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Late Quaternary evolution of Mediterranean poljes – the Vatos case study (Akarnania, NW Greece) based on geo-scientific core analyses and IRSL dating

by

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with 10 figures and 1 table

Summary. Sediments of the Vatos polje in the mountains of central Akarnania, NW Greece, were studied to reveal the late-Quaternary palaeoenvironmental landscape evolution and to detect phases of morphodynamic activity and stability. Four vibracores, up to 9 m long, were retrieved from the lower polje grounds and were studied by means of sedimentological, geochemical, micromorphological, mineralogical and geoarchaeological methods. Radiocarbon dating, archaeological age determination of diagnostic ceramic fragments and, for the first time, IRSL dating techniques were used to establish a local geochronological frame for the polje evolution.

Our results show that, between LGM and around 14 ka before present, a permanent freshwater lake existed. By the beginning of the Holocene, the lake was desiccating, probably due to a climatic change towards drier conditions. In the Neolithic epoch, morphodynamic activity strongly increased and led to the deposition of coarse-grained proximal alluvial fan sediments in the area of the former lake. This seems to be related to the strong 7 ka-increase in precipitation in the eastern Mediterranean known from many palaeoclimatological studies. After a subsequent period of ecological stability and prevailing soil formation, torrential systems in the Vatos polje were re-activated at the beginning of the 3rd millennium before present. Within this context, up to 2.5 m-thick alluvial deposits were accumulated until Roman times. Geoarchaeological findings of ceramic and wood fragments and charcoal indicate that human activities were responsible for this severe change of environmental conditions. Another increase in fluvial dynamics occurred in late Roman to Byzantine times when clearing of forests on the slopes of the surrounding Akarnanian mountains caused the temporary shift of proximal alluvial fan zones to the lower grounds of the polje. It is only since antiquity that the Vatos polje is characterized by a periodical freshwater lake during winter seasons.

The results are discussed against the background of similar studies on late Quaternary polje evolution in the wider Mediterranean area. In this context, our IRSL dating approach allows more detailed geochronological conclusions on the polje history than previous studies based on radiocarbon dating alone. This paper shows that, due to the high quality of the morphodynamic, sedimentological and palaeoenvironmental data recovered, poljes represent highly valuable, so far often neglected geo-archives for the reconstruction of the landscape evolution in the Mediterranean.

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Zusammenfassung. *Spätquartäre Poljen-Entwicklung im Mittelmeerraum – das Fallbeispiel des Vatos-Poljes (Akarnanien, Nordwestgriechenland) auf der Grundlage geowissenschaftlicher Sedimentkernanalysen und IRSL-Datierungen.* – In Zentral-Akarnanien, Nordwestgriechenland, wurden Sedimente des Vatos-Poljes zur Erfassung der spätquartären Landschaftsentwicklung und von geomorphodynamischen Aktivitäts- und Stabilitäts-Phasen untersucht. In den am tiefsten gelegenen Bereichen des Poljes wurden vier Schlaghammerbohrungen bis maximal 9 m Länge durchgeführt. Die erbohrten Sedimente wurden mit Hilfe sedimentologischer, geochemischer, mikromorphologischer, mineralogischer und geoarchäologischer Methoden analysiert. Zur Erstellung einer lokalen Geochronostratigraphie der Poljenentwicklung wurden Radiokohlenstoffdatierungen und archäologische Altersbestimmungen mittels diagnostischer Keramik sowie erstmals IRSL-Datierungsverfahren herangezogen.

Die Untersuchungsergebnisse zeigen, dass zwischen dem Letztglazialen Maximum (LGM) und ca. 14 ka vor heute ein Süßwassersee im Poljengrund existierte. Zu Beginn des Holozäns trocknete der See wahrscheinlich aufgrund zunehmend trockenerer Klimabedingungen aus. Im Neolithikum fand eine starke Zunahme der geomorphodynamischen Aktivität statt, die zur Ablagerung grobkörniger proximaler Schwemmfächersedimente im Bereich des früheren Sees führte. Die Ergebnisse legen nahe, dass dies mit einem signifikanten Anstieg der Niederschlagsmengen zusammenhängt, der im Rahmen anderer paläoklimatologischer Untersuchungen für die Zeit um 7 ka vor heute für das Mediterrangebiet festgestellt werden konnte. Nach einer sich anschließenden Phase ökologischer Stabilität und vorherrschender Bodenbildung kam es im Vatos-Polje im 3. Jahrtausend vor heute zur Reaktivierung der torrentiellen Abflusssysteme. In diesem Zusammenhang wurden bis in Römische Zeit bis zu 2.5 m mächtige alluviale Sedimente abgelagert. Geoarchäologische Funde von Keramik- und Holzfragmenten und Holzkohle deuten darauf hin, dass menschliche Eingriffe in den Naturhaushalt für die deutliche Veränderung der Umweltbedingungen verantwortlich sind. Eine weitere Steigerung fluvialer Dynamik ist für die spätrömische bis byzantinische Epoche festzustellen, als durch verstärkte Waldrodung an den Hängen des akarnanischen Gebirges eine vorübergehende Verschiebung proximaler Schwemmfächerbereiche in die Niederungen des Poljes stattfand. Erst seit der Antike ist das Vatos-Polje durch einen über die Wintermonate existierenden periodischen Süßwassersee gekennzeichnet.

Die Ergebnisse werden vor dem Hintergrund ähnlicher Untersuchungen zur spätquartären Poljenentwicklung im Mittelmeergebiet diskutiert. Im Vergleich hierzu erlaubt der vorgestellte IRSL-Datierungsansatz detailliertere geochronologische Schlussfolgerungen zur Poljengeschichte, als dies allein mit Radiokohlenstoffdatierungen bislang gelungen ist.

Dieser Aufsatz zeigt, dass Poljen aufgrund der hohen geomorphodynamischen und sedimentologischen Aussagekraft ihrer Sedimente und den daraus erwachsenden Möglichkeiten zur Paläoumweltrekonstruktion äußerst wertvolle und bislang oft vernachlässigte Geoarchive für die Erfassung der Landschaftsgenese und Geomorphodynamik im Mittelmeerraum darstellen.

1 *Introduction*

A polje is defined as an intra-mountainous tectono-karstic depression in a limestone region which is cut off from the superficial drainage network (Pfeffer 1978, 2005, Huggett 2003). It thus represents a sink for sediments brought in by alluvial systems and, in most cases, accumulated in conjunction with periodical or permanent freshwater lakes. Poljes are connected to the karst-hydrological system by sinkholes and ponors (in Greek: katavothres). In the Mediterranean, polje landscapes have played an important role for pasture farming and agriculture since ancient times due to their fertile soils, elsewhere mostly eroded and washed into the sea, and due to the presence of freshwater.

For Quaternary research, poljes represent excellent geological archives by means of which environmental and climatological changes, phases of morphodynamic stability and activity as well as anthropogenic signals may be detected. The history of polje sediment infilling is closely related to the erosional history of the adjacent mountains where, in most cases in the Mediterranean, the soil cover is stripped off. Hence, on the mountain slopes themselves there are no information and archives left which can be used for landscape reconstruction. Using poljes as sedimentary archives is most promising where lacustrine accumulation of sediments has prevailed over a long period of time and where lake deposits thus yield a more or less continuous and long record of palaeoenvironmental proxies (e.g. Jahns & van den Bogaard 1998, Frogley et al. 2001, Pérez et al. 2002, Tzedakis et al. 2003, Balbo et al. 2006).

Akarnania represents a peripheral region in NW Greece which, however, has been continuously populated since at least historic times. Based on the high density of ancient poleis and other archaeological remains (see Berkthold et al. 1996) intense man-environment interaction can be assumed. The present study was carried out as a completion of palaeogeographical investigations in the Palairos, Mytikas and Astakos coastal zones (see fig. 1 and Vött et al. 2006a, 2006b, 2006c, 2007) in the vicinity of the Vatos polje. The polje serves as model area to reveal the history of alluvial transportation and man-made soil erosion in the Akarnanian mountains which also affected the coastal systems. The Vatos polje further offers an ideal setting to reconstruct the intensity, the dimension and the age of periods of high morphodynamic activity.

The main objectives of this paper are (i) to document the late Quaternary palaeoenvironmental evolution of the Vatos polje, (ii) to assess the anthropogenic impact on landscape changes and (iii) to set up a geochronological frame for the evolution of the polje. This study represents the first systematic and core-based geomorphological and geochronological approach to a better understanding of polje sediment infilling in northwestern Greece.

2 *Topography and geological and tectonic settings*

The Vatos polje is situated in the central Akarnanian mountains some 7.5 km south-southeast of Monastiraki and 7.8 km east of Palairos (fig. 1). It has an average elevation of 760–800 m above sea level (m a.s.l.) with a maximum length of 3.2 km (NNW-SSE) and a maximum width of 1.7 km (ENE-WSW) following the general NNW-SSE strike of the surrounding mountain ranges. The intra-mountainous Vatos basin is flanked by the Kokkala (952 m a.s.l.) and Limerakia mountains (1,154 m a.s.l.) to the west and by the Perganti (1,422 m a.s.l.) and the Psili Korifi range (1,589 m a.s.l.) to the east (fig. 2). The polje lies along the most important traffic route between the villages of Mytikas, Palairos and Vonitsa which lost its function only since the 1970s when a modern coastal road was constructed (cf. Heuzey 1860, Leake 1835, Lolling 1876/77, Philippson 1958). The houses of Vatos at the southern fringe of the polje are inhabited by herdsman during the summer season and are connected to Kandila and Mytikas by a steep and winding dirt road.

Concerning local climatic conditions, no data exist from the polje itself or any other neighbouring settlement. However, precipitation is expected to reach about

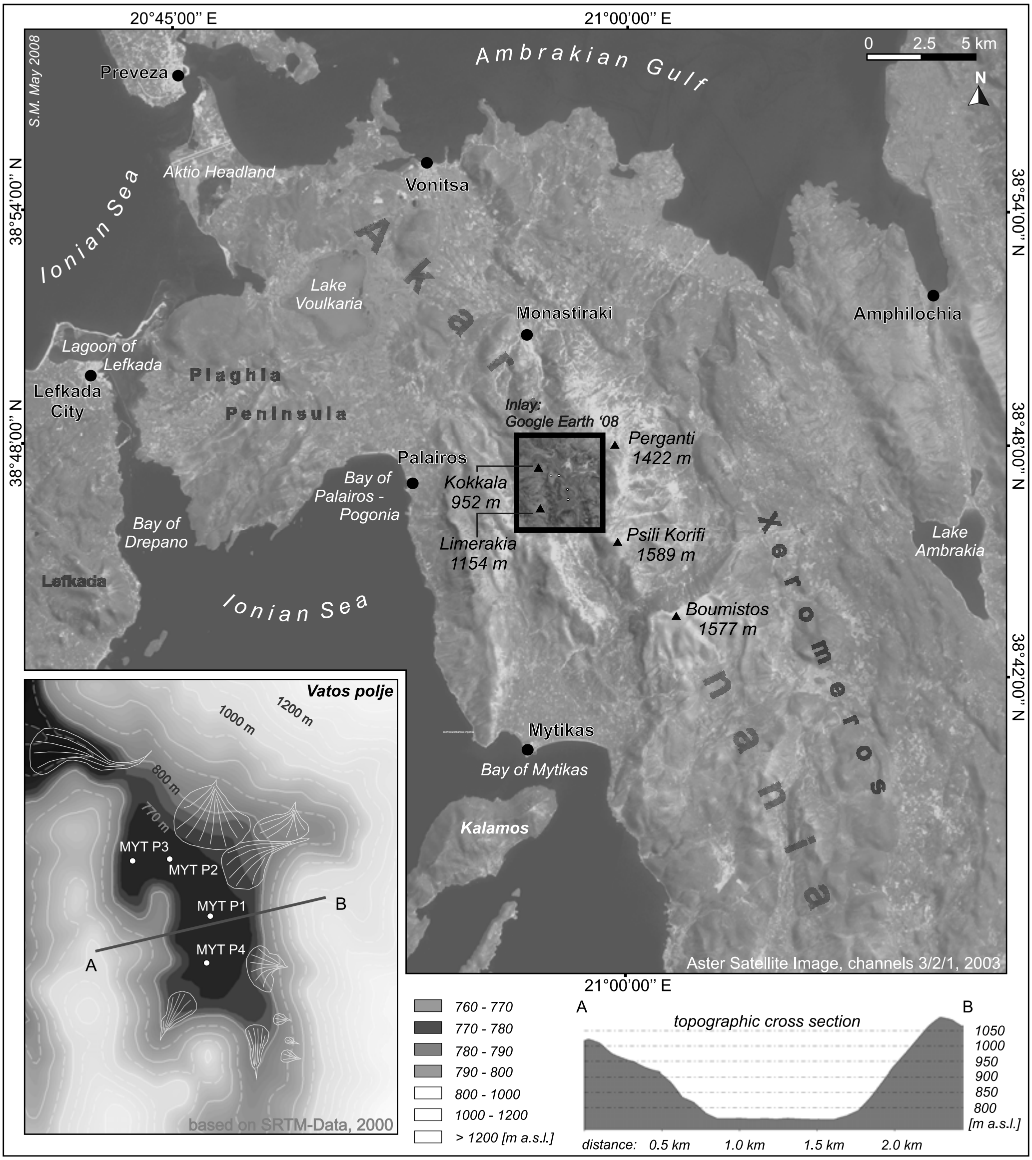


Fig. 1. Location and topographic overview of the Vatos polje in central Akarnania, NW Greece.

1,000–1,400 mm/a on the windward side of the Akarnanian main range around the Psili Korifi (Fotiadi et al. 1999, Haversath 2004, Lienau 1989) mostly related to rain and snowfalls during the winter season (November till March). Snow may cover the grounds in the Vatos polje until March (fig. 3). Several torrential river systems (Greek: remata) enter the polje from the eastern side and bring water as well as sediments into the basin during intense rain events. These remata have created large alluvial fan systems (fig. 2). During the winter season, a (quasily perodical) lake may exist in the lowermost western parts of the polje (fig. 3). During summer, the grounds above average lake level are used for farming and wet areas for pasturing; cattle and sheep are then provided with water by several groundwater wells. The mountains around the polje are covered by maquis which was established as a form of degradational vegetation after the original forests were cleared (cf. Grove & Rackham 2001). Nowadays, subnatural forests are restricted to the surrounding summit areas and mostly consist of deciduous *Quercus* sp. In places higher than 1,000 m a. s. l. and difficult to access, *Abies cephalonica* may occur (Horvat et al. 1974) due the similarity of ecological conditions compared to near Cefalonia Island. However, the Vatos polje maquis is characterized by intense overgrazing as reflected by dwarf forms of *Quercus coccifera* and other species.

From a geological point of view, the Akarnanian mountains are part of the Ionian Zone of the Western Hellenic Nappe of the outer Hellenides. The base of the strati-

Fig. 2. The northern part of the Vatos polje as seen from the western flank of the Perganti mountains (1,422 m a. s. l.). Several alluvial fan systems enter the polje from the east and northeast. Vibracoring sites MYT P2 and MYT P3 are located in the lower polje grounds at elevations around 761–763 m a. s. l. View to the west. Photo taken by A. Vött, 2005.

graphic sequence shows Triassic evaporites, up to 3.5 km thick. During Triassic to Tertiary times, 3 km thick dolomites and limestones were deposited on large carbonate platforms. During the Eocene, 2 km of clastic sediments, mostly clay, silt, and sand, were accumulated in the Western Hellenic Flysch trough (Jacobshagen 1986).

The geo-tectonic evolution of Akarnania is controlled by a multiple plate junction offshore of the Ionian Islands (Sachpazi et al. 2000). As parts of this junction, the right-lateral strike slip Cefalonia and Lefkada transform faults are responsible for the strong seismic activity in the area (Cocard et al. 1999, Louvari et al. 1999). Since the late Miocene, the rapid movement of the Aegean microplate towards the SW induced pull-apart dynamics resulting in the formation of WNW trending graben structures such as the nearby Ambrakian and Corinthian Gulfs and the Aitolo-Akarnanian Basin (Doutsos & Kokkalas 2001, Papazachos & Kiratzi 1996). The Amfilochia fault zone to the east of the Vatos polje separates the Akarnanian block from central Greece and reflects an initial rifting zone with a left-lateral strike slip motion (Clews 1989, Doutsos et al. 1987, Haslinger et al. 1999). It is known from differential GPS monitoring surveys along this zone that Akarnania is moving by 5 mm/a faster towards the SW than the rest of the central Greek mainland (Cocard et al. 1999). Moreover, palaeomagnetic investigations revealed an average 40° clockwise rotation of northwestern Greece during 15–8 Ma and a second phase of 10° clockwise rotation after 4 Ma (van Hinsbergen et al. 2005). Broadley et al. (2004) report on an up to 90° clockwise rotation of the Akarnanian block since Oligo-Miocene times.

The overall structure of the Akarnanian mountains is characterized by Tertiary Flysch basins being overthrusted by Triassic dolomite and limestone units along major faults since Oligo-Miocene times. The fault lines generally run in NNE-SSW to NNW-SSE directions and were activated by lateral compression (British Petroleum Co. Ltd. 1971, Clews 1989, Doutsos et al. 1987, Kontopoulos 1990).

The base of the Vatos polje is made up of upper Liassic to Eocene limestone and chert locally covered by Flysch-like mud-, silt- and sandstones from Eocene to

Fig. 3. Periodical freshwater lake in the northwestern part of the polje around vibracoring site MYT P3 as seen in March 2003. Several sinkholes and a ponor (in Greek: katavothre) are located near the western shore of the lake. Maximum water depth does not exceed 0.5 m. View to the south. Photo taken by A. Vött, 2003.

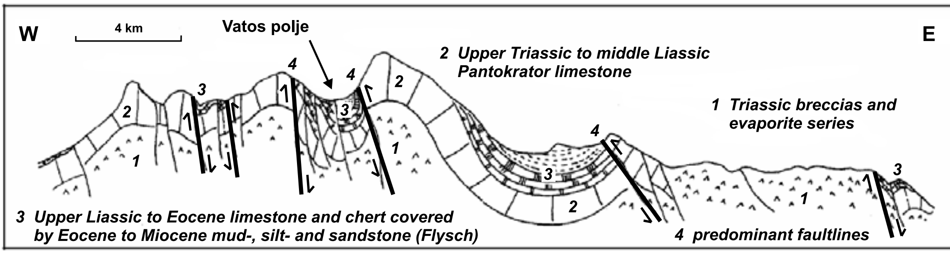


Fig. 4. Simplified and schematic geo-tectonic profile of the central Akarnanian mountains and the Vatos polje. Modified from Bousquet (1976).

Miocene times (IGME 1996). In contrast, its flanks are composed of Triassic to Liassic Pantocrator limestone (fig. 4) well separated from the basin by steep NNW-SSE trending faults. Due to the clastic nature of the underlying (Flysch) units, the Vatos basin was not formed by karstic edge planation but rather represents a tectonic intramountainous basin. However, where the Pantocrator limestone crops out, for instance along the northwestern flank of the polje, it shows typical karst features such as the (temporarily active) Vatos katavothre (see also Huggett 2003, Pfeffer 2005). A group of sinkholes is further situated some 20–50 m in front of the ponor. The Vatos basin is thus interpreted as a tectono-karstic structural polje.

3 *Methods*

Four vibracores were retrieved from the Vatos polje by means of an engine-driven Atlas Copco mk1 coring device. We used a core diameter of 6 cm and corresponding black plastic inliners. Maximum coring depths were between 7 and 9 m below surface (m b. s.). Position and elevation of coring sites were measured by differential GPS (Leica SR 530). In the laboratory, vibracores were first analysed by means of non-destructive computer tomography techniques. Subsequently, the cores were opened and photographed before sampling. Sediment colour was determined by means of the Munsell Soil Colour Charts. Geochemical analyses of sediment samples comprised parameters such as electrical conductivity, pH-value, loss on ignition, carbonate and (ortho-)phosphate contents, and concentrations of selected (earth) alkaline and heavy metals. Multivariate geostatistical analyses within the framework of palaeogeographical studies in nearby coastal zones showed that geochemical parameters of sediment samples are valuable facies indicators and can thus be used for the detection of environmental changes (Vött et al. 2002, 2003). Undisturbed samples were taken for producing thin sections for micromorphological and mineralogical studies. The four vibracores were further searched for material for radiocarbon dating; however, only one charcoal sample could be used for ^{14}C-AMS-dating. In the Marburg Luminescence Laboratory (MLL), sediment samples were retrieved from the cores and underwent separate dating efforts (Section 5). Diagnostic ceramic fragments found in nearby natural trenches were used for archaeological age determination. We refrained from palynological investigations of the Vatos polje deposits as test analyses on similar deposits from the nearby Palairos coastal plain did not result in sufficient pollen material.

4 *Results*

4.1 *Vibracore analyses of stratigraphic sequences*

Four vibracores (MYT P1 to MYT P4) were drilled in the Vatos polje (fig. 1); in this paper, cores MYT P2 and MYT P3 will be presented in detail.

Vibracoring site MYT P2 (ground surface 762.50 m a.s.l.; N 38°47.2349′, E 20°57.8571′) is situated about 1 km to the south of the northern edge of the polje and some 500 m to the east of the ponor. The base of the profile (6.70–6.37 m b.s.) is made up of rust-coloured to light yellowish brown stiff clayey silt including a small quantity of grus and abundant nodules out of iron and manganese hydroxides and oxides (Figs. 5 and 6). This core section is suggested to reflect deeply weathered fine-grained, possibly limnic, sediments overlying Eo- to Miocene Flysch units (IGME 1996). Subsequently follows a thick layer of homogeneous and soft clayey silt (6.37–4.55 m b.s.), light olive brown in the lower and dark grey in the upper part, which seems to have been deposited in a quiescent and shallow lacustrine environment. However, this unit is suddenly covered by dark brown to brown sandy to clayey silt (4.55–2.77 m b.s.) showing five intercalations of grus and gravel up to 3 cm in diameter. The larger clasts are in parts well rounded, in parts of an angular shape. The deposits are further characterized by numerous sesquioxidic and bleaching spots. This stratigraphic unit reflects strong torrential activity and the associated accumulation of proximal deposits by an alluvial fan system. Around MYT P2, this resulted in an abrupt change from limnic to fluvial conditions. Torrential impact is most probably due to a river system entering the polje from its eastern fringe. The whole core section did not contain any ceramic fragments or other artifacts so that the increase in fluvial activity cannot automatically be ascribed to human activities in the area.

The uppermost part of MYT P2 consists of clayey silt (2.77–0 m b.s.), light olive brown to greyish brown, with an intercalating layer of sandy loam (0.79–0.42 m b.s.). The material shows abundant hydromorphic features with prevailing bleaching spots that reflect temporary but long periods of prevailing anoxic conditions. This corresponds to the present distal alluvial fan environment with a periodical lake during winter season (see Section 2).

Vibracoring site MYT P3 (ground surface 761.02 m a.s.l.; N 38°47.3771′, E 20°57.5523′) is located about 100 m to the east of the ponor at the northwestern edge of the Vatos polje. The profile starts with stiff clayey silt (9.00–7.76 m b.s.), olive yellow (light rust-coloured) to whitish grey in colour, including some grus particles up to 0.5 cm in diameter, thin plant roots and spots of manganese and iron hydroxides and oxides (Figs. 5 and 6). Similar to MYT P2, this section is suggested to reflect weathered fine-grained deposits of a quiescent palaeo-waterbody that existed on top of Flysch-bedrock and older Pleistocene units. It is followed by a thick and homogeneous package of soft clayey silt of grey to dark grey colour (7.76–4.00 m b.s.). This core section is completely void of grus and shows root canals partly infilled with sediments which documents quiescent limnic shallow-water conditions over a long period of time. In its upper part, the limnic sequence is brownish-grey and bears pedogenic signs of predominant oxidation. This might be due to a change towards drier climatic conditions and reduced runoff. Subsequently, the limnic deposits are covered by light olive brown clayey silt (4.00–3.55 m b.s.) including abundant grus particles out of chert, especially between 3.80–3.55 m b.s. This documents the onset

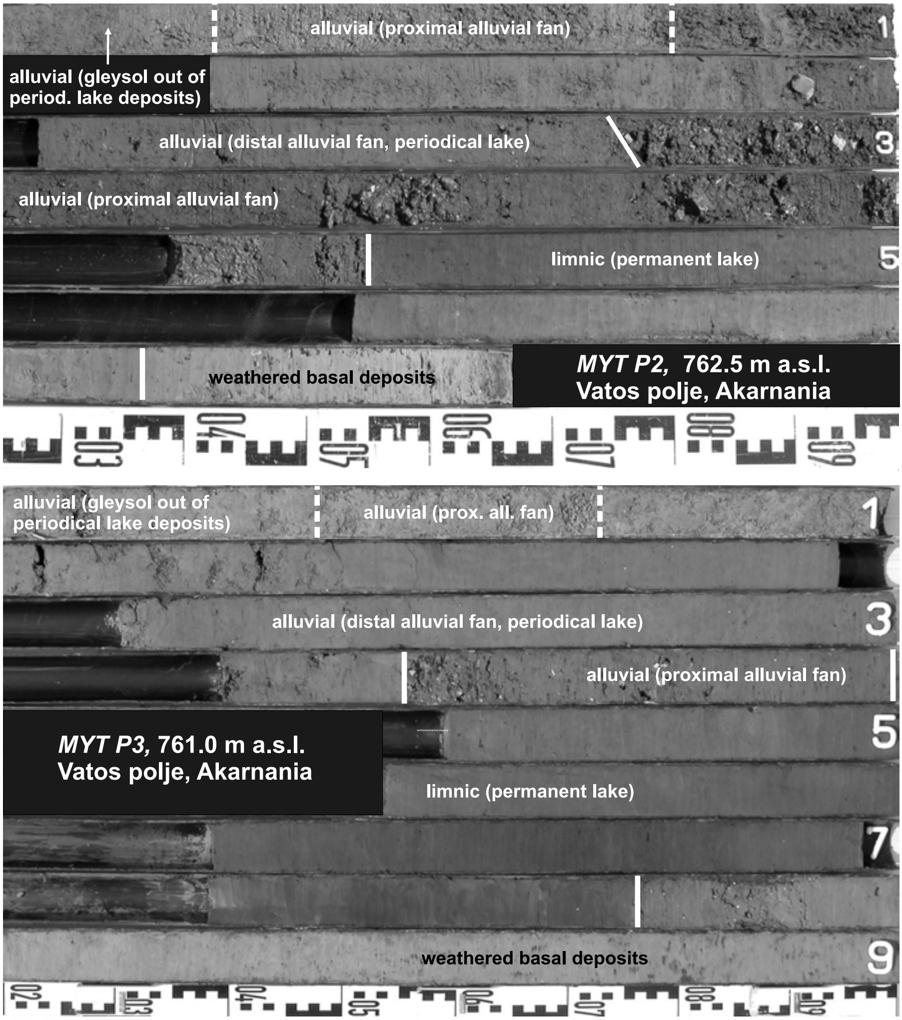


Fig. 5. Sedimentary sequences encountered in vibracores MYT P2 and MYT P3 and simplified facies distribution. Vibracore MYT P3 was drilled in front of the ponor of the polje. The top/up direction of the core segments is to the left; gaps are due to rodding.

of stronger alluvial activity and corresponds to the MYT P2 findings showing that proximal parts of the alluvial fan system were shifted towards the lower western grounds of the polje.

The following core section is made up of clayey to silty greyish-brown sediments (3.55–0.73 m b. s.) and is characterized by numerous hydromorphic features due to repeated changes between aerobic and anoxic conditions; the latter correspond to lacustrine phases during recent winter seasons. The material was thus accumulated in a distal alluvial fan environment with periodically limnic conditions. The upper-

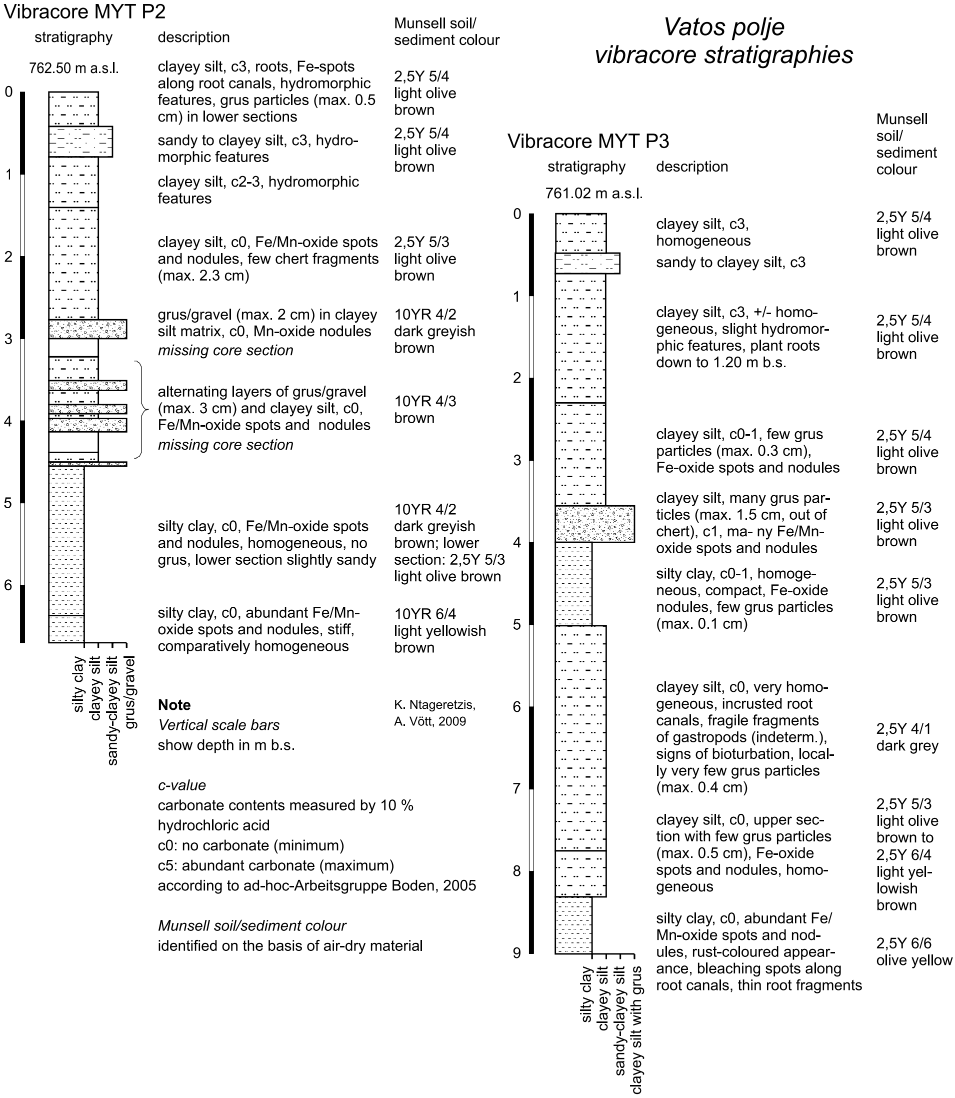


Fig. 6. Stratigraphies and lithologies of vibracores MYT P2 and MYT P3 drilled in the central lower grounds of the Vatos polje. Note: c-values indicate carbonate contents measured by 10% hydrochloric acid, c0: no carbonate – c5: abundant carbonate (according to ad-hoc-Arbeitsgruppe Boden, 2005).

most part of the core shows an intercalated layer of brownish sandy loam (0.73–0.48 m b. s.) which suggests a temporary shift towards intensified fluvial dynamics. Core top sections of both MYT P2 and MYT P3 correspond to gleysols.

4.2 *Geochemical analyses*

Palaeo-lake deposits encountered in cores MYT P2 and MYT P3 can be clearly discriminated from weathered basal units below and alluvial fan deposits above. Fig. 7 depicts selected geochemical parameters analysed from sediment samples.

Palaeo-lake deposits are characterized by low pH-values, that is by high contents of hydronium ions (= de-logarithmized pH-value, fig. 7). This explains the lack of carbonates in the corresponding core sections as well as missing ostracods which otherwise might have been useful facies indicators. Lower hydronium concentrations in the upper parts of the profiles are due to the increased number of carbonate particles in the form of grus or gravel brought into the system by alluvial transport. We further assume that the carbonate content of the palaeo-limnic deposits was originally higher but was reduced by post-sedimentary processes bound to the circulation of aggressive groundwater in and above the strongly weathered basal deposits.

Corresponding to their grey to dark grey colour, palaeo-lake deposits show maximum values of organic matter reaching up to 5–7 % in MYT P2 and 6–10 % in MYT P3 (fig. 7). In contrast, alluvial fan deposits are characterized by contents lower than 4–6 %. The highest value of around 9 % was detected for the uppermost part of core MYT P2 and is due to recent accumulation of plant debris in desiccation cracks.

Concentrations of (ortho-)phosphate are also highest in palaeo-lake deposits which seems to be due to the incomplete decomposition of organic material that was accumulated in the shallow-water lacustrine environment (fig. 7). We found up to 3 g/kg (ortho-)phosphate in MYT P2 and up to 6 g/kg in MYT P3.

Corroborating our sedimentological data, the presented geochemical parameters suggest that the palaeo-lake environment must have had its profundal and thus most stable ecological zone rather around MYT P3 than around MYT P2.

4.3 *Thin section studies*

Thin section analyses revealed micromorphological and mineralogical details of vibracore deposits. Fig. 8 gives a summarized view of selected thin sections from the different environmental facies encountered in cores MYT P2 from the central and MYT P4 (ground surface 763.67 m a. s. l.; N 38°46.6140′, E 20°58.0492′) from the southern part of the Vatos polje.

Alluvial deposits from the upper core section of MYT P2 are characterized by fine-grained clay and silt into which numerous sand grains are embedded (fig. 8a). These grains are of mostly angular shape indicating moderate to short transportation distances. Moreover, the sediment is badly sorted which documents transportation by a torrential river system. The particle in the lower right center, approximately 1 mm long, is a ceramic fragment. Both the sedimentary matrix and larger particles are coated by manganese and iron hydroxides and oxides. Opaque black dots represent abundant charcoal micro-fragments, mostly around 20–50 μm large. On a larger scale, corresponding alluvial fan sediments from core MYT P4 show sub-angular

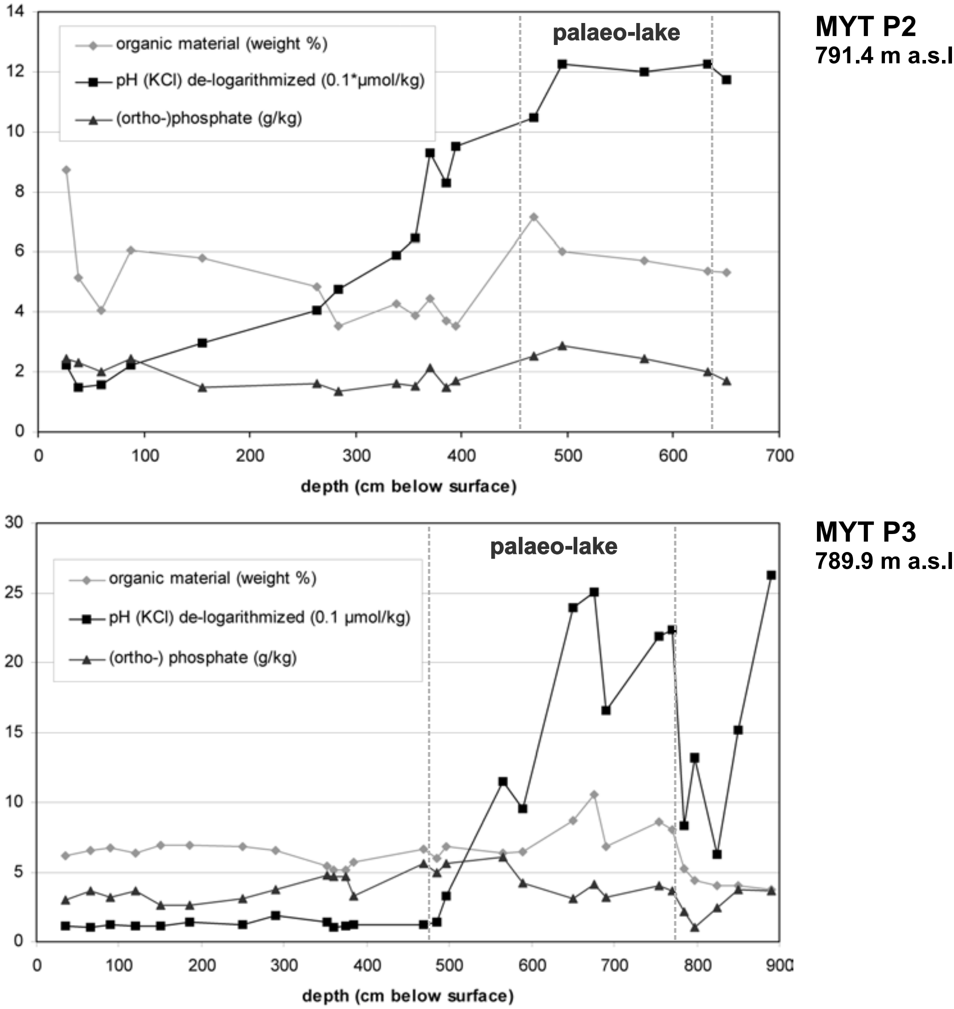


Fig. 7. Selected geochemical parameters of sediments from vibracores MYT P2 and MYT P3 from the central Vatos polje. Palaeo-lake sediments can be clearly distinguished from alluvial fan deposits as well as from the weathered subground material.

limestone fragments up to 200 µm and post-sedimentary sesquioxides (fig. 8b); in this context, a 1 mm-long piece of wood reflects high morphodynamic activity possibly connected to a reduced vegetation cover. Together with the ceramic fragments associated to charcoal findings in fig. 8a this might suggest that soil erosion was triggered by man.

Concerning the coarse-grained intercalations in alluvial fan deposits, the angular shape of the sand grains encountered and the bad degree in sorting document high-energy torrential transportation of the sediment (fig. 8c). Mineral clasts are often associated to ceramic fragments, for instance a 1 mm-large piece in the upper left corner of the photograph. In most cases, sand grains and grus are made out of limestone (fig. 8c). Only in some thin layers of the remote core MYT P4 we found sand grains out of quartz (fig. 8d). This sample also shows evaporite crystals and pores up to 0.5 mm in diameter.

Fine-grained distal alluvial fan deposits are also characterized by a bad degree in sorting and prevailing (sub-)angular particle shapes (fig. 8e). Influx of oxygen via the pore-system during periods of desiccation resulted in the pedogenic formation of hydromorphic features.

In contrast, the clayey to silty matrix of the palaeo-lake deposits encountered in core MYT P2 appear to be comparatively well sorted and fairly homogeneous (fig. 8f). However, in the lower part of the limnic sequence, there are abundant iron and manganese concretions up to 2.5 mm in diameter (fig. 8g) possibly documenting that temporary limnic conditions prevailed before a permanent waterbody could establish.

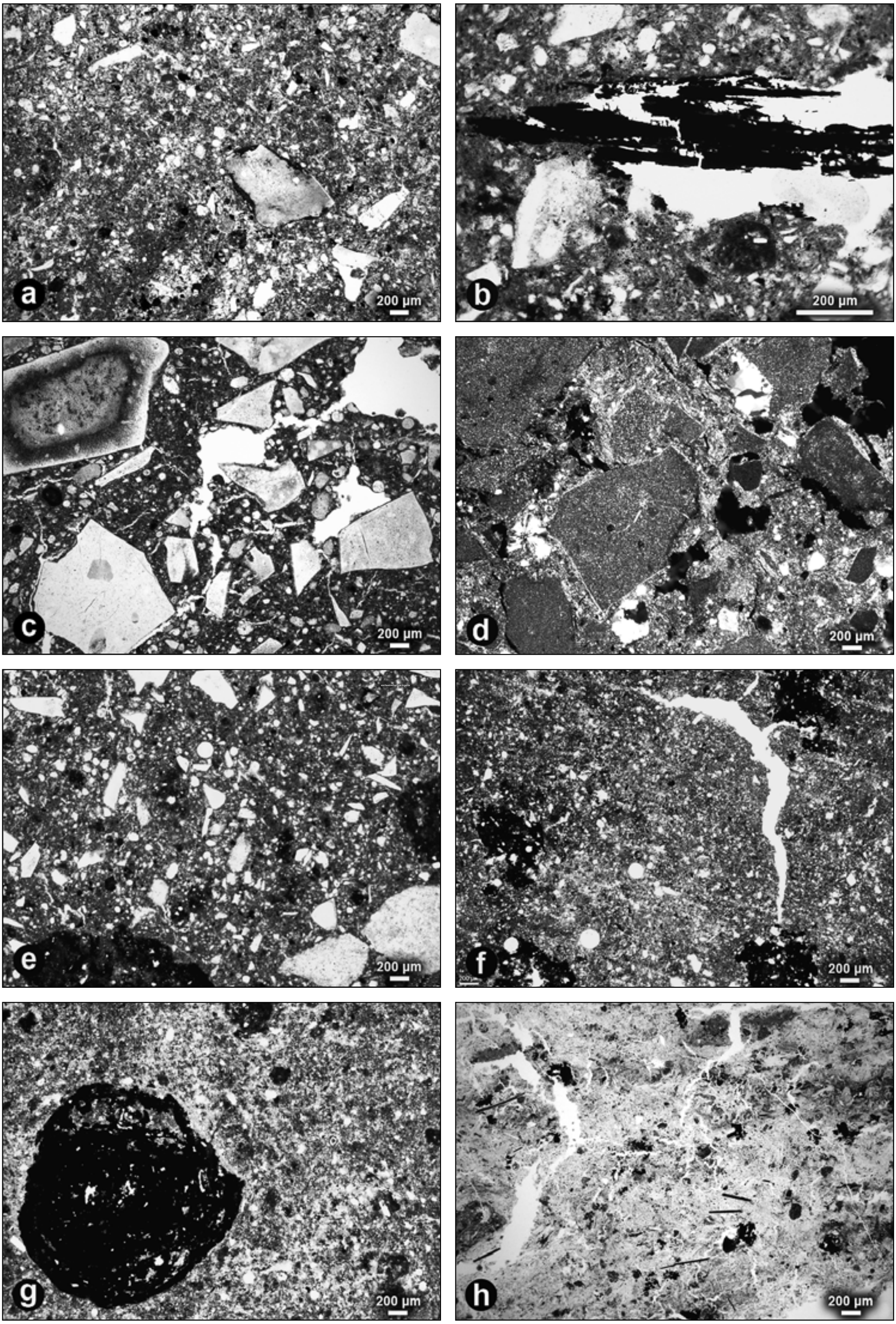
Fine-grained basal deposits encountered in cores MYT P2 and MYT P3 are densely packed and void of carbonate. They include remains of organic material and several intact stem-like muscovite minerals (fig. 8h, lower right center). The latter indicate a low energy environment; otherwise the minerals would have been broken. We also detected few sand grains and grus particles out of quartz. We suggest these deposits to have been accumulated in a quiescent water body under the slight influence of an inflowing (torrential?) river system. High contents of iron and manganese hydroxides and oxides show that the deposits later became subject to intense subaerial weathering and soil formation.

4.4 *Computer tomography*

Computer tomography (CT) analyses were accomplished for selected segments of cores MYT P1 (ground surface 762.20 m a. s. l.; N 38°46.8531′, E 20°58.0866′) and MYT P3 by means of a Siemens Computer Tomograph. Dimensionless density index values were calculated for each segment under study. In general, the CT density index increases with increasing specific density of the analysed material. CT studies were realized in steps of every 2 mm (MYT P1, 1–2 m) to 4 mm (MYT P3, 6–7 m and 8–9 m), each step covering a 3 mm-thick layer of sediment. Fig. 9 brings together CT density values standardized to 250 measurements per core meter.

It can be clearly seen that highest CT density index values around 2450 were found for alluvial fan sediments and weathered basal deposits. However, basal sediments of MYT P3 seem to be of a slightly higher specific density than distal torrential river deposits of MYT P1. In contrast, palaeo-lake deposits of the MYT P3 core show CT density index values 10 to 20 % lower than those observed for the two other facies types. This corresponds well to the soft appearance of the silty to clayey limnic mud and to its higher contents of organic matter (see Sections 4.1 and 4.2).

We thus conclude that the Vatos palaeo-lake deposits can be clearly discriminated from over- and underlying units by distinct sedimentological and geochemical criteria and differences in density.


a
200 µm
b
200 µm
c
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d
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200 µm

4.5 *Palaeoenvironmental evolution*

The summary view of the facies distribution encountered in vibracores MYT P1 to MYT P4 (fig. 10) shows that grey to dark grey palaeo-lake sediments, rich in organic matter and (ortho-)phosphate, were accumulated on top of weathered fine-grained basal deposits which might correspond to an older stage of the water body. Distinct subsequent palaeo-lake deposits, however, were found to be thickest around vibracoring site MYT P3 in the northwestern part and thinnest around vibracoring site MYT P4 in the southern part of the polje. This shows that the profundal zone of the palaeo-lake was located close to the ponor (see Section 4.1). The maximum lake level reached around 760 m a. s. l. (MYT P4); provided that the lake sediments were deposited in a coherent water body extending all over the lower grounds of the polje this results in a maximum water depth of 2–2.5 m around vibracoring site MYT P3.

In case of cores MYT P2, MYT P3 and MYT P4, limnic sediments are covered by coarse-grained proximal alluvial fan deposits. This indicates a severe change towards increasing morphodynamic activity. The fact that proximal alluvial fan deposits were not encountered in core MYT P1 is due to the central position of the coring site lying farthest away from the torrential rivers entering the polje (fig. 1). However, at sites MYT P2, MYT P3 and MYT P4, a subsequent shift back towards less intense fluvial dynamics took place and let the coarse deposits be covered by fine-grained distal alluvial fan sediments. The latter were associated with sediments of a periodical lake; this sedimentary environment corresponds to the present conditions typical of the lower polje grounds (see Section 2). Nevertheless, sand and grus intercalations in the uppermost core sections of vibracores MYT P2, MYT P3 and MYT P4 give evidence of another temporary increase of fluvial activity.

5 *IRSL dating of polje sediments*

Vibracore MYT P3, which was drilled in front of the ponor, was used for a luminescence dating approach of the Vatos polje sediments. However, contents of quartz minerals in the polje sediments revealed to be too low to be used for blue light stim-

Fig. 8. Thin section photographs from sediment samples of vibracores MYT P2 and MYT P4. (a) Alluvial fan deposits out of clayey silt with angular sand grains, a ceramic fragment and micro-pieces of charcoal (MYT P2/3+ 0.70–0.65 m b. s., PPL). (b) Alluvial fan deposits with post-sedimentary hydromorphic features and a wood fragment (MYT P4/4+ 1.70–1.65 m b. s., PPL). (c) and (d) Coarser grained proximal alluvial fan deposits, badly sorted, with abundant angular sand grains and ceramic fragments; the material mostly consists of limestone (c), in very few cases also of quartz fragments (d) (c: MYT P2/7+ 2.95–2.90 m b. s., PPL; d: MYT P4/3+ 1.35–1.30 m b. s., +N). (e) Distal alluvial fan deposits with few sand grains and abundant pores (MYT P2/10+ 3.80–3.75 m b. s. l., PPL). (f) Homogeneously fine-grained palaeo-lake deposits with post-sedimentarily formed spots and large nodules (g) of iron and manganese hydroxide and oxide (f: MYT P2/13+ 4.80–4.75, PPL; g: MYT P2/15+ 5.90–5.85 m b. s., PPL). (h) Weathered fine-grained basal deposits showing muscovite minerals, few sand grains and organic material (MYT P2/17+ 6.55–6.45 m b. s., PPL). Note: PPL = plain polarized light, +N = crossed Nichols.

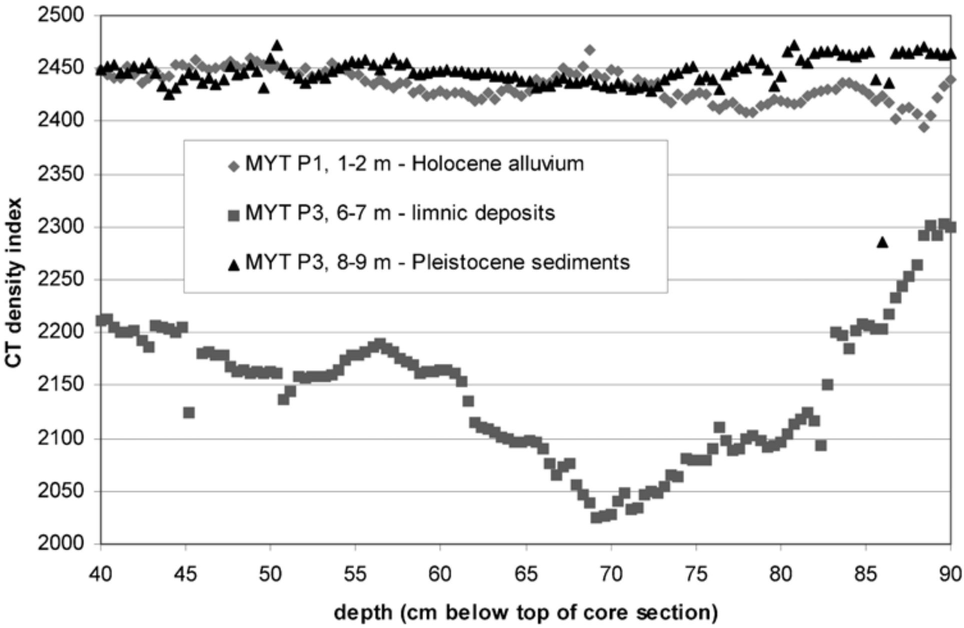

Fig. 9. Computer tomography (CT) measurements of selected segments of vibracores MYT P1 and MYT P3 depicting relative density values of x-rayed material against depth. Both alluvial fan sediments and weathered basal deposits show significantly higher CT density values than the palaeo-lake deposits encountered in front of the Vatos polje ponor.

ulated luminescence. Low contents of non-carbonate minerals were also observed by thin section analyses (see Section 4.3). Therefore, test studies were carried out using the single aliquot regenerative dose protocol (SAR) for feldspar minerals (WALLINGA et al. 2000, PREUSSER 2003) and the IRSL (Infrared Stimulated Luminescence) dating technique. First approaches, however, showed severe age underestimation. This is most probably due to anomalous fading effects as approved by fading tests. For this reason, we decided to use the multiple-aliquot additive (MAA) dose approach instead of the SAR technique for equivalent dose (ED) estimation. IRSL stimulation was accomplished at a temperature of 125 °C for a period of 300 s with a preheat temperature of 290 °C. The luminescence signal was detected using a combination of Schott BG 39 and GG 400 and Corning 7–59 filters (transmitting 440 ± 40 nm) to record the main feldspar emission between 390–440 nm (cf. KRBETSCHEK et al. 1997).

In total, eighteen samples were selected for IRSL dating. Equivalent dose estimation was successfully carried out for all samples except MYT4 (table 1). Dating results are classified in five geochronostratigraphic groups. Ages obtained for group I are around 64–60 ka corresponding to the late Pleistocene. These samples consist of weathered fine-grained basal sediments, olive grey to rust-coloured due to high contents of iron and manganese hydroxides and oxides. Group II IRSL ages were derived from greyish-white sediment samples from the upper section of the fine-grained basal deposits with 35–31 ka, however including a slight age inversion (table 1). Group III

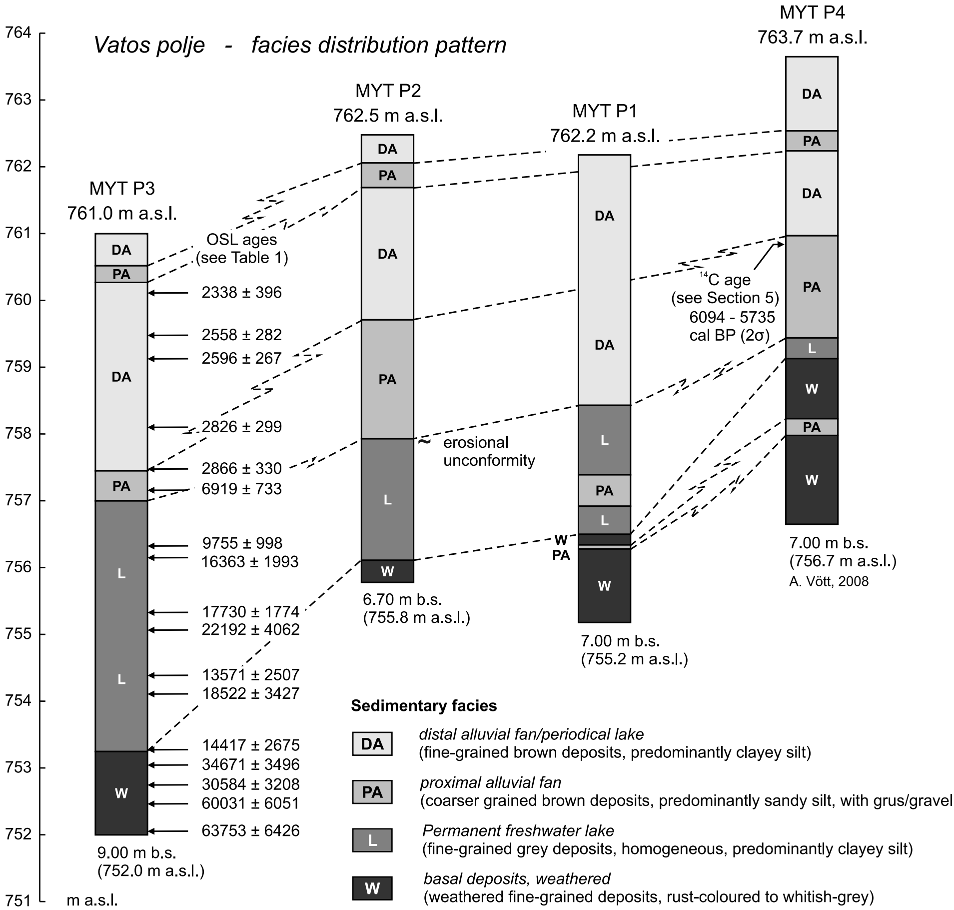

Fig. 10. Simplified facies distribution pattern reconstructed for the Vatos polje based on geoscientific vibracore analyses and IRSL datings. For locations of vibracores see fig. 1, for IRSL ages see table 1.

ages were all obtained for grey to dark-grey palaeo-lake deposits encountered in the lower central section of core MYT P3. The IRSL ages range between 22–14 ka and show some inconsistencies in the intra-group geochronostratigraphy. However, all IRSL dates indicate a post-LGM and pre-Holocene age of the palaeo-lake deposits. Early Holocene group IV ages document beginning desiccation of the lake environment around 10 ka and subsequent intensification of morphodynamic activity around 7 ka before present. Group V reflects the time span during which distal alluvial fan deposits were accumulated around MYT P3 in combination with a periodical freshwater lake that existed during winter seasons. Ages obtained range between 2.9–2.3 ka.

Cross-checking of IRSL dates by radiocarbon analyses was problematic because charcoal findings were mostly restricted to micro-pieces < 50 μm in diameter (see

Table 1. Luminescence dating results of sediment samples from vibracore MYT P3. Fine-grained samples were stimulated by infrared light (IRSL, MAA protocol). Note: ED = equivalent dose, DO = dose rate, – = ED was not determined. Luminescence datings were accomplished in the Marburg Luminescence Laboratory.

Sample ID	Lab code	Sampling depth (m b. s.)	Grain (μm)	U (ppm)	Th (ppm)	K (%)	Water content (%)	ED (Gy)	D_0 ($Gy\ a^{-1}$)	Age (a)
MYT1	MR0412	0.86–0.92	4–11	2.47 ±0.12	11.30 ±0.57	2.44 ±0.12	19.5	9.82 ±0.81	4200 ±623	2338 ±396
MYT2	MR0413	1.48–1.55	4–11	2.95 ±0.15	13.10 ±0.66	2.90 ±0.15	27.7	11.70 ±0.66	4573 ± 435	2558 ± 282
MYT3	MR0414	1.84–1.90	4–11	2.10 ± 0.11	13.50 ± 0.68	2.66 ± 0.13	27.3	10.78 ± 0.46	4152 ± 390	2596 ± 267
MYT4	MR0415	2.47–2.54	4–11	2.51 ± 0.13	12.60 ± 0.63	2.64 ± 0.13	26.1	–	4500 ± 430	–
MYT5	MR0416	2.86–2.93	4–11	2.43 ± 0.12	13.20 ± 0.66	2.91 ± 0.15	27.4	12.44 ± 0.60	4403 ± 415	2826 ± 299
MYT6	MR0417	3.49–3.55	4–11	2.85 ± 0.14	13.30 ± 0.67	2.92 ± 0.15	25.0	13.03 ± 0.84	4547 ± 434	2866 ± 330
MYT7	MR0418	3.80–3.87	4–11	2.90 ± 0.15	13.30 ± 0.67	2.08 ± 0.10	22.7	27.18 ± 0.97	3928 ± 392	6919 ± 733
MYT8	MR0419	4.64–4.70	4–11	2.61 ± 0.13	14.50 ± 0.73	2.35 ± 0.12	28.4	40.39 ± 1.12	4140 ± 408	9755± 998
MYT9	MR0420	4.82–4.88	4–11	1.81 ± 0.09	14.60 ± 0.73	2.43 ± 0.12	27.9	64.64 ± 1.07	3950 ± 379	16363 ± 1993
MYT10	MR0421	5.64–5.70	4–11	2.12 ± 0.11	14.20 ± 0.71	2.10 ± 0.11	28.0	66.59 ± 1.08	3756 ± 371	17730 ± 1774
MYT11	MR0422	5.90–5.96	4–11	2.50 ± 0.13	14.80 ± 0.74	2.37 ± 0.12	46.1	72.15 ± 0.82	3251 ± 594	22192 ± 4062
MYT12	MR0423	6.58–6.64	4–11	3.06 ± 0.15	14.00 ± 0.70	2.07 ± 0.10	36.7	42.78 ± 0.71	3152 ± 580	13571 ± 2507
MYT13	MR0424	6.86–6.92	4–11	2.82 ± 0.14	14.70 ± 0.74	2.14 ± 0.11	33.8	58.92 ± 1.04	3181 ± 586	18522 ± 3427
MYT14	MR0425	7.69–7.75	4–11	2.75 ± 0.14	14.50 ± 0.73	2.08 ± 0.10	40.5	44.78 ± 0.90	3106 ± 573	14417 ± 2675
MYT15	MR0426	7.92–7.98	4–11	2.66 ± 0.13	16.10 ± 0.81	2.40 ± 0.12	27.5	149.48 ± 1.70	3411 ± 432	34671 ± 3496
MYT16	MR0427	8.22–8.28	4–11	3.26 ± 0.16	18.40 ± 0.92	2.27 ± 0.11	27.1	141.33 ± 2.09	4621 ± 480	30584 ± 3208
MYT17	MR0428	8.50–8.56	4–11	2.66 ± 0.13	13.90 ± 0.70	2.14 ± 0.11	24.5	234.39 ± 2.15	3965 ± 392	60031 ± 6051
MYT18	MR0429	8.90–8.97	4–11	2.50 ± 0.13	12.80 ± 0.64	1.94 ± 0.10	22.0	229.29 ± 1.23	3597 ± 362	63753 ± 6426

Section 4.3). However, a piece of charcoal from core MYT P4 encountered in coarse-grained proximal alluvial fan deposits at 2.80 m b. s. was ^{14}C-AMS-dated to 6,094–5,753 cal BP (Lab code UtC 13199, 2 sigma, BP = 1950, calibrated by means of the calibration software CALIB, version 5.0.2html). It is concluded that the stratigraphic position of the sample, the facies of the hosting sediment and the radiocarbon age are consistent with the upper group III IRSL sample position, facies and age (6,919 ± 733 a, see table 1).

A number of natural trenches were studied in proximal alluvial fan areas in the northeastern part of the polje and to the north of the northern polje entrance (fig. 1). We found several ceramic fragments embedded in the uppermost sections of the outcropping sediments (at 1–2 m b. s.) which were archaeologically dated to late Roman to Byzantine times. The hosting sediments seem to correspond to the predominantly distal alluvial fan sequence encountered in the uppermost core meter of MYT P3 which are IRSL dated to be younger than 2338 ± 396a (see table 1). Thus, there is good accordance between IRSL ages and archaeological dates.

6 *Discussion*

The present topographic and geomorphological settings of the Vatos polje are predominantly due to the tectonic graben-like structure in combination with overthrusting activities (figs. 2 and 4). Several other studies from the Mediterranean revealed similar tectonic control of polje evolution (for instance Ekemkci & Nazik 2004, Gams 2005, Gracia et al. 2003, Prohic et al. 1998). In the Vatos polje, karst features such as ponors and sinkholes are restricted to the northwestern edge of the polje where thick limestone strata crop out. As the subground, however, mainly consists of minero-clastic Flysch-deposits covered by loose Quaternary sediments the formation of the polje grounds is rather due to tectonic graben dynamics and subsequent sedimentary infilling by fluvial systems than by lateral corrosive planation processes (see Rubio et al. 2007).

Runnels & van Andel (2003) investigated loutsas and poljes in nearby Epirus around the city of Preveza within the framework of the Nikopolis archaeological project; their major objective was to document Palaeolithic and Mesolithic sites in their geological context. Sedimentological studies focused on profiles along natural trenches and on the formation and re-deposition of terra rossa material. By luminescence dating, it was found that, in several selected karstic depressions, formation of terra rossa palaeosols occurred between 91–52 ka before present (see also Zhou & van Andel 2000). This time span corresponds to the group I ages found for the Vatos polje that are related to the deposition of fine-grained deposits encountered at the base of core MYT P3. Both studies thus indicate intense subaerial weathering processes for approximately the same time period.

Balbo et al. (2006) investigated polje sediments in Istria, Croatia, by means of a 17 m-long core from Polje Čepić. Within this study, age determination was accomplished by radiocarbon dating. Balbo et al. (2006) found that lacustrine or wet phases of the polje date back to pre-historic times and that by about 6,900 cal BP, fluvial activity increased. Moreover, pollen analyses revealed severe changes in the vegetation cover around 6,500 cal BP which the authors ascribe to the clearing of forests by the Neolithic man. The general evolution of the Čepić polje described by Balbo et al. (2006) corresponds well with our sedimentological and geochronological results from the Vatos polje where morphodynamic activity increased around 7–6 ka before present (see Section 5). However, we did not encounter archaeological evidence of man being present in the local area.

Fuchs (2007, see also Fuchs et al. 2004) carried out OSL-dating studies on Holocene colluvial deposits, associated to ceramic findings, in the Phlious basin in the northeastern Peloponnese. According to his results, there is evidence of increased sedimentation at the beginning of Neolithic times triggered by man-made soil erosion and subsequent colluviation. Increased fluvial dynamics were also found for the beginning Neolithic epoch in the Vatos polje; however, we did not make archaeological findings associated to the sediment cores. Moreover, Jahns (2005), who carried out detailed palynological analyses of sediment samples from a 7 m-long core from the nearby Lake Voulkaria (fig. 1) did not encounter clear evidence of anthropogenic impact on the vegetation before the end of Neolithic times around 3,500 BC. Nevertheless, several artifacts document that man is present in the wider area since the Palaeolithic period (Berkthold 1996, Lang et al. 2007).

Sedimentological and geochronological analyses of core MYT P3 show that at some time between 14–9 ka before present the Vatos palaeo-lake was on the point of desiccating. Apart from changes of the local drainage system, this may indicate a change towards drier climatic conditions; such a decrease of palaeorainfall was calculated from $\delta^{18}O$ values measured in Soreq Cave speleothems, Israel, by Bar-Matthews et al. (2003, see also Wilson et al. 2007). The increase in fluvial dynamics found for the Vatos polje for 7–6 ka before present matches well with palaeorainfall scenarios that show very wet conditions between 8.5–7 ka (Bar-Matthews et al. 2000, Bar-Matthews & Ayalon 2005) and around 7 ka before present (formation of the S1 sapropel, Ariztegui et al. 2000). Additional sedimentological evidence of strongly increased morphodynamic activity during Neolithic times and, at the same time, maximum extents of coastal freshwater (palaeo-)lakes was found for the nearby Palairos, Mytikas and Astakos coastal plains (Vött et al. 2006a, 2006b, 2006c), neither of these findings being directly connected to man-made artifacts. Thus, it can be concluded that the cessation of limnic conditions and the beginning of strong torrential alluviation in the Vatos polje and the adjacent coastal plains at the beginning of the Neolithic is consistent with an abrupt change towards wetter climatic conditions. Clear evidence of human impact at this time is, however, missing.

The hiati in the IRSL geochronostratigraphy found for core MYT P3 may be explained as follows. We suggest major periods of palaeosol-formation between 60 ka and 35 ka before present and between the Neolithic period and the beginning of the 3rd millennium before present. Such long lasting periods of ecologically stable conditions were also reconstructed for the adjacent coastal plains of Mytikas (Vött et al. 2006a, May et al. 2008) and Astakos (Vött et al. 2006c) for the Bronze Age (ca. 5–3 ka before present). The hiatus following the late Pleistocene limnic phase seems to be due to the gradual desiccation of the Vatos palaeo-lake. However, further studies are necessary to detect the reasons for the time gap between IRSL age groups I and II.

At the beginning of the 3rd millennium before present, fluvial activity clearly increased and thus ceased a long period of ecological stability lasting since the Neolithic. Large quantities of fine-grained alluvial deposits were transported to the lower polje grounds where, during winter, sediment deposition partly took place in a periodical lake environment. According to the high contents of associated non-diagnostic ceramic (micro-)pieces, wood fragments and charcoal (micro-)particles (see Section 4.3), this increase was caused by man-made interferences of the vegetation and soil covers and subsequent soil-erosion. Based on our results, such conditions persisted from Archaic until Roman times. In late Roman to Byzantine times, proximal alluvial fan deposits reached the lower polje grounds indicating another increase in fluvial morphodynamics. This impulse seems to be connected to increased clearing activities in the surrounding mountains and corresponds to the results of geomorphological and sedimentological studies along the Glosses rema in the adjacent Mytikas coastal plain (Vött et al. 2006a, May et al. 2008) where most severe man-made soil erosion was found for post-Roman times.

7 *Conclusions*

The sedimentary infill of the Vatos polje in central Akarnania, NW Greece, was used as an archive to detect phases of morphodynamic activity and stability and to reveal palaeoenvironmental changes. Based on geomorphological studies as well as on sedimentological, geochemical, micromorphological and geochronological analyses of vibracore sediments we come to the following conclusions.

(i) The Vatos polje is a structural polje located in a graben-like situation and controlled by tectonic overthrusting (fig. 4). The subground is made up of minero-clastic Flysch deposits and karst phenomena are restricted to small areas of laterally outcropping limestone.

(ii) IRSL age determinations of vibracore sediments yielded a reliable geochronostratigraphy cross-checked by radiocarbon and archaeological age determination. However, due to the low contents of quartz minerals, further corings are required for quartz mineral condensation out of sediment samples; the application of the SAR dose protocol will then enable a refinement of the local geochronostratigraphy.

(iii) During the late Quaternary, probably between 22–14 ka, a permanent freshwater lake existed in the Vatos polje. The late-Pleistocene Vatos lake desiccated around the beginning of the Holocene possibly due to a climatic change towards drier conditions.

(iv) We found evidence of clearly increased fluvial activity for the beginning Neolithic epoch during which the lake did not exist; instead, coarse-grained alluvial fan deposits were accumulated. However, it cannot be clarified whether this change in morphodynamics is only due to climatic reasons or also by Neolithic settlement and clearing activities.

(v) Vibracore data suggest a subsequent period of geomorphological stability until the beginning of the 3rd millennium BC, when torrential systems were re-activated. Pieces of ceramics, plant remains, wood, and charcoal associated to the sediments indicate that this re-activation was due to severe anthropogenic impact on the vegetation and soil covers. During winter, alluviation was connected to a periodical lake environment.

(vi) In late Roman to Byzantine times, another increase of soil erosion and fluvial activity occurred due to human interferences.

(vii) Mediterranean poljes are valuable geo-archives, so far often neglected, revealing dense palaeoenvironmental and palaeoclimatological data to be used for the reconstruction of landscape evolution and man-environment interactions.

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