CHAPTER

20

APPROACHES TO HOLOCENE CLIMATE RECONSTRUCTION USING DIATOMS

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Abstract: Diatom analysis has been used extensively to reconstruct past environments, and increasingly attention is being given to developing the technique to model Holocene climate variability. This chapter reviews progress in the field, including both qualitative and quantitative interpretations: (i) the relationships between diatoms and climate indicators such as solar insolation (Elk Lake, Minnesota), snow cover (Lake Baikal) and ice-cover (Elison Lake, Ellesmere Island); (ii) the development of models to reconstruct diatom inferred climates, either directly (e.g. surface water temperature, Scandanavia) or indirectly (e.g. pH in the Austrian Alps and on Baffin Island; e.g. salinity in lakes in the Northern Great Plains region, North America); and (iii) the development of high resolution studies in coastal and marine environments (including the Icelandic Shelf, the Antarctic Peninsula and the eastern Norwegian Sea). The importance of autecological and taphonomic studies is highlighted, although they still receive too little attention when attempts are made to interpret past climates using diatom analysis.

Keywords: Closed lakes, Diatoms, Marine diatoms, Open lakes, Qualitative reconstructions, Quantitative reconstructions, Transfer functions

Diatoms are unicellular algae and are used extensively in palaeoecological studies because they are excellent indicators of past environmental conditions. They are particularly useful palaeoecological proxies because they can be identified to the species level using light and scanning electron microscopy. Thus by inspection of assemblages in sedimentary records, we can make direct and indirect inferences about past environmental conditions. A detailed recent review on diatom analysis and applications can be found in Battarbee *et al*. (2001b).

Diatoms have been used as proxy indicators to reconstruct Holocene climate variability in every continent, and work on continental aquatic ecosystems has been much more common than marine or coastal studies. The majority of recent studies use quantitative multivariate techniques to reconstruct past climatic variables either directly, such as surface-water temperature (e.g. Vyvermann and Sabbe, 1995; Rosén *et al*., 2000; Bigler and Hall, 2002) and air temperature (e.g. Korhola *et al*., 2000), or indirectly by reconstructing, for example, salinity (e.g. Fritz *et al*., 1991; Laird *et al*., 1996; Gasse *et al*., 1997; Verschuren *et al*., 2000), DOC (Pientiz *et al*., 1999), conductivity (e.g. Davies *et al*., 2002) and pH (e.g. Psenner and Schmidt, 1992; Koinig *et al*., 1998a). However, qualitative information provided by assessing changes in diatom species themselves, especially with respect to their habitat, survival strategies and autecologies in both freshwater (e.g. Smol, 1988; Bradbury *et al*., 2002) and marine environments (e.g. Rathburn *et al*., 1997; Gersonde and Zielinski, 2000) should not be ignored.

In this chapter we review some recent developments in the use of diatom analysis to reconstruct climate variability during the Holocene. We describe some recently observed relationships between planktonic taxa in freshwater lakes and possible climate forcing factors, such as solar insolation. We then outline two studies that make use of diatom assemblages in the sediments of open-basin systems to (i) reflect past ice-cover in North American polar regions and (ii) reconstruct past climates in Northern Europe, both directly through reconstructing surface water temperatures, and indirectly by reconstructing pH and establishing links with changing air temperatures. We then outline the potential for using diatom-inference models for reconstructing past salinity in closed-basin systems in agriculturally important sub-humid regions of North America (where water quantity and quality are vulnerable) and, finally, we summarize recent progress in using diatom analysis in marine sequences to reconstruct Holocene climate variability.

Interpretation of the climate record held by diatom proxies in lake and marine sediments is enhanced in cases where there is knowledge of population growth and succession in the water column, and an understanding of how diatoms are transported to the sediment surface, and finally incorporated into the sedimentary record (e.g. through what we will call here integrated studies). In this way the quality of the diatom preservation can be assessed and key, controlling climatic variables evaluated. Diatom-inferred climatic interpretations therefore require knowledge of taphonomic processes, most notably dissolution (Flower, 1993). In saline systems, it is well known that diatom valve preservation is affected by the dissolution of biogenic silica; valves may either be partly dissolved so that identification becomes more difficult, if not impossible, or whole assemblages may be simply removed from both the training set and the stratigraphic record. Accordingly, recent attempts to improve diatom-inferred salinities from saline lake training sets have employed a very different approach of quantifying the relationships between the resistance of specific taxa to dissolution through the establishment of dissolution indices to help validate transfer functions (Ryves *et al.*, 2001). Dissolution is also a problem in many freshwater ecosystems, such as Lake Baikal in central Asia. A recent study found that approximately 50 per cent of diatom frustules in surface sediments are affected to some degree by dissolution, and provisional results suggest that only a small proportion of the cells produced in the water column are ultimately preserved in the sediments (Mackay *et al.*, 2000). Nevertheless, transfer functions from dissolved assemblages can still be effective (e.g. Pichon *et al.*, 1992), and although there is not the scope in this chapter to give a thorough representation of the problems of dissolution in lacustrine ecosystems, readers are instead encouraged to read Fritz *et al*. (1999) and Ryves *et al*. (2001), and references contained therein.

20.1 PLANKTON RESPONSES TO CLIMATE VARIABLES

Integrated studies provide an effective way of maximizing our knowledge of the processes that affect diatoms, which can subsequently be used to aid interpretation of past climates. Such studies ideally incorporate:

1. monitoring of the diatom populations, and sometimes also of the hydrophysical and hydochemical properties of the water body through space and time
2. an estimation of fluxes of diatoms down through the water column using open and/or sequencing sediment traps, followed by
3. an assessment of the rate of diatom incorporation into the surface sediments.

Here we present two examples of approaches taken towards integrated studies, both of which make use of sediment traps and accompanying environmental data. The first example is of Elk Lake, in Minnesota (e.g. Bradbury, 1988; Bradbury *et al*., 2002) and the second is of research currently being carried out on Lake Baikal (Jewson and Granin, 2000; Ryves *et al*., in press).

Elk Lake is a dimictic lake with annually laminated sediments that began forming approximately 11,000 years ago. Between 1979 and 1984, phytoplankton populations and succession were monitored using sediment traps (Bradbury, 1988), and population blooms of specific diatoms were linked to ice-cover and lake circulation patterns, especially the spring and autumn overturn. In this study, the importance of air temperature in controlling ice-cover, and circulation patterns in controlling nutrient availability, were highlighted especially with regard to two diatom species, *Fragilaria crotonensis* and *Stephanodiscus minutulus*. The study concluded that *S. minutulus* is indicative of a long, and 'vigorous' spring overturn period, which itself could be brought about by thin ice-covering over the lake, a warm, dry, early spring (to help prevent ice-cover becoming thick) and a cool late spring to help promote wind-driven circulation and postpone summer stratification. Bradbury suggests that after long, cold springs, when ice-cover is thick, the water column in lakes can quickly become stratified once the ice-cover has disappeared due to prevailing warm weather conditions. Water stratification prevents the resuspension of nutrients such as phosphorus from the bottom sediments; consequently, only diatoms that require small amounts of phosphorus in relation to silica (derived from groundwater and allochthonous inputs) can bloom, e.g. *F. crotonensis*. Taxa such as *S. minutulus*, on the other hand, bloom when the Si : P ratio is low (e.g. < 1).

Information obtained from the trapping experiments was used in a subsequent study to help interpret changes in the diatom assemblage composition throughout the Holocene in the context of climate variability (Bradbury and Dieterich-Rurup, 1993) (Fig. 20.1). Changing ratios between *S. minutulus* and *F. crotonensis* suggest shifts between long, dry springs, when the ratio between the two species is high, and warm stormy summers, when the ratio between the two species is low. Knowledge of the autecology of a further species, *Aulacoseira ambigua*, is used to suggest that during the Mid-Holocene at Elk Lake (between *c.* 6 ka yr BP and 4 ka yr BP) (Fig 20.1) the region experienced a marked increase in stormy weather during the summer and late autumn: *A. ambigua* is a summer species which blooms when silica is abundant, but also requires an increased degree of turbulence in the water column to keep the species in suspension.

The relationship between *S. minutulus* and *F. crotonensis* and other taxa, including benthic diatoms (e.g. *Cymbella* spp.) and chrysophyte cysts, has been further studied at Elk Lake over the last 1500 years (Bradbury *et al*., 2002), using a combination of wavelet transformation analysis and transfer function methodologies. Wavelet transformation analysis differs from Fourier analysis as it can be used to analyse data that exhibit periodicity (i.e. variation with both amplitude and frequency in time) (Torrence and Campo, 1998). In this study, wavelet analysis of, for example *Cymbella* spp., suggests strong periodic correlations between individual diatoms species and various sunspot cycles, including the 11-year Schwabe cycle, the 22-year Hale sunspot cycle, together with other multi-decadal- and multi-centennial-cycles (Fig. 20.2). These results suggest that solar insolation is an important explanatory variable for diatom population succession, whether directly, for example through ultraviolet penetration, or indirectly through changes in air masses. However, the results also clearly indicate that controls on diatom populations must come from a combination of factors, confirming that knowledge of the

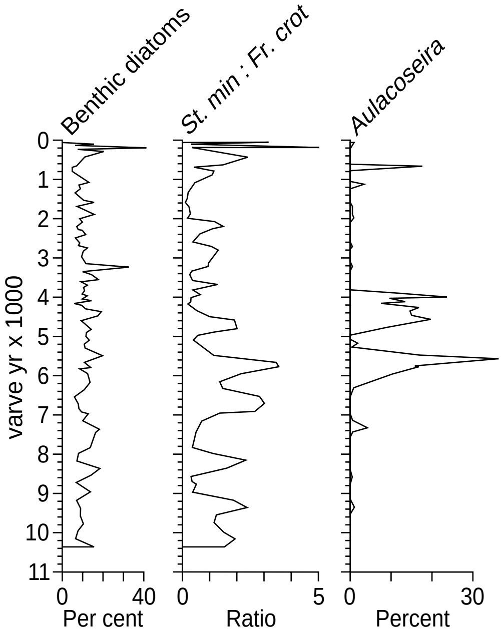

Figure 20.1 Relative proportion of benthic diatoms and *Aulacoseira* species, and the ratio between *S. minutulus* and *F. crotonensis* in varved sediments from Elk Lake. Adapted from Bradbury and Dieterich-Rurup (1993).

autecologies of diatom species greatly helps in palaeolimnological interpretations of Holocene climate.

Climate predictions for southern Siberia suggest that temperatures in winter will increase by 2–5 °C in the next 50 years (IPCC, 2001). Lake Baikal in southeast Siberia is therefore a key site for Holocene palaeoclimate research as it is positioned close to the boundaries of the Siberian high-pressure and the Asian monsoon weather zones, far from oceanic influences. Lake Baikal is extremely continental and its mid-latitude position makes it sensitive to insolation changes: winters are long, cold and dry, and summers (although short) are relatively warm and wet. Studies of the phytoplankton in Lake Baikal were pioneered by Skabitchevsky (1929), and have since been followed up by many other studies (for more details, see Jewson and Granin, 2000). The diatom phytoplankton of Lake Baikal is largely affected by physical parameters of the lake, e.g. ice-cover, seasonal overturn and other mixing properties, and recent studies have used diatoms to reconstruct Holocene climate variability in this region (e.g. Bradbury *et al*., 1994; Edlund *et al*., 1995; Mackay *et al*., 1998; Bangs *et al*., 2000).

Seasonal ice formation is an important feature of Lake Baikal, lasting for about 4–6 months of the year, although ice persists longer in the north basin than in the south. Ice formation and eventual duration is complex (Verbolov *et al*., 1965) and recent studies have shown ice-cover to be linked to large-scale atmospheric circulation patterns, including the Scandinavian and Arctic Oscillation patterns, the position of the Siberian High, and sea surface temperature anomalies in the North Atlantic Oscillation (NAO) during the autumn winter period (Livingstone, 1999;

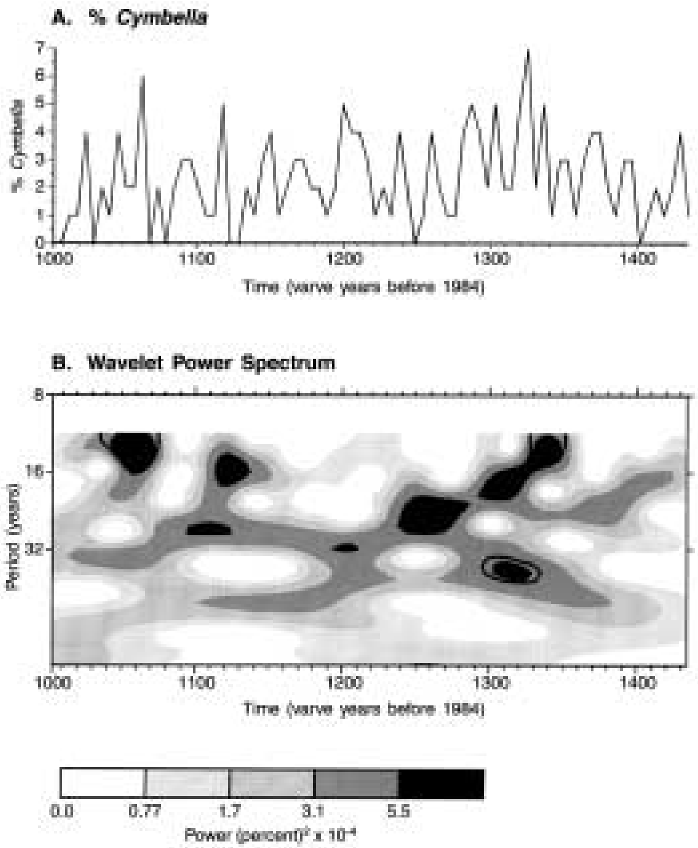

Figure 20.2 (a) Per cent *Cymbella* species (detrended and standardized) in the varved Elk Lake core between 1535 and 1000 years ago. (b) Wavelet power spectrum of *Cymbella* per cent. Shaded contour levels were chosen so that 75, 50, 25 and 5 per cent of the wavelet power is above each level, respectively. Black contour lines represent the 10 per cent significance level relative to the global wavelet background spectrum. Redrawn with kind permission from Bradbury *et al.*, (2002) and Kluwer Academic Publishers.

Todd and Mackay, in press). The water column under clear ice supports a dynamic and extensive diatom assemblage, including the heavily silicified endemic species *Aulacoseira baicalensis*; thermal heating and convective mixing keeps these large cells in suspension (Jewson and Granin, 2000). Kelly (1997) estimates that between 4 and 11 per cent of solar radiation is able to penetrate through clear ice, providing enough energy for algal growth in spring. Light penetration, however, is also dependent on snow cover on top of the ice: as little as 5 cm of snow cover on the ice can reduce solar transmission by a factor of 50 (Kelly, 1997), and when snow cover on Lake Baikal exceeds 10 cm, population growth of *A. baicalensis* is inhibited (Jewson and Granin, 2000). Over the last 150 years, populations of *A. baicalensis* have dominated the sediment record, but before then concomitant with the period commonly known as the Little Ice Age (LIA) the autumnal blooming endemic *Cyclotella minuta* is the dominant species (Mackay *et al.*, 1998), suggesting that ice and/or snow conditions on the lake were too extreme at this time for spring diatom populations to flourish. Work is ongoing to further establish relationships between both endemic and cosmopolitan diatom species in the lake through culturing studies (Jewson *et al*., unpublished data) and integrated monitoring of diatom populations and hydrophysical properties of the water column (Ryves *et al*., in press). A recent study by Mackay *et al*. (2003) explored the relationships between diatoms and environmental variables using multivariate techniques, including the direct gradient technique of canonical correspondence analysis (CCA), together with forward selection, a form of stepwise regression. In order of importance it was found that snow cover on the lake, water depth, suspended matter, annual solar radiation and mean July temperature of the surface water were significant in independently explaining diatom distribution across the lake, opening up the possibility of reconstructing Holocene climate variability using diatom analysis of the bottom sediments.

20.2 ICE-COVER RECONSTRUCTION USING DIATOM ANALYSIS

The IPCC (2001) also reported that the effects of global warming are likely to be more keenly experienced in high latitude regions, such as the Arctic. However, these regions are remote and the availability of long-term monitoring records is poor. In these situations, palaeoecological records with robust chronologies can provide important information on when the most recent trend in global warming first started to have significant ecological impacts. In other regions, pollen and macrofossil studies are important tools used to reconstruct past climates (see Birks and Birks, pp. 000–000 in this volume) but in the Arctic trees are sparse and so other techniques need to be employed. Consequently, the use of proxy data from lake ecosystems, such as diatoms, has allowed researchers to extend climate records where monitoring data are otherwise absent (e.g. Overpeck *et al*., 1997).

In polar regions, ice-cover is an important variable in determining functioning of lake ecosystems. Ice-cover influences light penetration into surface waters, which has a direct influence on diatom photosynthesis, and consequently population growth. Ice-cover also plays a major role in the stratification of the water column, which in turn has an influence on lake mixing and nutrient cycling processes (e.g. as determined by Bradbury, 1988, summarized above). Together, these influences affect the extent and types of habitat available to diatom species, which Smol (1988) suggests can be used to reconstruct palaeoclimates in polar environments. For example, in extreme polar environments, lakes (such as Lake Vanda in Antarctica) are permanently covered by ice and biological productivity is very low. However, ice-cover in many other polar lakes at least partially thaws around the margins every summer, resulting in an increased area of littoral habitat. In warmer years this area increases, sometimes even to the extent that the whole of the lake is ice-free (Smol, 1988). It follows that as a greater area of littoral habitat is opened up, then diatom responses change accordingly (see Table 20.1). If the whole of the lake does become ice-free during summer months (and providing that the lake is deep enough) then planktonic taxa will become more abundant in the lake. Several studies have investigated the interactions between diatom assemblages and ice and snow cover in lakes in extreme environments, including the Arctic (e.g. Smol, 1988; Douglas *et al*., 1994; Sorvari *et al*., 2002), high-altitude regions such as the Alps (e.g. Lotter and Bigler, 2000; Ohlendorf *et al*., 2000) and in very continental regions such as Lake Baikal in central Asia (e.g. Mackay *et al*., 2003; Ryves *et al*., in press). Here we review the case study of Elison Lake in the polar region of North America.

Prevailing climate	Lake conditions	Diatom responses
Cold	Extended ice and snow cover	Aerophillic diatoms Shallow water taxa
	Very small moat	Low production
Moderate	Moderate sized moat	Deeper water taxa Moderate production
Warm	Pelagic region of the lake is ice-free	Progressively more deep water and planktonic taxa High production

Table 20.1 Climatic changes and the corresponding responses in the diatom community. Adapted from Smol (1988)

Elison Lake is located in Cape Herschel on Ellesmere Island, the northernmost island in the Canadian Arctic archipelago (Douglas *et al*., 1994). It is one of a number of small freshwater ponds and lakes abundant in the region, which for most of the year are covered by ice, except for a short period of about 1–2 months between June and August. Douglas *et al*. (1994) provide evidence for marked increased ice-free periods on Elison Lake since the beginning of the 19th century, which were not evident in recent millennia, and which they attribute to recent increases in global warming.

The sediment records were dated using a combination of ^{210}Pb analysis for the uppermost samples, and ^{14}C for the basal samples, indicating that the base of their core was just over 4000 calibrated years BP. Diatom analysis revealed (Fig. 20.3) that for the majority of this time,

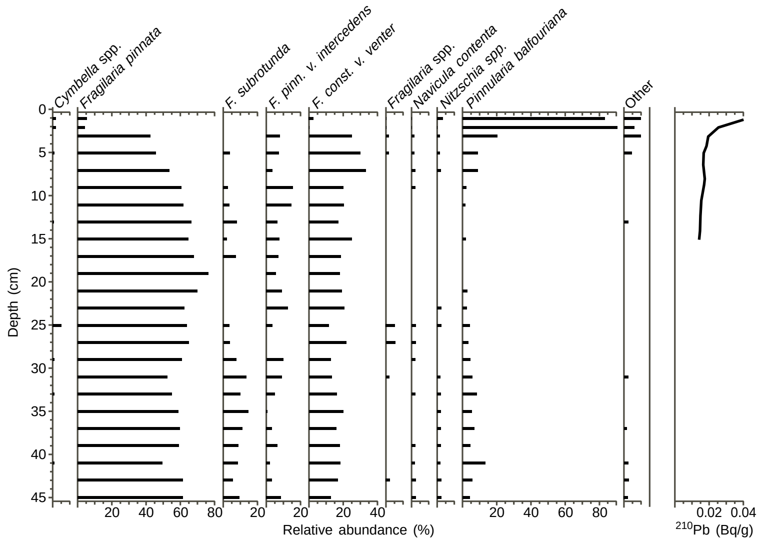

Figure 20.3 Relative percentages of major diatom taxa in a core taken from Elison Lake, Ellesmere Island. ^{210}Pb activity is shown on the right. Redrawn from Douglas *et al*. (1994) with kind permission from the American Association of the Advancement of Science.

assemblages were dominated by benthic *Fragilaria* taxa (especially *F. pinnata* and *F. construens* v. *venter*) which are characteristic of species found growing in the littoral zones of lakes. Lotter and Bigler (2000) suggest that *Fragilaria* species are r-strategists, and are thus able to colonize habitats that undergo frequent environmental changes, such as the littoral zones of lakes that have seasonal ice-cover. However, since the early 19th century up to the present day, the diatom assemblage at Elison Lake changed dramatically, with *Pinnularia balfouriana* becoming the dominant species. In polar regions, *P. balfouriana* is found growing on arctic mosses, and the Douglas *et al*. (1994) study indicates, therefore, that the lake has opened up sufficiently to allow aquatic mosses to colonize. Douglas *et al*. . (1994) also convincingly argue that other causal agents, such as anthropogenic pollution or increasing ultraviolet radiation could not have been the determining factors. These findings are supported by a more recent study of contemporary processes on the effects of ice-cover on diatom habitats in the high altitude Alpine lake, Hagelseewli (Lotter and Bigler, 2000), confirming that ice-cover acts to inhibit plankton development, while prolonged periods of ice-cover tended to favour the growth of *Fragilaria* species.

20.3 QUANTITATIVE CLIMATE RECONSTRUCTIONS IN OPEN-BASIN SYSTEMS

20.3.1 Diatom-Inferred Surface Water Temperatures

An increasing number of studies have employed numerical techniques to reconstruct climate directly (e.g. temperature) and indirectly (e.g. pH, DOC and salinity) from both open- and closed-lake systems. Perhaps the more contentious palaeoenvironmental reconstructions using diatoms in recent years have been those for summer surface-water temperatures (Pienitz *et al*., 1995; Vyvermann and Sabbe, 1995; Joynt and Wolfe, 2001; Wolfe, 2003) and mean July air temperatures (Korhola *et al*., 2000; Rosén *et al*., 2000; Bigler and Hall, 2002) from diatoms in lake sediments (see Anderson, 2000 for a critical review).

There is some controversy as to whether diatoms can be effectively used as proxies to reconstruct past temperatures. On the one hand, (i) water temperature plays a crucial role in regulating algal photosynthetic processes and metabolic activity (e.g. see appropriate references in Pientiz *et al*., 1995); (ii) optima and tolerances have been determined for many species using culturing studies (e.g. Dauta *et al*., 1990; Richardson *et al*., 2000; Jewson *et al*., unpublished data); and (iii) many taxa exhibit distinct relationships with increasing latitude and altitude (e.g. Foged, 1964; Vyvermann and Sabbe, 1995). On the other hand, however, (i) it is argued that over extended time periods such as the Holocene, indirect climatic effects on lake catchment processes (which in turn affect e.g. DOC, pH and nutrients in lakes), are likely to have a much greater influence on diatom species composition than changes in temperature alone (see Anderson 2000) as the amplitude of temperature change during the Holocene is often close to the prediction errors for diatom-based temperature models (Battarbee, 2000); and (ii) throughout the Holocene, changes in lake depth due to e.g. hydroseral succession, result in changing habitat availability to diatoms and alter the thermal regime of the water column.

Recent studies have tried to take account of some of these concerns, especially with regard to initial project design. One such development includes the use of multi-proxy studies, so that models are constructed using other proxies as well as diatoms from the same stratigraphical samples. For example, Lotter (pp. 000–000 in this volume), highlights the study by Rosén *et al.* (2001), who demonstrate that modelled temperature reconstructions from diatoms, pollen, chironomids and near-infrared spectroscopy of organic sediments can be used to confirm mean July air temperature oscillations over the last 7300 cal yr BP in northern Sweden. Another important development has been the use of independent cross validation techniques for diatom-inferred temperature models (Bigler and Hall, 2002). This study, together with that by Rosén *et al.* (2000), have modelled temperature optima for species in both datasets, and comparison between studies demonstrate an encouraging level of agreement for many taxa, although some important differences are apparent. An alternative approach has been taken by a joint consortium of European and Russian scientists working on Lake Baikal: interestingly, many of the initial objections raised by Anderson (2000) in terms of using diatoms to reconstruct climate parameters are not valid for this lake. For instance, the lake is so deep, that infilling is not an issue, and even though there is concern about pollution, the recent sediment record of diatom assemblages does not indicate any significant acidification or eutrophication trends in the lake (Mackay *et al.*, 1998). Anderson further highlighted that many of the diatom taxa currently used in training sets to reconstruct temperatures are very cosmopolitan, and so are unlikely to have distinct optima and narrow tolerances for surface-water temperature. However, in Lake Baikal, the majority of the dominant taxa are endemic, and preliminary investigations suggest that many of them have very clearly defined responses to temperatures (Richardson *et al.*, 2000; Jewson *et al.*, unpublished data).

Much research has still to be done, therefore, to fully understand the complexity of diatom–temperature interactions, and although the criticisms by Anderson (2000) need to be taken into account, recent studies continue to demonstrate the potential of diatom-inferred temperature models.

20.3.2 Diatom-Inferred pH and its Relationship to Prevailing Air Temperatures

Because of their remote, high-altitude location, alpine lakes are sensitive to changes in climate that influence ice and snow cover on the lake and in the catchment: for example, as climate ameliorates, both weathering of the catchment and the growing period in the lake, increase. The impact of anthropogenic contamination on alpine lakes is generally lower than that for lowland lakes, although they are still prone to acidification from industrial pollutants (Jones *et al.*, 1993). Given the above uncertainties of reconstructing past temperatures directly using diatom-based transfer functions, indirect climate relationships via changing diatom-inferred pH (e.g. Psenner and Schmidt, 1992; Sommaruga-Wögrath *et al.*, 1997; Koinig *et al.*, 1998a, 1998b) and DOC (Pientiz *et al.*, 1999) in freshwater lakes have proved fruitful in recent years. This approach has been adopted in the Austrian Alps, and a strong relationship between diatom-inferred pH values with changing Austrian mean air temperatures for the period 1778–1991 demonstrated (Koinig *et al.*, 1998a).

Using a previously developed training set for diatoms and pH, initial pH reconstructions at Schwarzsee ob Sölden and Brechsee (two remote, soft-water lakes in the study region) reveal interesting relationships between diatom-inferred pH and air temperatures and glacier mass trends respectively (used as a climate proxy prior to 1780) (Fig. 20.4). At Brechsee, the record extends the pre-industrial period, and results show that during periods of warmer climate, pH values increased, and vice versa (i.e. during periods of colder climate, lake water became more acidic). Even during industrialization, and in spite of increasing deposition of acidifying

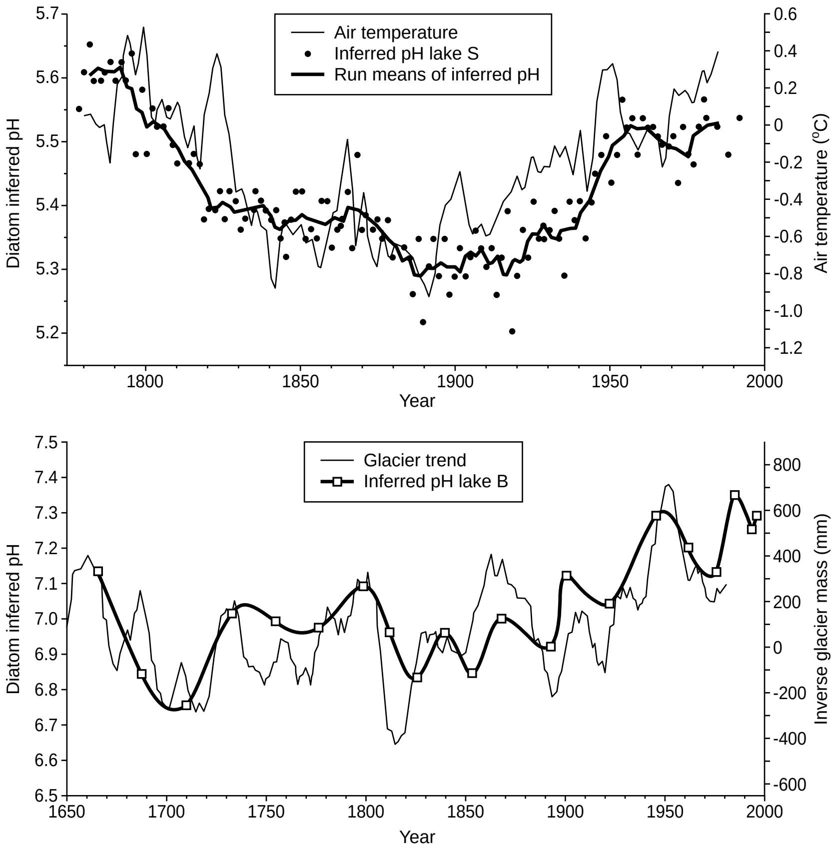

Figure 20.4 The upper graph shows the comparison between reconstructed pH and mean air temperature for Schwarzsee ob Sölden (lake S). The lower graph shows the comparison between reconstructed pH for Brechsee (lake B) with glacier trends. (Note different time-scales). Redrawn from Kionig *et al.* (1998a) with kind permission from AA Balkema Publishers.

compounds at these two sites, diatom-inferred pH continued to follow closely mean air temperatures (and glacier trends). This is in contrast to other sites in the region where pH reconstructions often showed a decoupling of inferred pH and temperature as acid deposition increased, i.e. as levels of acid rain increased during the period of recent warming, diatom-inferred pH also declined (Koinig *et al*., 1998a).

There are several mechanisms that can account for increasing values of diatom-inferred pH during warmer climates, linked to prevailing snow and ice conditions in the catchment and on the lake. Periods of warmer weather lead to decreased amounts of snow and ice-cover, which in turn allows for an in increase in catchment weathering rates and increased primary productivity in the lake itself, due to the concomitant lengthening of the growing-season and light penetration into the lake (Psenner and Schmidt, 1992; Sommaruga-Wögrath *et al*., 1997). Sommaruga-Wögrath *et al*. (1997) analysed monitoring data for 57 low-alkalinity high mountain lakes (all between 2000 and 2900 m a.s.l.). Each lake was sampled annually (during the autumn overturn between 1985 and 1995 for a range of chemical variables, including pH, conductivity, alkalinity, silica, dissolved inorganic nitrogen (DIN), major anions and cations, amongst others. Rather surprisingly, despite falling levels of sulphur deposition and small increases in nitrogen deposition, linked to prevailing deposition trends, concentrations of base cations and SO_4^{2-} increased in most lakes, whilst for DIN they declined. These changes were also accompanied by small increases in overall lake water pH and silica concentrations. Sommaruga-Wögrath *et al*. (1997) linked these changes to a marked increase in mean annual Austrian air temperatures measured over the same period of *c*. 1 °C, confirming distinct temperature- and pH-related processes within the lakes.

While these alpine studies are confined to records going back no more than 200 years, Wolfe (2002) investigated the relationship between pH and climate in two ultra-oligotrophic Arctic lakes (Kekerturnak Lake and Fog Lake) on Baffin island over the last 5000 years. His study shows a distinct fall in diatom-inferred pH, coincident with regional neoglacial cooling over the last *c*. 4000 years. Whereas Sommaruga-Wögrath *et al*. (1997) attribute a decline in alpine lake pH during colder years to reduced catchment weathering, aeolian dust transport and reduced primary production in the lake, Wolfe (2002) attributes the fall in pH in the Arctic lakes mainly to a decline in photosynthesis and primary productivity due to enhanced snow and ice-cover. Wolfe (2002) does not consider weathering of the catchment and aeolian transport of minerals as important pH regulators in these lakes, as the bedrock consists of hard Archaen granite and gneiss, and the lakes are ice-bound for about 10 months of the year, which precludes increased input of base cations. Furthermore, increased snow and ice-cover also tend to inhibit photosynthesis and primary production, which in turns reduces the uptake of CO_2 by biological processes, leaving excess CO_2 in the water. Speciation of dissolved inorganic carbon (DIC) in these lakes is very important, as the lakes are covered by ice for such a long period of the year, resulting in supersaturation of lake water CO_2 as water–air exchange of CO_2 is inhibited and photosynthesis reduced (Wolfe, 2002). During warmer periods it is hypothesized that ice-cover is reduced, which in turn leads to reduced CO_2 in the water and a concomitant increase in pH.

20.4 QUANTITATIVE CLIMATE RECONSTRUCTIONS IN CLOSED-BASIN SYSTEMS

10.4.1 Diatom-Inferred Salinity Relationships

Closed-basin systems are extensive throughout arid and semi-arid regions of the world, where the balance between precipitation and evaporation (P–E) and the influence of groundwater principally control lake water levels. These lakes are therefore found in regions of the world where pressures on water resources are high, both from natural (e.g. drought) and anthropogenic (e.g. abstraction) processes. As in open-basin systems, diatoms are an important component of closed-basin lakes (thereafter referred to as saline lakes), and although the comprehensive nature of the relationship between diatoms and changing ionic composition of lake water is still poorly understood (Fritz *et al*., 1999), diatoms have been extensively used in recent years to reconstruct past climates indirectly.

The relationships between diatoms and lake water salinity have been explored in detail (e.g. Bradbury *et al*., 1981; Gasse *et al*., 1987), culminating in an extensive range of projects since the 1990s, including the seminal study by Fritz *et al*. (1991) on reconstructing Holocene climate in the Northern Great Plains (NGP), North America. There have been many subsequent studies establishing the relationship between diatoms, salinity and brine composition and conductivity in closed-lake basin systems to Holocene climates from around the world, e.g. North America (Cumming and Smol, 1993; Wilson *et al*., 1994; Laird *et al*., 1996, 1998a, 1998b; Wilson *et al*., 1997; Last *et al*., 1998), Central America (Metcalfe, 1995; Davies *et al*., 2002), Africa (Gasse *et al*., 1997), Australia (Gell, 1997), Europe (Reed, 1998; Reed *et al*., 1999), Antarctica (Roberts and McMinn, 1998) and Greenland (Ryves *et al*., 2002).

Here we focus on one of the more comprehensive studies carried out at Moon Lake, situated within the NGP region (Laird *et al*., 1996, 1998a, 1998b), which provides an example of how diatom-inferred salinity reconstructions can be used to reconstruct past climates at high resolution, and of the potential problems associated with these types of analyses. The NGP region lies in continental North America, where winter temperatures are very low, and summer temperatures hot: mean annual temperature at Moon Lake is *c*. 6 °C (range –29 °C to +38 °C) (Laird *et al*., 1996). The negative effective moisture gradient is responsible for prevailing prairie and steppe vegetation, and for the hundreds of saline lakes found in the NGP region. Overall, the region is especially important for agriculture but it is also prone to severe drought, for example the dust-bowl event during the 1930s and 1940s.

The training set used to develop the diatom-inferred salinity model was adapted from Fritz *et al*. (1991), but its suitability was first validated by comparing inferred values to historical records of mean annual P–E, determined from nearby climate stations recorded since the late 19th century. An initial diatom-inferred salinity reconstruction for the Early Holocene at Moon Lake (see Fig. 16.4 in Fritz, pp. 000–000 in this volume) suggested that during the Early Holocene, Moon Lake was actually a freshwater lake. However, concomitant with the development of a prairie landscape from a forested one, lake levels fell, turning it into a closed basin: these features taken together point to a strong shift from cool moist conditions to a warmer, drier climate. In a subsequent study, climate variability at Moon Lake was reconstructed at a higher resolution over the last two millennia to establish drought patterns in the context of a longer-term perspective (Laird *et al*., 1998a). This study is important both from a methodological point of view (model validation), and in its societal contribution in terms of adding to the debate on water resources in this vulnerable, but agriculturally important region. Initially, diatom-inferred salinity values were compared to instrumental records of salinity over the last 100 years (Bhalme and Mooley drought index (BMDI) – see Laird *et al*., 1998a for full details). Overall, a good correspondence was found between modelled and historical values (Fig 20.5), resulting in increased confidence that modelled values for the remaining Holocene period are a good reflection of past climates (Laird *et al*., 1996). The importance of validating such climate models cannot be overestimated (e.g. see Fritz *et al*., 1994 for another case study). Diatom-inferred salinity changes over the last 2300 years (Fig. 20.6) suggest that droughts were more prevalent prior to 1200 yrs BP, and that these droughts were more extreme than those witnessed during the dust bowl years of the 1930s and currently have no modern analogues (Laird *et al*., 1998a). Their analysis suggests that forcing mechanisms causing climate change during the last 2000 years in the NGP region have shifted more frequently than in the Early Holocene, and may be linked to changing patterns in El Niño Southern Oscillation (ENSO) development, culminating in a general shift to wetter conditions, coincident with the Little Ice Age (LIA) (Laird *et al*., 1998a).

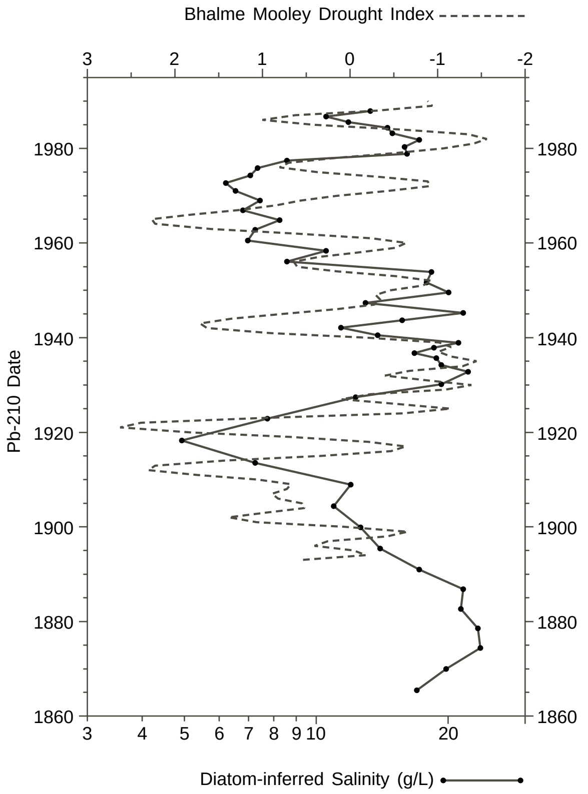

Figure 20.5 Comparison between diatom-inferred salinity at Moon Lake (solid line), with the Bhalme Mooley Drought Index (BMDI) (dashed line), developed for the NGP region from monthly summer precipitation records from nearby climate stations. Redrawn from Laird *et al.* (1998a) with kind permission from Kluwer Academic Publishers.

Diatom-inferred climate change studies from saline lakes are affected by both diatom dissolution (as outlined in the Introduction), and problems of 'no analogue' (see Birks, pp. 000–000 in this volume). It is appropriate therefore to outline some of the problems encountered in the development of the salinity model for the NGP region. In the Great Plains, dissolution has resulted in poor diatom preservation in approximately 20 per cent of the samples used in the training set, and there is a direct relationship between the number of samples with poor preservation and increasing salinities (Fritz *et al.*, 1993). Dissolution therefore results in selective preservation of the more robust valves, such as *Cyclotella quillensis*. This in turn results in samples with low species diversity, which leads to bias in reconstructed salinity values. A second major weakness found during development of diatom-inferred salinities in North America is the problem of 'no analogue' situations between the training set used, and the core selected for reconstruction. Both Fritz *et al.* (1993) and Laird *et al.* (1996) acknowledge that the original training set suffers from a lack of sites at the lower end of the salinity gradient, i.e. freshwater lakes. At Moon Lake, samples with no analogues are further exacerbated by the presence of high proportions of *C. choctawatcheeana* in the core, which are not present in the training set.

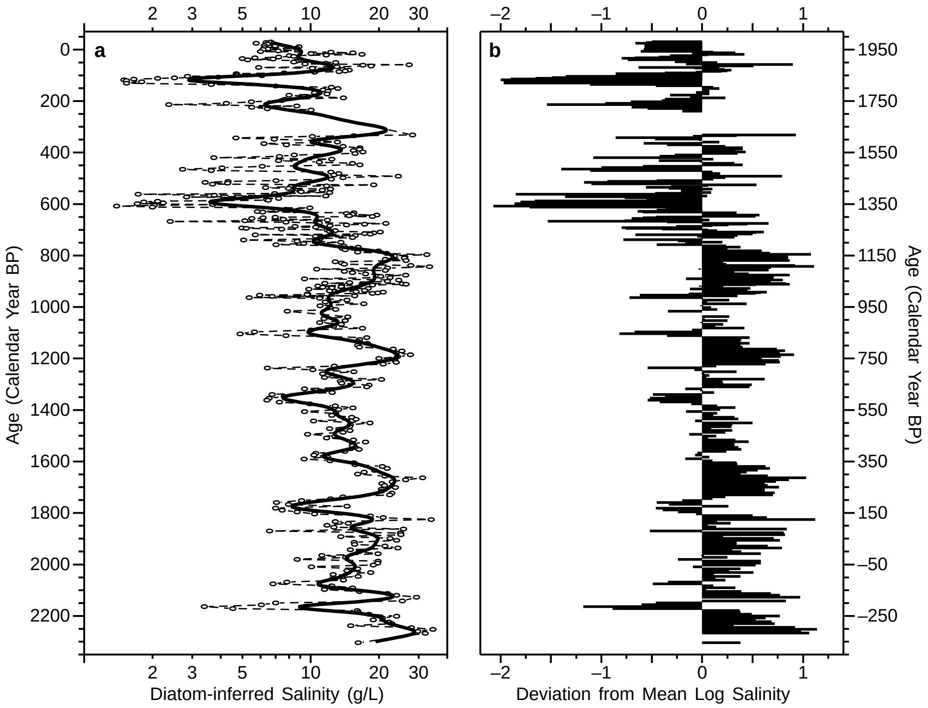

Figure 20.6 (a) Diatom inferred salinity (dashed line) for Moon Lake over the last 2300 years plotted alongside a Fast Fourier transformation (see Laird *et al*., 1998a for full details). (b) Deviations from the mean log salinity. Redrawn from Laird *et al*. (1998a) with kind permission from Kluwer Academic Publishers.

To overcome these difficulties and to improve estimates of diatom-inferred salinities, Juggins *et al*. (1994) recommend the development of regional training sets, which serves to increase the number of sites used at the lower concentrations of salinity for example, and to increase the number of species present for model development. The CASPIA project was set up specifically to harmonize diatom collections from saline lakes from the NGP, East and North African and the southeastern Australian datasets (Juggins *et al*., 1994). More recently, the EDDI project was designed to harmonize diatom-inferred pH, nutrient and salinity training sets, the latter collected from Africa, Europe and western Asia (Battarbee *et al*., 2000).

In summary, saline lakes in arid and semi-arid regions of the world provide unparalleled opportunities for palaeoclimate reconstructions. However, these studies also need to take into account problems of taphonomy, such as dissolution, and no analogue situations, where the range of sites within any one training set is too small. Major steps are being taken to compensate for these problems, with an increasing amount of modern process-based studies (e.g. Lent and Lyons, 2001; Ryves *et al*., 2001) and the merging of training sets, where appropriate, from around the world.

20.5 EVIDENCE OF DIATOM-INFERRED HOLOCENE CLIMATE VARIABILITY FROM COASTAL AND MARINE REGIONS

In comparison to studies from lacustrine ecosystems, there are comparatively few studies that use diatoms to reconstruct high-resolution Holocene climate variability from marine sequences, although there has been an increase in the number of such studies in recent years, e.g. of the coast of Antarctica (Rathburn *et al*., 1997; Cunningham *et al*., 1999; Taylor *et al*., 2001; Taylor and McMinn 2001, 2002); in the shallow waters in the proximity of the Baltic Sea (e.g. Jiang *et al*., 1998; Westman and Sohlenius 1999), off the coast of Iceland (e.g. Jiang *et al*., 2001, 2002) and in the Norwegian Sea (Birks and Koç, 2002). Many of these studies tend to use information provided by diatoms in the form of habitat availability. For example, diatoms are usually the most abundant organisms under sea-ice (Horner, 1985), and their abundance can be used to indicate changing patterns in sea-ice in relation to volume of open water, and ultimately to climate (Gersonde and Zielinski, 2000), e.g. *Nitzschia curta* forms a large biomass when cells are released from melting ice (Wilson *et al*., 1986).

Other studies have taken a multivariate approach, in relating diatoms in marine surface sediments to environmental variables, including sea-surface temperatures (SST). Jiang *et al*. (2001) used CCA to investigate the relationships between diatom species and environmental variables (including SST and winter SST) off the north Icelandic shelf. They recognized five diatom assemblages characteristic of different oceanic habitats: sea-ice, cold water, warm water, mixed water and coastal water. A diatom-inferred SST model was subsequently developed and applied to a marine core, located 50 km offshore on the north Icelandic shelf (Jiang *et al*., 2002). Their diatom model suggests a distinct period of cooling from around 2200 cal yrs BP up to the present day, coincident with neoglacial cooling in other regions. However, as with temperature reconstructions from freshwater lakes, the magnitude of reconstructed SSTs are relatively small, and within the range captured by error analysis.

Perhaps a more conclusive study of marine diatom evidence for Holocene climate variability comes from a multi-proxy study by Taylor *et al*. (2001) from the Antarctic Peninsula. They make use of known ecological characteristics of key diatoms, together with multiple regression analysis between sedimentary environmental variables and diatom data. Their results indicate three distinct climatic periods during the Holocene in this region: an early deglaciation phase between 10,600 and *c*. 7800 yr BP, a mid Holocene climatic optimum between 7800 and 4000 yr BP, and ending in a neoglacial period from c. 4000 yr BP up to the present day. The diatom assemblages during the neoglacial are different from those present during the Early Holocene, and so may represent a response to an increase in ice extent, and or an advance of the Müller ice shelf (Taylor *et al*., 2001.). Further during this period, as summer insolation in this region was at a maximum at *c*. 2000 yr BP, the neoglacial cooling prior to then is likely to be due to other factors such as changes in deep water circulation. Diatom-inferred climate studies have therefore opened up some interesting questions on climate forcing mechanisms in this region of the world and the concomitant biological and physical responses.

The last case study presented in this chapter combines traditional palaeoceanographic approaches to reconstructing SST (i.e. Imbrie and Kipp, 1971; factor analysis methodology) with the now commonly used palaeolimnological technique of weighted averaging partial least squares (WA-PLS) (see Birks, pp. 000–000 in this volume). Birks and Koç (2002) used high-resolution diatom analysis to reconstruct Late Glacial to Holocene, February and August SSTs from the Vøring Plateau in the eastern Norwegian Sea. Both models were robust, i.e. had high r^2 values, low error and a maximum bias of *c*. 1 °C. Throughout the Holocene the models show similar trends, although differences between the two were apparent. Both models, for example, record maximum SSTs between *c*. 9700 and 6700 cal yr BP. However, February SSTs reconstructed using WA-PLS fluctuated between 9.5 °C and 11 °C from *c*. 8750 to 7250 cal yr BP before falling to between 8.5 °C and 9.5 °C from 7250 to 6700 cal yr BP. Whereas factor analysis recorded higher temperatures fluctuating around 11 °C throughout the whole of this period. With regard to the varimax factors associated with the time period, the dominant diatom assemblages suggest a strong influence from North Atlantic Water. Interestingly, any response of the diatoms to the 8.2 ka event remains inconclusive: whilst there is a drop in concentrations at this time, there is no concomitant reconstructed cooling of SSTs. The role of sea-ice in influencing diatoms is also highlighted, and the authors conclude that diatom-free levels, e.g. during the period coincident with the Younger Dryas, can be attributed to extensive ice-cover prohibiting photosynthesis thereby reducing production, although the authors, rightly, cannot and do not preclude the influence of dissolution processes affecting the sedimentary diatom record.

20.6 CONCLUSIONS

In recent years, the number of diatom-based Holocene climate reconstructions has increased dramatically, although most studies are still confined to terrestrial ecosystems, rather than marine or coastal environments. As with other chapters in this book, it has not been possible to cover the full range of studies that have used diatom analysis; rather the intention has been to outline selected highlights in diatom research (including both qualitative and quantitative approaches), and recent developments that take account of the importance of site selection, sampling resolution, application of numerical methods and taphonomical processes, such as dissolution.

Implicit in each of the case studies is knowledge of the autecology of individual diatom species. Both direct and indirect climate reconstructions have furthered our understanding between diatoms and their environment, although the results are often contentious, and while quantitative studies are increasingly being improved, interpretations from more qualitative work should not be ignored. Many challenges to the discipline remain, which include increasing our understanding of the ecological requirements of diatom species (from *in vivo* and culturing studies) and diatom life-cycle strategies, while databases should be used more widely to explore the relationships between diatom biogeography with climate, habitat and environmental chemistry, thereby generating new hypotheses for future study.