For QSR, special issue on “Natural Hazards, Extreme Events, and Mountain Topography” by John Clague and Oliver Korup. 24 March 2008.

The tectonic influence on the last 1500-year infill history of a deep lake located on the North Anatolian Fault: Lake Sapanca (N-W Turkey)

Suzanne A. G. Leroy*[1], Markus J. Schwab[2] and Pedro J. M. Costa[3], Department of Geography and Earth Sciences, Brunel University, Uxbridge UB8 3PH (West London), UK

* Corresponding author: tel: +44-1895-266087; fax: +44-1895-269761; suzanne.leroy@brunel.ac.uk
1 present address: Institute for the Environment, Brunel University, Uxbridge UB8 3PH (West London), UK
2 present address: Leibniz Centre for Earth Surface and Climate Studies at the Potsdam University via GeoForschungsZentrum Potsdam, Section 3.3, Telegrafenberg, D-14473 Potsdam, Germany
3 present address: Departamento de Geologia, Universidade de Lisboa, Campo Grande, Edifício C6, Sala 6.3.60, 1749-016 Lisboa, Portugal

Abstract

Lake Sapanca on the North Anatolian Fault zone (NW Turkey) is a pull-apart basin at the junction between the İzmit-Sapanca fault segment, the Sakarya segment and the westernmost end of the Mudurnu Valley fault. Multiproxy analyses of a 586-cm-long sediment core taken in the lake centre have revealed a complex history of earthquake events. The radiocarbon chronology, affected by reworking of plant remains, suggests that the sediment sequence retrieved from the centre of the lake covers approximately the last 1500 years. The bottom metre of the sequence is a gley soil indicating that at least the eastern half of the lake was a wetland, a prolongation of the floodplain between the lake and River Sakarya, that has collapsed to form the modern deep lake. A series of sedimentological and palynological indicators have been used to highlight four major episodes of mass movements linked to earthquakes. The short existence of the eastern part of the lake highlights the complexity of the morphology of the Sakarya Straight, a possible past connection between the Gulf of İzmit and the Black Sea.

Key words

Sapanca Lake, earthquake, North Anatolian Fault Zone, palaeogeography

1 Introduction

Lake Sapanca (NW Turkey) is a key area in many aspects of earth sciences. It is located on a possible palaeo-connection (an isthmus or a bosphorus) between the Black Sea and the Marmara Sea, bypassing the Straight of İstanbul (Ryan and Pitman, 1998) (fig. 1). It is also located on a strand of the North Anatolian Fault Zone (NAFZ), Turkey, which is very active. The last two major earthquakes in 1999 in İzmit and Düzce were very destructive. The sediment of this lake is a potential archive for the local history of the Sakarya and İzmit-Sapanca fault segments, and the western end of the Mudurnu Valley rupture of the NAFZ (Neugebauer et al., 1997; Lettis et al., 2002) (fig. 2). Previous work on short Kajak cores (up to 45 cm) taken in the same lake has demonstrated that using a multiproxy approach it was possible to retrieve a detailed earthquake history over the last 55 years (Leroy et al., submitted; Schwab et al., submitted). In addition Lake Sapanca is also located on the main route between Africa and Europe for the human expansion out of Africa (Ben-Avraham et al., 2005). It is therefore an area of ancient human impact on the environment and vice versa. The vegetation history of the Late Glacial to the Holocene in the region is mostly known from marine cores (Çaner and Algan, 2002; Mudie et al., 2007). So far lacustrine records are too short (Bottema et al., 2001; Leroy et al., 2002) and palaeoenvironmental studies would benefit from a higher resolution record in a lake. With a long Reasoner corer (6 m) in Lake Sapanca and with a multiproxy approach - lithology, magnetic susceptibility, Loss-on-Ignition, geochemistry and palynology including non-pollen palynomorphs - knowledge in the palaeogeography, palaeoseismology and palaeoenvironmental reconstruction of the region could be considerably enhanced.

fig. 1 and 2

2 Setting and previous studies

2.1 Palaeogeography of the region

Pfannenstiel (1944) suggests that the valley between the Black Sea and the Gulf of İzmit (the Sakarya Straight) has been a sea arm during the diluvial times (i. e. the last melting of the Eurasian ice cap) (fig. 1 and 2). Some geomorphological factors and the unusual fauna of the lake with a strong Pontic component are taken as proof of this ancient passage. More precisely, Ryan and Pitman (1998, pp. 158 and 230) have suggested that, before the Younger Dryas, the huge volumes of meltwater concentrated in the Black Sea (then a lake) flowed through the Sakarya Straight. This contact would have been progressively severed by tectonic movements around the transition from Late Pleistocene to Holocene and replaced by the İstanbul Straight when a two-way contact between the Black Sea and the Mediterranean would have been established. Despite this exciting background and hypothesis, no one has so far cored the sediment of Lake Sapanca. Some drill-holes have been made in the Adapazarı plain and reveal a great thickness of Holocene sediment but their results were not conclusive for the palaeo-connection (Emre et al., 1998). Boreholes made in the Gulf of İzmit reveal the persistence of Mediterranean fauna over the last 10,000 yr BP, significantly longer than for the İstanbul Bosphorus (Kerey et al., 2004) (fig. 1 and 2).

2.2 Climate and modern vegetation

Annual precipitation of 830 mm and an annual mean temperature of 13°C over the last 30 years were recorded in Adapazarı (data from Devlet Meteoroloji İşleri Genel Müdürlüğü, i. e. the General Directorate of State Meteorological Works). The mountain ranges to the south of Lake Sapanca are up to 1600 m high and receive a much higher precipitation (even including snow in the winter) than the remaining catchment area.

The vegetation in the overall region of Lake Sapanca is part of the Euxinian domain (Quézel and Barbéro, 1985). The lake is directly surrounded by agricultural zones and villages. A map of the potential local terrestrial vegetation can be found in Ceylan (1990) and a species list in Yılmaz (2000). Some open spaces are occupied by macchia. The northern hills belong to a formation with various species of *Quercus* and are generally drier and more open than the southern slopes. On the southern slope, the *Quercus* sp formation is followed upwards by several altitudinal zones: *Carpinus betulus - Castanea sativa -Quercus* sp., *Castanea sativa - Carpinus betulus*, a *Fagus orientalis* forest (with *Rhododendron ponticus)*, and finally *Fagus orientalis* with *Pinus* sp. On the mountaintops, *Abies bornmülleriana* and *nordmaniana* are present.

Aquatic plants grow on the lake shelf, mostly on the narrow strip in the south, as well as in the shallow western tip of the lake and near the wetland at the east of the lake. On the northern coast, the slope is too steep leaving too narrow a shelf for any significant macrophytic development.

2.3 Lake origin and lake morphology

Lake Sapanca is at 40° 43' N, 30° 15' E and at an altitude of 31 m asl (Turkey; fig. 1 and 2). The lake has a depth of 55 m in its centre, bringing the present sediment-water interface well below sea level. Lake Sapanca's origin is the result of a pull-apart basin created by a step-over in fault rupture (Barka et al., 2000; Lettis et al., 2000; Rathje et al., 2004). The Sapanca basin forms the intersection between the Kocaeli/İzmit fault rupture (M_w 7.4 on 17 Aug. 1999) and the southern branch of the NAFZ that most recently ruptured during the Mudurnu Valley earthquake (M_w 7.0 on 22 July 1967) (Ambraseys and Zatopek, 1969; Lettis et al., 2002; Müller et al., 2003) (fig. 2).

Although the NAFZ is mostly behaving as a right-lateral strike-slip fault, south of Adapazarı there is also a normal component (Emre et al., 1998). On the Sakarya segment, east of the lake, after the 1999 earthquake, there was a significant right lateral displacement of 2-5 m and a minor vertical displacement of 0.25-0.5 m. Normal fault displacements were also documented for the 1967 Mudurnu Valley earthquake (Rathje et al., 2004). Neugebauer et al. (1997) studying the micro-earthquake activity were able to highlight faults that are hardly or not visible in the field. The model indicates normal faulting near Sapanca. A few rupture traces with a NW-SE strike were observed after the Mudurnu Valley 1967 earthquake. The Sakarya plain is a pull-apart basin that developed as half graben and becomes younger towards the NE (Emre et al., 1998). The bathymetry of the lake shows that the basin is bordered on the north by the İzmit-Sapanca fault segment and on the south by diffuse normal faulting (Lettis et al., 2002).

The mountains of Samanlı border the south shore of the lake. These are still undergoing an upward movement (Neugebauer, 1995). This mountain range consists of Triassic and Lower to Middle Jurassic schist, marble and metabasite. To the northeast and to the northwest of the lake are two small areas of Upper Lutetian and Upper Eocene andesitic and basaltic rock units. The rest of the sediments and rocks surrounding Lake Sapanca are sandstones, limestones and gravel outwash (Ternek, 1964).

Lake Sapanca is a warm monomictic, holomictic freshwater lake with water mixing in February-March (Morkoç et al., 1998). It receives the water of fifteen rivers (many of them ephemeral), with the largest inflow from the south. Some groundwater inflow has also been noted (Ertürk, 1994; Gürbüz and Gürer, 2007). Lake Sapanca discharges its water into the Sakarya River through a watercourse, the River Çark (on the NE shore). The link with the River Sakarya is somewhat confused. Although the outflow of the lake is towards the river via the Çark River, during high waters the Sakarya River provides water and sediment to the lake via the marshy floodplain that separates it from the lake (Russel, 1954; Doğan, 2004) (fig. 2). Most of the perennial rivers flowing to Lake Sapanca originate in the steep catchment directly surrounding the basin. Their incised valleys reach close to the lakeshore. The margins of much of the lake consist of coalescing alluvial fans and terraces, Holocene beach deposits and prograding delta fans at the mouth of the rivers (Rathje et al., 2004). The severe subsidence observed along the margins of Lake Sapanca during the Kocaeli earthquake was mainly concentrated at the nose of the delta fans. The most significant failure occurred along the south coast at Hotel Sapanca (Çetin et al., 2002) and a smaller failure along the north coast within the town of Eşme (Rathje et al., 2004).

2.4 Past palaeoseismological reconstructions from Lake Sapanca sediment

A Kajak gravity corer (diameter of 6 cm) was used to retrieve up to 45 cm-long sediment cores during a coring campaign in summer 2003. A total of 14 cores were taken along two transects to identify events that affected the whole lake: across the fault and in the deep and central lake basin (south of the fault). The results of the sedimentological and geochemical studies have been published in Schwab et al. (submitted). They are briefly summarised here. Five cores were dated by E. McGee (UCD, Dublin) using ^{137}Cs and ^{210}Pb radionuclides. All the cores show a similar chronology (Leroy et al., in prep.). The exponential ^{210}Pb decay curve is interrupted by periods of low values. This corresponds well to sedimentary events that disrupted a relatively uniform sedimentary record. Geochemical analyses showed higher values for elements which characterize a clastic sediment origin in these event layers. Sediment thin-sections showed turbidites and reworked sediment, while palynological studies showed a drop of the concentration and an input of reworked palynomorphs and fungal spores from soils (Leroy et al., submitted). All these proxies indicate that during a mass movement event there is a considerable input of soil facilitated by the steep river slopes of the south catchment. The chronology indicated a sequence covering the last 55 years. It was therefore possible to link the events to well-known earthquakes.

The present sampling strategy does not allow seeing small thickness events such as those detected in the short Kajak cores. These cores were studied at extremely high resolution, often down to 0.25 to 0.1 cm (Leroy et al., submitted; Schwab et al., submitted).

2.5 Pollen transport, preservation and concentration

For lake sediment, the main pollen and spores sources are usually divided into air (pollen rain), water and redeposition, in sequence of decreasing importance (Pennington, 1979; Birks and Birks, 1980). Pollen assemblages from river sediment and high-energy environments are different from the assemblages of lakes (Birks and Birks, 1980; Leroy, 1992), often with more spores (fern spores are more transported by water), more bisaccate pollen (e. g. *Pinus*) and more heavy grains such as the tetrads of Ericaceae. The origins of pollen in rivers are direct fall from plants growing along the rivers, bank erosion (important during floods) and surface run-off (the main source). A higher ratio of spores to pollen was found in a detailed study of Lake Malawi surface samples in front of major river deltas and where smaller rivers enter the lake (deBusk, 1997).

In a lake of S. France, Andrieu et al. (1997) find higher *Pinus* percentages and lower concentrations in slumped sediment.

Pollen is usually not well preserved in soils (unless pH <5.5) (Pennington, 1979; Birks and Birks, 1980; Wilmshurst and McGlone, 2005a) where it is chemically corroded. Pollen and spores with resistant exines are nevertheless sometimes preferentially preserved, and during periods of soil erosion they can become incorporated into lake sediments (Wilmshurst and McGlone, 2005b). The soils around Lake Sapanca have a pH between 6.5 and 7.5 (M. Kibar, pers. comm., Dec. 2005); so pollen is unlikely to be preserved there.

2.6 Palynology of regional modern samples and of a short core

Ultra high-resolution palynological investigations were led on a core taken in Lake Sapanca, i. e. core SA03K7.1 (Leroy et al., submitted). Moreover, a survey of the modern sources and traps of palynomorphs (such as river deltas, mosses and lake core tops) indicated that the soils around the lake and the river delta sediment are very poor in pollen and proportionally richer than the lake sediment in spores and pollen grains with an exine resistant to transport and oxidation. In the short core, two types of events were found, both with very low pollen concentrations. One is by inwash of soil from areas away from river influence (over-representation of Liguliflorae), and the other one is by inwash of soil and sediment from the river deltas (over-representation of spores and altitudinal elements).

3 Material and methods

3.1 Core sampling

Using a 9-cm-diameter Reasoner corer (Reasoner, 1993), five cores (240-586 cm long) have been taken in Lake Sapanca. The work has focused on the central one, nominally SA03R6, the longest (R6 for short) taken at 51 m depth and 40° 43’ 05.2 N and 030° 15’ 30.4 E. The sampling resolution of most proxies is aimed to provide a general idea of the quality of the record and of the main changes (tectonic or not) over this 586 cm long record.

3.2 Lithological description, Loss-on-Ignition, geochemistry and magnetic susceptibility

The sediment of the successive core sections was described on open half cores (lithology including colour, structures, grain-size, X-ray and digital photography). Loss-on-Ignition (LOI) data (88 samples) were obtained by the combustion of 10 g of wet sediment samples in a furnace at 550 °C and 925 °C. The percentages of organic matter and carbonates are calculated on the dry weight. The water content was measured after drying the sediment at 105 °C.

The sub-sampling for geochemistry (2.5 g of wet sediment) was aimed at obtaining samples from various lithologies, which were noted carefully. Three major elements were measured on 32 samples by atomic absorption spectrometry analysis.

For the magnetic susceptibility analysis, two different methods were used. At first, magnetic susceptibility was measured in the laboratory on 90 discrete samples (10 g) with a Bartington susceptibility metre *MS2* and a *MS2*B sensor. Later, as the opportunity arose to get a more detailed intensity signal, magnetic susceptibility was measured at a higher resolution every mm with a Bartington *MS2*B sensor system with the automatic split-core logging method (Nowaczyk, 2001).

3.3 Palynological treatment, diagrams and statistical analyses

The sampling resolution is of a sample every 7 cm below 448 cm and of a sample every 25 cm above that depth. The palynological extraction (38 samples) took place at Brunel University. The treatment consisted of a succession of $Na_4P_2O_7$, HCl, HF, HCl, 125 µm and 10 µm sieving, with no acetolysis. The concentration (in number of microfossils per ml of wet sediment) is calculated with the initial addition of *Lycopodium* tablets. Slides were made by mounting some of the residue in a glycerol medium. The palynomorphs were counted with a light microscope at a magnification of 400x routinely and at 1000x for special identification. The pollen preservation is variable, with often > 10 % of indeterminable grains. In addition to the pollen and spores, a range of non-pollen palynomorphs has been recorded. The dinoflagellate cysts were identified with the help of the taxonomy provided by Marret et al. (2004) paper on the Caspian Sea.

The diagrams were plotted using the software psimpoll4.10 (Bennett, 2007).

All the pollen grains and the spores (terrestrial and aquatic) were included in the concentration. In the percentage diagram, all terrestrial pollen grains add up to 100% (the ‘sum’ curve in the diagram - usually around 300). The aquatic plants and other microfossil remains were calculated as a percentage of the 100% terrestrial pollen, i.e. they were not included in the 100%. The statistical analysis was done using psimpoll4.10 (Bennett, 2007). The zonation (using CONISS after logarithmic transformation) is made on all taxa except ‘indeterminate grains’, as the aim was to highlight the taphonomical signal rather than the palaeoenvironmental one.

3.4 Core chronology

A considerable effort was put into finding adequate material for radiocarbon dating. The sediment of the core was sieved in contiguous 5-cm-thick samples through a 500-µm mesh. No seeds from terrestrial plants have been found. The second best material for dating is small and mostly unidentifiable plant remains, which are often sufficiently abundant in the core to provide a sequence of dated points. The samples were then sent to the Poznan Radiocarbon Laboratory (Poland) for AMS ^{14}C dating (table 1). Calibration was done using the OxCal4.0 software with the IntCal04 curve (Bronk Ramsey, 1995 and 2001).

table 1

4 Results

fig. 3 and 4

4.1 Lithology, LOI, geochemistry and magnetic susceptibility

The sediment is overall a grey to grey-brown silty clay with some rare sandy layers (fig. 3). The main lithozones are the following.

Lithozone I, from the base at 586 cm to 448 cm depth

From the base to 557.5 cm, the sediment is a chaotic deposit of wood and branches in a clay to silty clay matrix of very light grey colour. A large 6x6 cm piece of poplar wood (*Populus* sp., identification by E. Asouti, UCL, pers. comm., 2004) is located at the bottom. From 557.5 to 448 cm, the sediment is overall rather massive and very-light-grey coloured, with a mottled, silty-clayish section at 557.5 to 532.5 cm, characterized by fining upward sequences of silty-sandy layers (up to some centimetre thickness), and a darker clayish, slightly laminated section at 507.5-483 cm. This lithozone ends abruptly at a distinct contact to the following zone.

Lithozone II, 448-342.5 cm depth

Lithozone II begins with a 4 cm thick, distinctly fining upward sequence (sand to silty clay). The overlying sediment is made of a relative uniform grey to yellowish grey silty clay, often characterized by mottled structures (a deformed, faint and thin lamination). There is a sharp boundary with the following unit.

Lithozone III, from 342.5 cm depth to the top

The overall mottled, partly slightly laminated, silty clayish sediment (most distinct slight lamination between 42-0 cm) is interrupted by very dark grey, mainly massive, and silty-clayish to sandy clayish layers. The clearest massive layers are at 342.5-280, 242-169, 99-87 and 71-42 cm depth. A detailed sedimentological investigation using thin sections would most likely reveal a series of smaller events, as the investigation for the short cores did (Schwab et al., submitted).

LOI (fig. 4) reveals that the sediment contains an average of 7.5 % carbonates and 5 % of organic matter. The water content fluctuates between 30 and 60 %. These percentages remain largely stable throughout the core with the exception of the base where the large piece of wood is. In the upper part (lithozones II-III), there are however significant declines in the curves of these three parameters. This is largely influenced by the lithology and grain-size composition. For example the lowering of water content correlates positively with a more silty-sandy lithology in the massive horizons of lithozone III (e. g. 240-170 and 100-40 cm), and with a lower content of organic matter and carbonate. The more fine-grained clayish silty, partly laminated or mottled sequences are characterized by positively correlated higher contents of water, organic matter and carbonate. Relative high water contents, a uniform organic matter value, and the highest carbonate contents characterize lithozone II.

The results of the geochemical analysis (fig. 4) show higher values of Ca, Mg and K below 448 cm depth (lithozone I). This is positively correlated to the grain-size and indicates a higher clastic content deposited under a more energetic regime. Above that (lithozones II and III), Ca, Mg and K correlate slightly negatively to the organic carbon content in the more fine-grained and silty to clayish sediments. Ca is positive correlated to the carbonate values.
The magnetic susceptibility values measured on discrete samples and with the logging method reflect the main lithozones. For the discrete sample method the following values were obtained. In lithozone I, progressively up to high values (30-50 SI) from the base to 448 cm, lithozone II intermediate values between 17 and 27 SI and lithozone III low values from 342.5 cm to the surface (15-20 SI) (fig. 5). The high-resolution magnetic susceptibility data show the same signature but the values vary between 12 10^{-6} SI (at 583.5 cm) and 745 10^{-6} SI (at 414.9 cm) (fig. 5). Overall, magnetic susceptibility changes significantly (i.e. changes > 10 10^{-6} SI) and allows the identification of some sharp contacts, distinct layers and transitions. Between the base and 557.5 cm, the values are very low. Between 557.5 and 448 cm, values are high, usually above 400 10^{-6} SI. From 448 to 342.5 cm, values decrease progressively between 400 and 250 10^{-6} SI; then from 342.5 cm to the top, values are low and usually below 250 10^{-6} SI.

fig. 5

4.2 Palynological results

A zonation in 21 palynological zones (pz R) best reflects the changes in the diagram and the events observed in the sediment. The main subdivisions fall at 448 and 346 cm depth (fig. 6). Owing to the highly variable spectra of the diagram below 448 cm, only two groups of pollen zones will be kept thereafter for these depths, leading to the use of 9 zones (fig. 6). The pollen concentration (fig. 6 and 7) is variable and ranges from 598 to 98,089 grains per ml. The lowest concentrations occurred below 448 cm.

fig. 6

Non-pollen palynomorph list

A range of taxa usually known from brackish and marine environments has been found: *Spiniferites cruciformis, Brigantedinium* and *Impagidinium caspienense*. Their origin is probably from the time when Lake Sapanca was connected to the Black and the Marmara Seas (Pfannenstiel, 1944). *S. cruciformis* has however also been found in an altitudinal lake in Greece (Kouli et al., 2001). It is interesting to note that the dinocysts are absent above 300 cm depth. In the short core (Leroy et al., submitted), they are present again and have been interpreted as originating either from the complex regional palaeogeographical history or from a reintroduction via fish translocation (Innal and Erkakan, 2006). The presence of these marine or brackish elements in the sediment cores is in agreement with the survival of other marine life forms in the lake: a Ctenophore jellyfish, a *Syngnathus* sea horse and some species of ostracods (Pfannenstiel, 1944; pers. com., M. Albay, İstanbul University).

The fungal spores are very diverse. The large quantities of fungal spores are interpreted as inwash with soil. Amongst the various types, *Glomus* (type 207, van Geel et al., 2003) is the most useful as it forms a symbiotic relationship with plant roots, and is taken as an excellent erosion indicator. *Gloeotrichia* is cyanobacteria that is N-fixing. It is observed with and without its sheath. Biological monitoring indicates its presence in the very shallow (<1 m) vegetated southern shores of the lake only (M. Albay, pers. comm., 2005). It is worth noting the absence of *Radiosperma,* which however is common in the short core (Leroy et al., submitted).

Diagram description

pz R1 (base to 520 cm): High *Quercus*, spores, indeterminable grains and fungal spore values are observed along with a good representation of *Juglans, Olea*, Cyperaceae and Poaceae.

pz R2 (520-448 cm): Very high values of *Pinus*, high values of Liguliflorae, and a good representation of Cerealia, *Sanguisorba minor* and reworked pollen characterise this zone.

pz R3 (448-342.5 cm): Progressively decreasing values of *Pinus* and increasing values of *Alnus* and *Quercus* are observed. The first part of this zone sees a peak of *Carpinus betulus*, paralleled by the concentration curve.

pz R4, R6 and R8 versus pz R5, R7 and R9: The former group of pollen zones have slightly higher percentages of *Abies, Castanea, Rhododendron*, and reworked elements. Clear increases in spores, indeterminable grains, *Gloeotrichia*, fungal spores and *Glomus* percentages occur, as well as a drastic drop in their concentration.

General trends in vegetation history

Overall, there is a good forest cover (*Quercus* and *Carpinus betulus*), with also a higher vegetation belt (*Fagus*), and a local riparian belt of *Alnus*. The change from very high values of *Pinus* (pz R2) to higher values of *Quercus* at 448 cm (pz R3 and following) will be commented in the taphonomical section as it is most likely does not reflect a true change in vegetation cover.

Indicators of cerealiculture (Poaceae >37µm) are present already from the base of the diagram. From the base to 520 cm depth, some hints of a Beysehir Occupation-like Phase (van Zeist et al., 1975; Leroy et al., 2002) can perhaps be seen by the presence of *Olea* and *Juglans*.

fig. 7

Disturbance indicators

Besides the general drop in concentration from > 45,000 to < 10,000 grains per ml (fig. 6 and 7), the indicators are two groups of taxa, as in the short core (Leroy et al., submitted). From the soil outside river influence, the lake sediment receives the following palynomorphs: *Pinus*, Liguliflorae and to a small extent fern and fungal spores (including *Glomus*). The soil transported by rivers to the deltas bring fungal spores and *Glomus* from river shore erosion, pollen grains of altitudinal plants from the southern mountain range and fern spores from the soils/sediment along the river shores.

4.3 The age-depth model and some limitations

The small size of many of the samples caused a relatively large error (fig. 8; table 1).

The calibrated date plot clearly shows an outlier which is the sample coming from the large piece of wood encountered at the base of the core. This is considered as too old on the basis that it was most likely stored in the gley soil for a long time.

If the mean age is used (continuous thick line in fig. 8), many dates are too old. This could explain that amongst the eleven dates, several small reversals are observed (fig. 8; table 1). Moreover, it is recognised that the organic matter dated in the events is probably reworked from soils. If however a line is plotted inside the error bars of the calibrated ages (dashed line on fig. 8), a normal sedimentation, though with noticeable changes in sedimentation rates, can be shown. In both cases, distinctive changes in the sedimentation rate can be recognised with a higher rate – or a reworking – in the massive horizons and with a lower rate in the slightly laminated and mottled sediment.

A trend line on the mean ages of the calibrated dates (not shown on fig. 8) suggests a total sedimentation rate of 0.33 cm per year including the poplar wood and of 0.29 cm per year without the wood. However if the thickness of the events is eliminated from the sequence, the sedimentation rate becomes much lower.

fig. 8

5 Discussion

5.1 Earthquake indicators in core SA03R6 and in core SA03K7

A comparison of the various indicators found in the events of the long core SA03R6 (R6) and the short core SA03K7 (K7) helps to see which mechanisms are in play (for data from K7, see Schwab et al., submitted and Leroy et al., submitted).

Briefly, for lithozone I in core R6, there is no real equivalent in core K7, except briefly in the reworked zone R1, where there are very high magnetic susceptibility values, very high Liguliflorae percentages and low palynological concentration. For both cores, it is inferred that sediment or soil formed outside of river-delta influence (most likely in the wetland between the Sakarya River and Lake Sapanca) was present.

For the upper part of core R6 (lithozone III) and for most of core K7, the same alternation of lithological facies is observed (by visual inspection), i. e. dark and massive for the events, mottled & oxidised for the ‘normal’ lake sediment. The palynological spectra display the same indicators of river-transported soil in the events, such as fern spores, *Glomus* and low concentration. Moreover in core K7 and in core R6, elements typical of a clastic sediment origin (e. g. Mg and K in core R6 and Si, K and Ti in core K7) increase in the event layers. In the same way the event facies of cores K7 and R6 are characterized by decreasing contents of organic matter and water.

In the short core, the main cause for the fast mass movement events has been attributed to earthquakes, because a historical record is available to link the dated events to well-known local earthquakes. However here in core R6, the dating limitation does not allow linking the events to earthquakes. Therefore other causes, although less likely - such as instability of the sediments on the lake basin slopes and mass movement by gravity caused by heavy rains and flooding - cannot be totally excluded. It is therefore assumed that the same seismic process was the dominant source of the energy required to induce a sedimentation event in the longer sequence of core R6.

fig. 9

5.2 The overall sequence evolution

Zone I: a wetland

This lower part of the sequence is mostly formed by a gley-type soil. The existence of a gley is further supported by the presence of a large piece of poplar wood, which is a shore line and wetland type of tree, the high magnetic susceptibility typical of soils and the very low pollen concentration also typical of soils in the region (fig. 9). One explanation is that a large block of the wetland has slipped down and formed a slump at the bottom of the deep lake. Alternatively before the deep lake of today, there was a wetland that sank along a normal fault. Although this can only be completely resolved with seismic profiling and multiple coring, there are some arguments in favour of the second hypothesis (see next lithozone). The wetland could have been a westward prolongation of what is still on the surface to the east of the lake, i. e. a large zone of uncertain drainage between Lake Sapanca and River Sakarya, regularly flooded by the river during heavy rains and earthquakes.

Zone II: sudden inundation followed by a deep lake formation

This is a transitional zone to the deep lake of today. After the proposed sudden collapse of the wetland block, there is stepwise decrease of soil influx marked first by a sharp lithological change and the main palynological change both at 448 cm (collapse of the eastern part of the lake), then by a magnetic susceptibility drop below 500 10^{-6} SI at 414 cm and then by a further drop of the magnetic susceptibility below 250 10^{-6} SI at 342 cm. The artificially high values of *Pinus* caused by the greater resistance of this pollen grain to erosion are progressively replaced by higher values of other trees, especially *Alnus*, a tree bordering the lake. Because of this progressive decreased influence from the east and to a lesser extent because of the relative thickness of zone (> 106 cm), the existence of a shallow lake/wetland in lithozone I is more likely than a block of wetland soil fallen in the lake.

Zone III: a deep lake affected by seismic events

The four main events are clearly marked in many proxies. Owing to the steep catchment in the south of the lake a lot of loose material is usually available. The rivers transport it quite easily to the river deltas which themselves are very unstable. The deltas are affected by coastal subsidence. Additional underwater mechanisms (turbidites and homogenites) bring the sediment to the lake centre.

5.3 Age of the sequence

Other studies on lakes with mass movement deposits have shown that radiocarbon dates are often older in event layers (Monecke et al., 2007). Edwards et al. (2001) go as far as using reversals in age sequences in British and Irish lakes, alongside palynology, to highlight phases of erosion and inwash of soil in lakes.

Because of the large number of big and small mass movement events, a continuous age-depth model cannot be applied, as for example in Bertrand et al.'s

(2008) study in Chile on a lake affected by earthquakes at the foot of an active volcano producing loose ash. In Lake Sapanca, further sedimentological analysis should help in separating rapid sedimentation deposits (e.g. from earthquakes, and landslides) from slow sedimentation deposits. Only then a real sedimentation rate and chronology can be obtained.

In brief, with perhaps some exceptions, most of the dates are too old. Nevertheless it is likely that a large part of the last 1500 years is represented in the sequence. Based on a trend line excluding the large piece of wood at the base of the core and running up to 2003 (coring date), the transition between lithozones I and II is at AD 576 and the transition between lithozones II to II at AD 913. These two ages are perhaps 100 or 200 years too old.

5.4 Relevance to the local seismic history and to the palaeogeography of the Marmara-Black Sea region

The seismic history of Lake Sapanca seems to have been very intense over the last couple of millennia. Owing to dating problems, it is however impossible at this stage to relate the observed events to historical earthquakes, which are well known in the region (Ambraseys and Finkel, 1991). The thickness of the instantaneous deposits depends both on the availability of the loose material in the catchment and on any clustering of earthquake events, and cannot be related directly to earthquake magnitudes.

The presence of over a metre of gley soil indicates that quite a portion of a wetland is present at the bottom of the central part of the lake. It is either the result of a large slump into the lake, most likely from the wetland between River Sakarya and Lake Sapanca or it is a part of the floodplain that has collapsed to form the lake (a pull-apart lake) later. The second hypothesis is preferred, as the gley is thick (at least 106 cm) and followed by a deep lake with progressively less influence from the wetland. The seismological lessons derived from this are the relatively recent age of at least part of Lake Sapanca and the possible impact of seismic activity on the Mudurnu Valley strand at its westernmost tip as it ends just north of Lake Sapanca. This would agree with the hypothesis of Müller et al. (2003) who suggest that the western termination of the 1967 rupture is at Lake Sapanca.

Part or even the whole of Lake Sapanca is most likely to be a lake formed relatively recently as a series of collapsed compartments. It is therefore not necessarily an erosional valley from the last glacial period as discussed by Emre et al. (1998). The absence of terraces along the shores of Lake Sapanca (Emre et al., 1998) may be explained by their submersion after the compartment collapses.

The history of the connection between the İzmit Gulf and the Black Sea could be searched deeper in the location of core SA03R6, as the wetland phase highlighted here is not necessarily the beginning of the lake. There could have been several phases of collapse, and that illustrated here may not be the only one. Cores taken in the western part of the lake (west of the end of the Mudurnu Valley rupture zone) may reveal a different history of wetland collapse.

6 Conclusions

A gley soil has been found in the bottom metre of a 586-cm-long core (SA03R6) taken in the deep part of Lake Sapanca, NW Turkey. It is likely that a part of Lake

Sapanca is a recent basin (c. only 1500 years old), at least the part east of the fault crossing the lake in a NW-SE direction. This collapse would result from normal movement on the Mudurnu Valley rupture.

A range of indicators in the lithology, geochemistry, magnetic susceptibility and palynology of the sediment core have proven to be possible tools to determine seismic events in the Lake Sapanca sedimentary sequence. The mountainous nature of the southern half of the lake catchment enhances the earthquake signal as it provides an abundance of loose material (mostly soil) to be transported into the lake as well as an altitudinal signal in the lacustrine pollen spectra.

The present results do not preclude the existence of sediment of the Sakarya Straight further down below the subsiding Lake Sapanca.

The long sediment sequence of Lake Sapanca presented here contains more displaced sediment than ‘normal’ lacustrine sediment. This should be kept in mind’ when studying lakes in seismic areas for palaeoecological and palaeoclimatic reconstructions.

Acknowledgements

The long cores were collected with the help of the Faculty of Fisheries of the İstanbul University, especially M. Albay, of L. Doner (ITU, now at Plymouth State University), of G. Hargreaves (USGS) and of I. Stewart (Brunel University, now at Plymouth University). The multiproxy analysis of Reasoner cores was done by a group of researchers and students from Brunel University including N. Hill, P. Werner and V. Tomaz. This study was funded by the EU as part of the EC Project RELIEF (EVG1-CT-2002-00069). M. Turner (Brunel University) has kindly revised the English of the manuscript. This is a contribution to the IGCP 490 project, ICSU Dark Nature project and INQUA-TERPRO commission.

References

Ambraseys, N.N., Finkel, C.F., 1991. Long term seismicity of İstanbul and of the Marmara Sea region. Terra Nova 3, 527–539.

Ambraseys, N.N., Zatopek, A., 1969. The Mudurnu Valley, west Anatolia, Turkey, earthquake of 22 July 1967. Bull. Seism. Soc. Amer. 59, 521-589.

Andrieu, V., de Beaulieu J.-L., Ponel, P., Reille M., 1997. Les distorsions de l’enregistrement pollinique de l’histoire de la végétation du dernier cycle climatique: exemples de séquences lacustres du sud de la France. Geobios 21, 191-202.

Barka, A., Akyüz, S., Altunel, E., Sunal, G., Çakır, Z., Dikbaş, A., Yerli, B., Rockwell, T., Dolan, J., Hartleb, R., Dawson, T., Fumal, T., Langridge, R., Stenner, H., Christofferson, S., Tucker, A., Armijo, R., Meyer, B., Chabalier, J. B., Lettis, W., Page, W., Bachhuber, J., 2000. The August 17, 1999 İzmit earthquake, M=7.4, Eastern Marmara region, Turkey: study of surface rupture and slip distribution. In: Barka A, Kozacı, Ö., Akyüz, S., Altunel, E. (Eds.), The 1999 İzmit and Düzce Earthquakes: Preliminary Results. İstanbul Tech. Univ., İstanbul, pp. 15–30.

Ben-Avraham, Z., Lazar, M., Schattner, U., Marco S., 2005. The Dead Sea Fault and its effect on civilization. In: F. Wenzel (ed.), Lecture Notes in Earth Sciences: Perspectives in Modern Seismology. Springer Verlag Heidelberg 105, 145-170.

Bennett, K., 2007. psimpoll and pscomb programs for plotting and analysis. Version psimpoll 4.10. http://www.chrono.qub.ac.uk/psimpoll/psimpoll.html. It has been accessed on 27 Feb. 2008.

Bertrand, S., Charlet, F., Chapron, E., Fagel, N., De Batist, M., 2008. Reconstruction of the Holocene seismotectonic activity of the Southern Andes from seismites recorded in Lago Icalma, Chile, 39°S. Palaeogeography, Palaeoclimatology, Palaeoecology, 259, 2-3, 301-322.

Birks, H.J.B., Birks, H.H., 1980. Quaternary Palaeoecology. Edward Arnold, London.

Bottema, S., Woldring, H., Kayan, I., 2001. The Late Quaternary vegetation history of western Turkey. In: Roodenberg, J.J., Thissen, L.C. (Eds.), The Ilipinar Excavations II. Nederlands Instituut Voor Het Nabije Oosten, Leiden, pp. 327-354.

Bronk Ramsey, C., 1995. Radiocarbon calibration and analysis of stratigraphy: The OxCal program. Radiocarbon 37, 2, 425-430.

Bronk Ramsey, C., 2001. Development of the radiocarbon calibration program OxCal. Radiocarbon 43, 2A, 355-363.

Çaner, H., Algan, O., 2002. Palynology of sapropelic layers from the Marmara Sea. Marine Geology 190, 1-2, 35-46.

Çetin, K. O, Youd, T. L., Seed, R. B., Bray J. D., Sancio, R., Lettis, W., Yılmaz, M.T., Durgunoglu, T., 2002. Liquefaction-Induced Ground Deformations at Hotel Sapanca During Kocaeli (İzmit), Turkey, Earthquake. International Journal of Soil Dynamics and Earthquake Engineering 22, 1083-1092.

Ceylan, M. A., 1990. The hydrological research of Lake Sapanca, (in Turkish), Unpublished MSc thesis. Institute of Social Sciences of İstanbul. pp. 97.

deBusk, G. H., 1997. The distribution of pollen in the surface sediments of lake Malawi, Africa, and the transport of pollen in large lakes. Rev. Palaeobot. and Palyn. 97, 123-153.

Doğan, A., 2004. Sakarya Havzası (Plio-Kuvaterner) Güney Kesimi Holosen İstifinin Sedimanter Özellikleri ve Jeolojik Evrimi (Sedimentary characteristic and geologic evolution of the south segment of Holocene stack of the Sakarya Basin (Pliocene-Quaternary)). University of Ankara, Graduate School of Natural and Applied Science. MSc thesis, pp. 72 (not printed).

Edwards, K.J., Whittington, G., 2001. Lake sediments, erosion and landscape change during the Holocene in Britain and Ireland. Catena 42, 143–173.

Emre, Ö, Erkal, T., Tchepalyga, A., Kazancı, N, Keçer, M., Ünay, E., 1998. Neogene-Quaternary evolution of the eastern Marmara region, northwest Turkey. Mineral Res. Expl. Bull. 120, 119-145,

Ertürk, O., 1994. Geology, minerological and geochemical analysis of Sapanca Lake bottom sediments. PhD Thesis (unpublished). I.U.F.B.E., İstanbul, pp. 113 (in Turkish, with English abstract).

Gürbüz, A., Gürer, Ö. F., 2007. Anthropogenic affects on lake sedimentation process: a case study from lake Sapanca, NW Turkey. Environ Geol. 10.1007/s00254-007-1165-0.

Innal, D., Erkakan, F., 2006. Effects of exotic and translocated fish species in the inland waters of Turkey. Rev. Fish Biol. Fisheries 16, 39-50.

Kerey, I. E., Meriç, E., Tunogfllu, C., Kelling, G., Brenner, R. L., Doğan, A. U., 2004. Black Sea–Marmara Sea Quaternary connections: new data from the Bosphorus, İstanbul, Turkey. Palaeog., Palaeoclim., Palaeoecol. 204, 277-295.

Kouli, K., Brinkhuis, H., Dale, B., 2001. *Spiniferites cruciformis*: a freshwater dinoflagellate cyst? Rev. Paleobot. Palynol. 133, 273-286.

Leroy, S., 1992. Palynological evidence of *Azolla nilotica* Dec. in Recent Holocene of eastern Nile Delta, and its environment. Veget. Hist. Archaeobot. 1, 43-52.

Leroy, S. A. G., Boyraz, S., Gürbüz, A., submitted. High-resolution palynological analysis in Lake Sapanca as a tool to detect earthquakes on the North Anatolian Fault over the last 55 years. Quat. Sc. Rev. 12 Feb. 08.

Leroy, S., Kazancı, N., İleri, Ö., Kibar, M., Emre, Ö., McGee, E., Griffiths, H. I., 2002. Abrupt environmental changes within a late Holocene lacustrine sequence south of the Marmara Sea (Lake Manyas, N-W Turkey): possible links with seismic events. Marine Geology 190/1-2, 531-552.

Lettis, W., Bachhuber, J., Barka, A., Witter, R., Brankman, C., 2000. Surface Fault Rupture and Segmentation during the Kocaeli Earthquake. In: Barka, A., Kozacı, Ö., Akyüz, S., Altunel, E. (Eds.), The 1999 İzmit and Düzce Earthquakes: Preliminary Results. I.T.U., İstanbul, pp. 31-54.

Lettis, W., Bachhuber, J., Witter, R., Brankman, C., Randolph, C.E., Barka, A., Page, W.D., Kaya, A., 2002. Influence of releasing step-overs on surface fault rupture and fault segmentation: examples from the 17 August 1999 İzmit earthquake on the North Anatolian Fault, Turkey. Bulletin of the Seismological Society of America 92, 1, 19-42.

Marret, F., Leroy, S., Chalié, F., Gasse F., 2004. New organic-walled dinoflagellate cysts from recent sediments of central Asian seas. Rev. Palaeobot. Palyn. 129, 1-20.

Monecke, K., Anselmetti, F. A., Becker, A., Schnellmann, M., Sturm, M., Giardini, D., 2007. Earthquake-induced deformation structures in lake deposits: A Late Pleistocene to Holocene paleoseismic record for Central Switzerland. Eclogae geol. Helv. 99, 343–362.

Morkoç, E., Tuğrul, S., Öztürk, M., Tüfekçi, H., Egesel, L., Tüfekçi, V., Okay, O.S., Legović, T., 1998. Trophic characteristics of the Sapanca lake (Turkey). Croat. Chem. Acta 71, 2, 303-322.

Mudie, P.J., Marret, F., Aksu, A.E., Hiscott, R.N., Gillespie, H., 2007. Palynological evidence for climatic change, anthropogenic activity and outflow of Black Sea water during late Pleistocene and Holocene: Centennial- to decadal-scale records from the Black and Marmara Seas. Quaternary International 167, 73-90.

Müller, J. R., Aydin, A., Maerten, F., 2003. Investigating the transition between the 1967 Mudurnu Valley and the 1999 İzmit earthquakes along the North Anatolian fault with static stress changes. Geophys. J. Int. 154, 471-482.

Neugebauer, J., 1995. Structures and kinematics of the North Anatolian Fault zone, Adapazarı-Bolu region, northwest Turkey. Tectonophysics 243, 119-134.

Neugebauer, J., Löffler M., Berckhemer, H., Yatman, A., 1997. Seismic observations at an overstep of the western North Anatolian Fault (Abant–Sapanca region, Turkey). Geol. Rundsch. 86, 93-102.

Nowaczyk, N.R., 2001. Logging of Magnetic Susceptibility. In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments. Vol. 1: Basin Analyses, Coring, and Chronological Techniques. Kluwer Academic Publishers, Dordrecht, pp. 155-170.

Pennington, W., 1979. The origin of pollen in lake sediments: an enclosed lake compared with one receiving inflow streams. The New Phytologist 83, 1, 189-213.

Pfannenstiel, M., 1944. Die diluvialen Entwicklungstadien und die Urgeschichte von Dardanellen, Marmarameer und Bosporus. Geol. Rundsch. 43, 342-434.

Quézel, P., Barbero, M., 1985. Carte de la végétation potentielle de la région Méditerranéenne. Feuille 1: Méditerranée Orientale. Scale 1:2,500,000. Ed. du Centre Nationale de la Recherche Scientifique, Paris, France.

Rathje, E. M., Karatas, I., Wright, S., Bachhuber, J., 2004. Coastal failures during the 1999 Kocaeli earthquake in Turkey. Soil Dynamics and Earthquake Engineering 24, 699-712.

Reasoner, M.A., 1993. Equipment and procedure improvements for a lightweight inexpensive percussion core sampling system. J. Paleolimnol. 8, 273-281.

Russell, R. J., 1954. Alluvial morphology of Anatolian Rivers. Annals of the Association of American Geographers 44, 4, 363-391.

Ryan, W.B., Pitman, W.C., 1998. Noah's Flood: The new scientific discoveries about the event that changed history. New York: Simon & Schuster.

Schwab, M., Werner, P., Dulski, P., McGee, E., Nowaczyk, N., Bertrand, S., Leroy, S. A. G., submitted. Identification of past earthquake signals in the sediment of Lake Sapanca (Northern Anatolian Fault Zone, Turkey). Terra Nostra.

Ternek, Z., 1964. Geologic map of Turkey, İstanbul, and Zonguldak sheets. Institute of Mineral Research and Exploration, Ankara, Turkey, scale 1:500,000.

van Geel, B., Buurman, J., Brinkkemper, O., Schelvis, J., Aptroot, A., van Reenen, G., Hakbijl, T., 2003. Environmental reconstruction of a Roman Period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. J. of Archaeol. Sc. 30, 873-883.

van Zeist, W., Woldring, H., Stapert, D. 1975. Late Quaternary vegetation and climate of southwestern Turkey. Palaeohistoria 17, 53-143.

Wilmshurst, J. M., McGlone, M. S., 2005a. Corroded pollen and spores as indicators of changing lake sediment sources and catchment disturbance. J. Paleolimnol. 34, 503-517.

Wilmshurst, J. M., McGlone, M. S., 2005b. Origin of pollen spores in surface lake sediments: comparison of modern palynomorphs assemblages in moss cushions, surface soils and surface lake sediments. Review of Palaeobotany and Palynology 136, 1-15.

Yılmaz, B., 2000. Sapanca Gölü su havzasının flora ve faunasının araştırılması. (Research on the flora and fauna in the drainage area of Sapanca Lake). MSc Thesis. Institute of Science, Sakarya University pp. 41.

Tables

Table 1: Radiocarbon dates of core SA03R6.

Sample name	Composite depth in cm	Material	Laboratory number	Uncalibrated age	Reported error	Calibrated age in BC/AD, 95.4 % prob	
SA03 R26.2 45-50 14	134.5	plant remains	Poz-10321	310	40	1470	1665
SA03 R26.2 95-100 17	184.5	plant remains	Poz-10322	790	40	1174	1281
SA03 R26.3 25-30 7	214.5	plant remains	Poz-09861	970	60	973	1213
SA03 R26.3 50-55 v1	239.5	plant remains	Poz-09645	900	140	783	1389
SA03 R26.3 70-75	259.5	plant remains	Poz-09656	1380	90	544	934
SA03 R26.4 25-30 16	314.5	plant remains	Poz-10324	1100	40	828	1021
SA03 R26.5 0-5 13	389.5	plant remains	Poz-10326	1040	200	612	1297
SA03 R26.5 50-55 v6	439.5	plant remains	Poz-09647	1410	40	569	671
SA03 R26.6 25-30 9	510.5	plant remains	Poz-09864	1630	30	347	535
SA03 R26.7 5-10 12	540	plant remains	Poz-10327	1460	190	138	970
SA03 R26.7 30-35	565	wood	Poz-08711	2565	35	-808	-551

Captions

Fig. 1: Location of Lake Sapanca in NW Turkey. LS = Lake Sapanca, GI = Gulf of İzmit. Made with the help of www.aquarius.geomar.de.

Fig. 2: Location of core SA03R6 in Lake Sapanca and of the main recent ruptures near Lake Sapanca. LS = Lake Sapanca. Fault location modified after Müller et al. (2003). The grey strip between the Black Sea and the Gulf of İzmit illustrates the location of the Sakarya Straight. Made with the help of www.planiglobe.com.

Fig. 3: Lithology of core SA03R6. The left-hand side column shows the core sections. Visual description supported by X-ray photos.

Fig. 4: Water content, LOI, and geochemistry for core SA03R6. Geochemical data from V. Tomaz. For lithological column legend: see fig. 3.

Fig. 5: Magnetic susceptibility of the SA03R6 core. Top scale for discrete sample logging, and bottom scale for high-resolution split-core logging. For lithological column legend: see fig. 3.

Fig. 6: Percentage palynological diagram of the core SA03R6 in Lake Sapanca. Ten times exaggeration curve. Analyses: S. Leroy. For lithological column legend: see fig. 3.

Fig. 7: Concentration palynological diagram of the core SA03R6 in Lake Sapanca, selected taxa only. X-axis units in number of palynomorphs per ml of wet sediment. Ten times exaggeration curve. Analyses: S. Leroy. For lithological column legend: see fig. 3.

Fig. 8: Dating of core SA03R6: calibrated radiocarbon dates plotted against depth. For lithological column legend: see fig. 3.

Fig. 9: Interpretation of the sequence of core SA03R6. For lithological column legend: see fig. 3.