05	0

SS14d	36627360	4243955	Mining	16	72	85.14	26.38	0	351.29	43.84	131.88	9271.78	667.65	0
SS15a	36627656	4244262	Mining	11	146	55.21	13.53	0	678.75	105.69	179.17	19391.81	432.6	835.67
SS16a	36627749	4244346	Mining	13	176	51.27	17.31	0	743.99	138.74	198.45	26869.52	408.56	0
SS16b	36627777	4244313	Mining	14	191	54.17	15.76	0	803.98	219.69	199.52	26619.34	419.91	0
SS16c	36627790	4244307	Mining	12	171	56.59	15.37	0	681.78	122.69	192.42	26322.69	478.55	93.86
SS16d	36627803	4244272	Mining	11	316	20.31	0	0	1392.82	172.94	221.32	34711.68	386.48	0
SS17a	36627814	4244303	Mining	9	265	33.29	7.83	74.92	936.13	154.7	232.37	34185.52	445.74	0
SS18a	36627284	4243796	Mining	15	63	87.69	25.66	0	326.68	33.03	127.13	7802.08	730.72	0
SS18b	36627287	4243795	Mining	16	71	85.45	25.06	0	385.61	43.07	137.26	9338.4	663.1	0
SS19a	36627280	4244087	Mining	14	165	53.6	15.18	0	651.43	160.84	201.32	26523.46	397.7	0
SS19b	36627924	4244279	Mining	12	252	41.92	10.53	0	826.28	136.14	261.18	33169.46	455.7	0
SS20a	3662707	4243757	Mining	15	100	75.64	20.65	0	214.84	51.35	217.66	9863.02	687.73	1778.65
SS20b	36627018	4243759	Mining	15	91	71.51	23.44	0	128.33	44.14	203.31	9414.5	614.03	2353.18
SS21a	36627198	4242800	Mining	15	94	76.29	22.83	0	464.46	71.57	154.49	12420.06	587.71	198.16
SS22a	36626512	4244149	Mining	11	231	33.01	11.79	45.93	947	289.19	236.77	34499.23	349.34	0
SS23a	36626596	4244649	Mining	12	218	31.75	0	49.64	879.63	212.69	208.39	33727.04	329.52	0

Appendix 4

Correlation matrices (r-values) for the NAR10 sequence by lithostratigraphic unit. Correlation matrices for: Si (Silicon), S (Sulphur), K (Potassium), Ca (Calcium), Ti (Titanium), Mn (Manganese), Fe (Iron), Cu (Copper), Zn (Zinc), Se (Selenium), Br (Bromine), Rb (Rubidium), Sr (Strontium) and Zr (Zirconium). Strong correlations = $r \geq 0.6$ in red or $r \leq -0.6$ in blue. Correlations which are not significant at the 0.001 level (p-value >0.001) are shown with *.

Unit	**Correlation coefficients for key elements**														
		Si	S	K	Ca	Ti	Mn	Fe	Cu	Zn	Se	Br	Rb	Sr	Zr
Whole	S	0.46													
	K	0.69	0.34												
	Ca	-0.21	-0.01*	-0.40											
	Ti	0.65	0.28	0.88	-0.47										
	Mn	0.07	0.06	0.16	0.34	0.13									
	Fe	0.64	0.46	0.87	-0.52	0.92	0.12								
	Cu	0.39	0.15	0.53	-0.31	0.69	0.07	0.61							
	Zn	0.62	0.22	0.80	-0.29	0.83	0.20	0.75	0.60						
	Se	-0.23	-0.19	-0.24	-0.17	-0.20	-0.22	-0.25	-0.14	-0.21					
	Br	-0.20	-0.09	-0.23	0.04	-0.22	-0.11	-0.24	-0.16	-0.19	0.41				
	Rb	0.55	0.21	0.84	-0.61	0.87	0.03	0.84	0.56	0.72	-0.02	-0.11			
	Sr	-0.11	0.03	-0.14	0.26	-0.23	-0.27	-0.20	-0.16	-0.27	-0.02	0.04	-0.21		
	Zr	0.39	0.22	0.61	-0.52	0.61	-0.02	0.64	0.43	0.52	-0.11	-0.18	0.65	-0.18*	
	Pb	0.06	0.17	0.01	-0.09	0.02	-0.03	0.05	-0.02	0.02	0.25	0.30	0.12	-0.18*	0.00
		Si	S	K	Ca	Ti	Mn	Fe	Cu	Zn	Se	Br	Rb	Sr	Zr
1	S	0.30													
	K	0.88	0.18												
	Ca	-0.47	0.11	-0.55											
	Ti	0.79	0.11	0.85	-0.60										
	Mn	0.20	0.14	0.29	-0.11	0.25									
	Fe	0.76	0.31	0.83	-0.65	0.92	0.35								
	Cu	0.50	0.04	0.52	-0.42	0.73	0.14	0.65							
	Zn	0.79	0.09	0.87	-0.54	0.88	0.21	0.82	0.64						
	Se	-0.26	-0.21	-0.29	-0.07	-0.24	-0.25	-0.30	-0.18	-0.25					
	Br	-0.33	-0.18	-0.40	0.13	-0.36	-0.33	-0.42	-0.25	-0.33	0.44				

	Rb	0.72	0.04	0.82	-0.71	0.86	0.21	0.82	0.57	0.80	-0.03	-0.25			
	Sr	-0.41	-0.08	-0.49	0.54	-0.51	-0.17	-0.53	-0.34	-0.53	0.03	0.11	-0.57		
	Zr	0.60	0.07	0.68	-0.60	0.69	0.18	0.67	0.47	0.66	-0.11	-0.30	0.75	-0.39	
	Pb	0.07	0.25	0.03	-0.04	0.01*	-0.01	0.06	-0.04	0.02	0.18	0.18	0.12	-0.27	0.02
2		Si	S	K	Ca	Ti	Mn	Fe	Cu	Zn	Se	Br	Rb	Sr	Zr
	S	0.46													
	K	0.69	0.31												
	Ca	-0.04	0.01	0.10											
	Ti	0.66	0.30	0.89	-0.18										
	Mn	0.48	0.35	0.66	0.19	0.64									
	Fe	0.63	0.33	0.88	-0.20	0.97	0.67								
	Cu	0.43	0.24	0.52	-0.16	0.62	0.34	0.61							
	Zn	0.56	0.25	0.72	-0.20	0.80	0.42	0.80	0.58						
	Se	-0.26	-0.10	-0.50	-0.58	-0.32	-0.51	-0.32	-0.13	-0.20					
	Br	-0.26	-0.10	-0.49	-0.57	-0.32	-0.49	-0.31	-0.13	-0.19	0.78				
	Rb	0.28	0.05	0.36	-0.66	0.57	0.07	0.57	0.38	0.51	0.29	0.28			
	Sr	-0.42	-0.22	-0.39	0.37	-0.48	-0.42	-0.47	-0.26	-0.34	0.16	0.19	-0.32		
	Zr	0.20	0.08	0.38	-0.21	0.49	0.20	0.49	0.36	0.41	-0.12	-0.15	0.46	-0.26	
	Pb	-0.19	-0.07	-0.40	-0.55	-0.24	-0.40	-0.22	-0.09	-0.13	0.69	0.73	0.33	0.12	-0.12
3		Si	S	K	Ca	Ti	Mn	Fe	Cu	Zn	Se	Br	Rb	Sr	Zr
	S	0.47													
	K	0.67	0.41												
	Ca	0.19	0.07	0.34											
	Ti	0.54	0.29	0.76	-0.06										
	Mn	0.32	0.26	0.60	0.60	0.26									
	Fe	0.45	0.37	0.69	-0.17	0.86	0.26								
	Cu	0.22	0.11	0.24	-0.08	0.33	0.03	0.28							
	Zn	0.47	0.23	0.53	-0.01*	0.70	0.17	0.56	0.38						
	Se	-0.14	-0.11	-0.29	-0.23	-0.16	-0.27	-0.20	-0.10	-0.12					
	Br	-0.09	-0.04	-0.19	-0.10	-0.10	-0.17	-0.11	-0.11	-0.10	0.37				
	Rb	0.46	0.26	0.59	-0.32	0.73	0.06	0.71	0.23	0.49	0.00	0.01			
	Sr	0.31	0.15	0.36	0.74	-0.06	0.42	-0.14	-0.03	0.04	-0.21	-0.11	-0.12		
	Zr	0.04	0.04	0.04	-0.37	0.15	-0.15	0.16	0.15	0.12	-0.05	-0.14	0.22	-0.26	
	Pb	-0.04	0.07	-0.08	-0.26	0.05	-0.18	0.12	-0.06	-0.02	0.27	0.37	0.21	-0.23	-0.03
4		Si	S	K	Ca	Ti	Mn	Fe	Cu	Zn	Se	Br	Rb	Sr	Zr
	S	0.16													
	K	0.22	0.23												

	Ca	-0.36	0.10	-0.23											
	Ti	0.23	0.17	0.84	-0.34										
	Mn	-0.04	-0.02	-0.21	0.26	-0.16									
	Fe	0.23	0.16	0.90	-0.38	0.92	-0.20								
	Cu	0.04	0.02	0.10	-0.07	0.12	-0.03	0.12							
	Zn	0.11	0.04	0.19	-0.13	0.20	0.03	0.21	0.07						
	Se	0.00*	0.01*	-0.09	-0.08	-0.07	-0.04	-0.08	-0.01*	0.00*					
	Br	-0.01	0.05	-0.08	-0.02	-0.08	-0.06	-0.08	0.01*	0.00*	0.17				
	Rb	0.22	0.14	0.69	-0.45	0.69	-0.27	0.75	0.07	0.15	0.00*	-0.05			
	Sr	-0.04	-0.08	0.13	-0.27	0.10	-0.56	0.12	0.01*	-0.11	0.06	0.10	0.22		
	Zr	0.05	-0.02	0.04	-0.09	0.08	0.08	0.08*	0.05	0.03	-0.03	-0.06	0.06	-0.14	
	Pb	0.02	0.05	-0.03	-0.10	-0.02	-0.07	0.00*	0.01*	0.03	0.10	0.15	0.05	0.03	-0.01
		Si	S	K	Ca	Ti	Mn	Fe	Cu	Zn	Se	Br	Rb	Sr	Zr
5	S	0.44													
	K	0.46	0.29												
	Ca	-0.43	-0.09	-0.46											
	Ti	0.47	0.32	0.90	-0.58										
	Mn	-0.04	0.26	0.01*	0.27	0.03									
	Fe	0.49	0.40	0.84	-0.67	0.94	0.03								
	Cu	0.19	0.15	0.40	-0.26	0.47	0.03	0.47							
	Zn	0.31	0.21	0.57	-0.30	0.62	0.16	0.58	0.37						
	Se	-0.06	-0.02	-0.18	0.00*	-0.15	-0.04	-0.21	-0.09	-0.12					
	Br	-0.10	0.01	-0.21	0.17	-0.20	0.04	-0.27	-0.11	-0.14	0.39				
	Rb	0.45	0.26	0.84	-0.71	0.89	-0.10	0.87	0.37	0.51	-0.09	-0.18			
	Sr	-0.05	-0.17	-0.02	0.21	-0.14	-0.50	-0.16	-0.04	-0.19	-0.07	-0.09	-0.15		
	Zr	0.26	0.18	0.42	-0.44	0.47	-0.02	0.50	0.25	0.31	-0.11	-0.18	0.48	-0.11	
	Pb	0.03	0.15	-0.07	-0.01*	0.00*	0.16	-0.03	-0.02	-0.01*	0.30	0.39	0.03	-0.28	-0.05
		Si	S	K	Ca	Ti	Mn	Fe	Cu	Zn	Se	Br	Rb	Sr	Zr
6	S	0.00													
	K	-0.23	0.08												
	Ca	-0.45	-0.04	0.78											
	Ti	0.01*	0.22	0.20	0.11										
	Mn	-0.10	0.45	0.22	0.12	0.30									
	Fe	0.10	0.61	-0.13	-0.28	0.15	0.45								
	Cu	0.05	0.01	-0.03	-0.03	-0.06	-0.01	-0.01							
	Zn	0.08	0.02	-0.02	-0.05	0.00	-0.02	-0.02	0.11						
	Se	-0.08	-0.01*	-0.36	-0.44	-0.05	-0.02	0.00*	-0.03	0.01					

	Br	-0.14	0.01*	-0.29	-0.34	-0.09	-0.10	-0.02	-0.06	-0.01*	0.43				
	Rb	0.43	-0.05	-0.24	-0.41	-0.04	-0.13	0.05	-0.01	0.03	0.18	0.06			
	Sr	-0.04	-0.43	-0.04	0.12	-0.23	-0.70	-0.41	-0.01	0.02	-0.18	-0.01*	0.05		
	Zr	-0.05	-0.10	-0.17	-0.17	-0.08	-0.12	-0.04	0.05	0.00*	0.12	0.04	0.06	0.13	
	Pb	-0.09	0.21	-0.35	-0.43	-0.03	0.02	0.36	-0.03	-0.01	0.40	0.41	0.14	-0.19	0.03

		Si	S	K	Ca	Ti	Mn	Fe	Cu	Zn	Se	Br	Rb	Sr	Zr
7	S	0.30													
	K	0.25	0.51												
	Ca	-0.31	0.00*	0.13											
	Ti	0.30	0.40	0.76	-0.26										
	Mn	0.28	0.35	0.50	0.13	0.42									
	Fe	0.21	0.57	0.48	-0.48	0.65	0.29								
	Cu	0.05	0.05	0.00*	-0.15	0.07	-0.01	0.14							
	Zn	0.24	0.12	0.15	-0.09	0.21	0.25	0.14	0.08						
	Se	0.00*	-0.10	-0.14	-0.10	-0.11	-0.10	-0.17	-0.04	-0.02					
	Br	-0.03	-0.09	-0.10	0.05	-0.12	-0.07	-0.21	-0.06	-0.08	0.26				
	Rb	0.30	0.22	0.51	-0.52	0.66	0.21	0.55	0.03	0.11	0.04	-0.05			
	Sr	-0.29	-0.27	-0.11	0.32	-0.27	-0.53	-0.38	-0.06	-0.28	-0.02	0.07	-0.26		
	Zr	0.06	0.16	0.13	-0.21	0.18	0.03	0.25	0.09	0.05	-0.06	-0.10	0.14	-0.06	
	Pb	0.07	0.15	0.11	-0.18	0.12	0.01*	0.20	-0.02	-0.02	0.13	0.17	0.24	-0.07	0.03

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