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Seismic and sedimentological evidence of an early 6th century AD earthquake at Lake Ohrid (Macedonia/Albania)

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Abstract

Lake Ohrid shared by the Republics of Albania and Macedonia is formed by a tectonically active graben within the South Balkan and suggested to be the oldest lake in Europe. Several studies have shown that the lake provides a valuable record of climatic and environmental changes and a distal tephrostratigraphic record of volcanic eruptions from Italy. Fault structures identified in seismic data demonstrate that sediments have also the potential to record tectonic activity in the region. Here, we provide an example of linking tephrostratigraphic information and environmental changes with tectonic activity and anthropogenic impact. Historical documents indicate that a major earthquake destroyed the city of Ohrid in the early 6th century AD. This earthquake is documented in multichannel seismic profiles, in parametric sediment echosounder profiles, and in a ca. 10 m long sediment record from the western part of the lake. The sediment record exhibits a ca. 2 m thick mass wasting deposit, which is chronologically well constrained by the underlying 472 AD/512 AD tephra and cross correlation with other sediment sequences with similar geochemical characteristics of the Holocene.

1 Introduction

Lake Ohrid (40°54′–41°10′ N, 20°38′–20°48′ E, Fig. 1) is a transboundary lake located on the Balkan Peninsula and shared between the Republics of Macedonia and Albania. The lake is about 30 km long, 15 km wide and has an area of 360 km^2 (Stankovic, 1960). According to geological and biological age estimations the lake formed about 2–5 Ma ago (summarized in Albrecht and Wilke, 2008; Lindhorst et al., 2012a). The lake is situated in a tectonically active, N–S trending graben (Burchfiel et al., 2008; Lindhorst et al., 2012a), which results in a relatively simple bathtub-shaped morphology, with steep slopes along the western and eastern sides and less inclined slopes in the northern and southern part. The average water depth is 150 m and the maximum water depth is 293 m (Lindhorst et al., 2012a). The current lake level is at 693 m above sea level (a.s.l.) and the lake is surrounded by the Mokra Mountains to the west (1514 m a.s.l.) and the Galicica Mountains to the east (2265 m a.s.l.; Fig. 1).

Several studies on up to ca. 15 m long sediment sequences have shown that Lake Ohrid is a valuable archive of climatic and environmental changes over the last glacial/interglacial cycle (e.g. Wagner et al., 2009, 2010; Vogel et al., 2010a). Moreover, tephrostratigraphic studies revealed that Lake Ohrid and neighboring Lake Prespa are important distal archives of explosive eruptions from Italian volcanoes (summarized in Sulpizio et al., 2010a; Caron et al., 2010; Vogel et al., 2010b). Hiatuses and disturbed sedimentation in some of the studied sediment sequences from Lake Ohrid can probably be explained by tectonic activity in the region triggering several landslides (e.g., Wagner et al., 2009; Vogel et al., 2010a). These mass wasting deposits and associated fault structures are also recorded in seismic profiles from the lake and occur mainly in the marginal parts of the lake basin (Wagner et al., 2008a; Reicherter et al., 2011; Lindhorst et al., 2012a). A detailed morphological mapping of the floor of Lake Ohrid by means of an ELAC 1180 Seabeam system revealed that most of the southwestern part of the lake is affected by a large mass failure event, the so-called Udenisht Slide Complex (Lindhorst et al., 2012b). Though some of the mass wasting deposits may be triggered by distinct lake level fluctuations (Lindhorst et al., 2010), most of them likely formed due to tectonic activity (Reicherter et al., 2011). As Lake Ohrid is located within the Korca-Ohrid Earthquake Source Zone (ESZ, Fig. 1) several medium to large earthquakes have occurred within the last 2000 yr (Aliaj et al., 2004; Lindhorst et al., 2012b). For example, recent earthquakes occurred on 6 June 2012 ($M = 4.4$), on 6 September 2009 ($M = 5.6$) and on 23 November 2004 ($M = 5.4$) (European-Mediterranean Seismological Centre, EMSC, 2012). More destructive earthquakes in the younger history are recorded in 1963 close to capital city of Macedonia Skopje ($M = 6.1$, Suhadolc et al., 2004) or in 1911 at Lake Ohrid with a Magnitude of 6.7 (Ambraseys and Jackson, 1990; Muco et al., 2002). Unfortunately, the data basis is less well constrained for historical times. According to Aliaj et al. (2004), a major earthquake destroyed the city of Skopje at 518 AD. This data can also be found in most public reports for a destruction of the city of Ohrid. In contrast, Ambraseys (2009) reports that the 518 AD earthquake rather affected the city of Skopje ("Scupi"), whilst the city of Ohrid ("Lychnidus") was destroyed 9 yr later at 527 AD. This data could correspond with the data indicated in Reicherter et al. (2011, and references therein), according to which the city of Ohrid was destroyed in late May 526 AD, with a magnitude $M > 6$. Despite these uncertainties, it seems unquestionable that at least one major earthquake affected the Ohrid region in the beginning of the 6th century AD.

Here we present how seismic information can be combined with sedimentological, climatic, tephrostratigraphic, and historical information in order to evaluate the potential of Lake Ohrid for paleoseismicity investigations, as it was proposed by Reicherter et al. (2011) and demonstrated in other lacustrine (e.g. Schnellmann et al., 2002) or marine basins (e.g., Beck et al., 2012).

2 Material and methods

Hydro-acoustic surveys were carried out in Lake Ohrid between 2004 and 2009 in order to obtain information on the lake's bathymetry and sedimentary architecture. Multichannel seismic surveys in 2007 and 2008 using a Mini GI Gun and a Multibeam survey in 2009 using an ELAC 1180 Seabeam system are described in detail in Lindhorst et al. (2012a). These surveys have shown prominent faults and half-graben structures along the western and eastern margins of the lake, which were also indicated in shallow seismic profiles obtained by means of a parametric sediment echosounder (SES-96 light in 2004 and SES 2000 compact in 2007 and 2008, INNOMAR Co.). In front of the Lini Peninsula at the western margin of the lake, where a succession of mass wasting deposits was indicated in the multichannel seismic surveys (Reicherter et al., 2011; Lindhorst et al., 2012a; Fig. 2), also parametric echosounder profiles were obtained. The parametric sediment echosounder transducer was mounted on the side of a small research vessel. The effective frequency of the echosounder was set to 10 kHz in order to obtain the optimum settings ranging from deep penetration to high resolution. The sound velocity in the water was set to 1440 m s^{-1}. Post-processing was carried out with the INNOMAR software tool ISE 2.9.2.

Based on the hydro-acoustic surveys, a coring location in front of the Lini Peninsula (41°03′56.9″ N, 020°40′21.9″ E) at 260 m water depth was selected for the study of mass wasting deposits and their relation to earthquakes. Coring at this site was implemented in a deep drilling project at Lake Ohrid within the frame of the International Continental Scientific Drilling Program (ICDP). The 10 m long sediment sequence (Co1262) was recovered in front of the Lini Peninsula in June 2011 from a floating platform using a gravity corer and a 2 m long percussion piston corer (UWITEC Co. Austria) for deeper sediments. For the recovery of the piston cores, a re-entry cone was positioned on the lake floor. Extension rods of 2 m length controlled the exact release of the piston during the individual continuous coring process. Core recovery was in the order of 100 % including core catcher samples. Core loss or disturbance of sediment between the individual 2 m segments can therefore be regarded as low (< 6 cm). After recovery, the 2 m long sediment cores were cut into ca. 1 m long segments and stored in the dark at 4 °C until further processing.

In the laboratory at the University of Cologne, the core segments were opened and one core half was described macroscopically and subjected to high-resolution X-ray fluorescence (XRF) scanning. XRF scanning was performed using an ITRAX core scanner (COX Ltd., Sweden), which was equipped with a Cr-tube set to 30 kV and 30 mA, and a Si-drift chamber detector. Core Co1262 was scanned with a resolution of 2 mm and a scanning time of 10 s per measurement. Ca, K, and Sr were selected of the measured elements, as they are indicators for carbonate precipitation, the input of clastic material, and the occurrence of potential tephras and cryptotephras in sediment sequences from Lake Ohrid (Vogel et al., 2010a, b). Total carbon (TC) and total inorganic carbon (TIC) were determined with a DIMATOC 200 (DIMATEC Co.). Total organic carbon (TOC) was calculated by the difference between TC and TIC.

Tephrostratigraphy and cross correlation with other sediment cores from Lake Ohrid were used to provide a chronological framework for core Co1262. Samples from horizons with peaks in K and Sr were selected for tephrostratigraphic work. Volcanic ejecta from these horizons were analyzed with respect to their geochemical composition according to previous work on sediment cores from Lake Ohrid (Sulpizio et al., 2010a; Vogel et al., 2010b). Energy-dispersive spectrometry (EDS) of glass shards and micro-pumice fragments was performed using an EDAX-DX micro-analyser mounted on a Philips SEM 515 (operating conditions: 20 kV acceleration voltage, 100 s live time counting, 200–500 nm beam diameter, 2100–2400 shots s^{-1}, ZAF correction). Details about analytical precision, ZAF correction and inter-laboratory comparison can be found in Sulpizio et al. (2010a, b) and Vogel et al. (2010b). Radiocarbon dating on core Co1262 was not carried out, because terrestrial macrofossils were not detected and previous studies have shown that bulk organic matter dating on Lake Ohrid sediments provided erroneous ages (Wagner et al., 2008a; Vogel et al., 2010a). Cross correlation with other sediment cores from Lake Ohrid concentrated on TIC and Ca count patterns, as former studies have shown that the carbonate content in the sediments of Lake Ohrid sensitively records climatic and environmental changes during the Holocene (Wagner et al., 2009, 2010; Vogel et al., 2010a). Significant fluctuations in the carbonate content of formerly studied cores could have been attributed to significant events, such as the 8.2 ka cooling event, the Medieval Warm Period (MWP) or Little Ice Age (LIA) and were constrained by tephrostratigraphy and radiocarbon dating on macrofossil remains. Similar carbonate fluctuations in core Co1262 are assumed to represent the same events.

3 Results

3.1 Hydro-acoustic survey

The multichannel seismic survey revealed a succession of mass wasting deposits in front of the Lini Peninsula (Fig. 2), where one of the most active faults of the Lake Ohrid graben system is located (Lindhorst et al., 2012a). The topmost two mass wasting deposits are also imaged in the parametric sediment echosounder profile perpendicular to the Lini Peninsula as transparent and partly chaotic seismic units (Fig. 3). Whilst the thickness of the lower mass wasting deposit exceeds 10 m (Fig. 2), the thickness of the topmost mass wasting deposit can be estimated to about 2 m at the coring location Co1262 according to the parametric sediment echosounder profile (Fig. 3). Between the two mass wasting deposits and on top of the upper one, parallel to sub-parallel continuous reflections with low to medium amplitudes indicate widely undisturbed well-stratified sediments. A significant erosional unconformity at the base of the upper mass wasting deposit cannot be detected in the parametric sediment echosounder line at the coring location, probably because the mass wasting deposit pinches out only a few hundred meters to the east of the coring location and a potential erosion decreased with increasing distance from the steep slope (Fig. 3).

3.2 Sediment core

The geochemical characteristics of the 1008 cm long sediment sequence Co1262 correlate well with the parametric sediment echosounder data and with sediment cores previously recovered from Lake Ohrid. Overall, core Co1262 is mainly formed by relatively homogenous clayey to silty mud of grayish to olive color. The sediments appear massive, probably as a result of bioturbation, as it was also observed in other sediment sequences from Lake Ohrid at least throughout the Holocene (Wagner et al., 2009; Vogel et al., 2010a). Some weak color changes are probably due to distinct changes in the content of carbonate, which is represented by TIC and Ca, and organic matter, which is represented by TOC (Fig. 4). Significant changes in these constituents were also recorded in other sediment sequences from Lake Ohrid throughout the Holocene (Wagner et al., 2009; Vogel et al., 2010a). The lowermost meter of the sequence contains some gravel grains, which were interpreted as ice-rafted debris in other cores from lakes Ohrid and Prespa (Wagner et al., 2009; Vogel et al., 2010a; Aufgebauer et al., 2012). Some changes in grain size composition are correlated with minima in water content and likely represent mass wasting deposits. For example, a 20 cm thick horizon between 980 and 960 cm has low, but increasing water content and a fining upward trend in grain size composition from fine sand at the basis to fine silt and clay at the top. This is interpreted as a mass wasting deposit (turbidite). Smaller mass wasting deposits are also indicated at depths of 548 and 350 cm. These deposits are, however, likely too small to be visible in the hydro-acoustic data. More pronounced is a significant change of the sedimentological and geochemical characteristics at 320 cm depth, where a 1–2 cm thick sandy horizon overlays a thin grayish band of 1 mm thickness (Fig. 5). On top of this sand layer, the sediment is very homogenous and significant changes in carbonate or organic matter content do not occur until 121 cm depth. The water content throughout this horizon is low, but increases slightly topwards. The homogenous horizon between 320 and 121 cm depth corresponds with the transparent sediment body visible in the hydro-acoustic data and most likely represents a relatively thick mass wasting deposit. An erosional discordance at the basis of this mass wasting deposit is not distinct in the sediment core (Fig. 5) and matches with the hydro-acoustic data. The uppermost 121 cm of core Co1262 are characterized by silty to clayey mud of grayish to olive color, relatively high water content and some distinct fluctuations of the carbonate and organic matter content.

4 Chronology of core Co1262 and the mass wasting deposit

Although radiocarbon dating on core Co1262 from Lake Ohrid was not carried out, the occurrence of three well dated tephras and the significant patterns of TIC and Ca allow a good chronological control of the entire core and the mass wasting deposit between 320 and 121 cm depth.

Overall, the occurrence of ice-rafted debris, low Ca counts and low TIC at the core basis imply that the core reaches back into the last glacial period, when carbonate precipitation in Lake Ohrid was restricted or carbonates were not preserved and when the lake was at least partly ice covered during winter (Wagner et al., 2009; Vogel et al., 2010a). In several studied cores from lakes Ohrid and Prespa, the onset of carbonate precipitation and preservation was correlated with the Pleistocene/Holocene transition (Wagner et al., 2009, 2010; Vogel et al., 2010a; Aufgebauer et al., 2012). However, most of the existing records from Lake Ohrid apparently are disturbed at the Pleistocene/Holocene transition. In a record from nearby Lake Prespa, a first significant peak in carbonate content at the Pleistocene/Holocene transition was correlated with a ca. 800 yr long period at the transition from the Bölling/Alleröd to the Younger Dryas. We assume that the TIC and Ca peaks around 800 cm depth in core Co1262 (Fig. 4) also correspond with this period, which occurred around 13 000 cal yr BP (Aufgebauer et al., 2012). The TIC and Ca minima around 750 cm are likely correlated with the Younger Dryas cold reversal. However, the peaks in K and Sr at 709 cm can be attributed to a significant occurrence of glass shards. The geochemical composition of the glass shards suggest that they originate from the Mercato eruption (Table 1, Fig. 6; cf. Damaschke et al., 2012), which has proposed maximum ages of 8890 cal yr BP (Santacroce et al., 2008) and recently dated (using charcoal from the base of the fallout deposits) at 8540 cal yr BP (Zanchetta et al., 2011). This would imply that sedimentation rates were very low between the Younger Dryas and the Mercato deposition. The distinct increase of Ca counts and TIC suggest sedimentation during Holocene times after Mercato deposition and is similar to other sediment records from Lake Ohrid (Wagner et al., 2009; Vogel et al., 2010a). The minima in TIC and Ca and the maximum in K at ca. 660 cm depth are likely correlated with the 8.2 ka cooling event, as observed in other cores from lakes Ohrid and Prespa (Wagner et al., 2009, 2010; Vogel et al., 2010a; Aufgebauer et al., 2012). High TIC and Ca characterize the period after the 8.2 ka cooling event and are explained by warmer temperatures, high carbonate precipitation and preservation (Wagner et al., 2009, 2010; Vogel et al., 2010a; Aufgebauer et al., 2012). The existing records also indicate a second cooling/drying event around 4000 cal yr BP. This event is only poorly resolved in core Co1262, but the occurrence of the FL tephra at 517 cm depth (Table 1, Figs. 4 and 6) provides a chronological tie point with an age of 3370 ± 70 cal yr BP (Coltelli et al., 2000; Wagner et al., 2008a). A significant decrease of TIC and Ca around ca. 2500 cal yr BP was observed in other cores from Lake Ohrid (Fig. 4), when anthropogenic impact led to higher erosion in the catchment and increased the clastic matter input into Lake Ohrid. A similar pattern can be observed in core Co1262 and allows chronological cross correlation with the existing records. A third independent chronological tie point comes from a tephra layer that appears as a thin grayish band just below the extensive mass wasting deposit at 320 cm depth and corresponds to a Sr peak (Figs. 4 and 5). Geochemical identification of volcanic material from this horizon attributes the tephra to the 472/512 AD eruption (Table 1, Fig. 6; Wagner et al., 2008b; Vogel et al., 2010b; Sulpizio et al., 2010a). The geochemical differentiation between the 472 AD and 512 AD tephras is relatively easy, if the entire succession of the 472 AD eruption is preserved, because the composition of tephras from this event straddles the fields of phonolite, foidites and tephra-phonolites (Fig. 6; Santacroce et al., 2008). It becomes more difficult if only the final products of the 472 AD eruption are recognized, due to the large compositional overlap between them and the 512 AD tephra (Sulpizio et al., 2010a, b). Volcanic ejecta from the 472 AD eruption were clearly identified in Lake Shkodra, (Sulpizio et al., 2010b; Zanchetta et al., 2012). In formerly studied cores from lakes Ohrid and Prespa, however, a mixture of 472 AD and 512 AD tephras was proposed (Vogel et al., 2010b; Damaschke et al., 2012). As the geochemical composition of the tephra at 320 cm depth in core Co1262 is similar to those previously found in lakes Ohrid and Prespa, we assume that it also includes the 512 AD deposits. Right on top of the 472/512 AD tephra, the sandy horizon and low fluctuations of K, Ca, and Sr counts and TIC and TOC values between 320 and 121 cm sediment depth suggest a mass wasting deposit, which is also observed in the hydro-acoustic data (Fig. 3). Calculating a mean sedimentation rate of ca. 1 mm yr^{-1} between the carbonate decline at ca. 420 cm depth or 2500 cal yr BP and the occurrence of the 472/512 AD tephra (1478/1438 cal yr BP) at 320 cm depth, we can assume that the mass movement occurred very shortly after the deposition of the 472/512 AD tephra. Most likely, the mass wasting deposit correlates with a historical earthquake, which destroyed the city of Ohrid in the early 6th century AD. Potential candidates for such an earthquake are the 518 AD earthquake, which according to some authors

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more affected the city of Skopje (Aliaj et al., 2004; Ambraseys, 2009), or the 526 or 527 AD earthquake, which concentrated more on the Ohrid region (Ambrasyes, 2009; Reicherter et al., 2011). Although the bioturbated structure of the sediment core and the impossible the differentiation between the 472 AD and 512 AD tephra do not allow a chronological discrimination between the two (or three) earthquakes, it is evident that the mass wasting event must have occurred during the early 6th century AD and is likely related to one of these earthquakes. An early 6th century AD age of the mass wasting deposit is confirmed by the patterns of TIC and Ca on top of it, which are again similar to those of former cores from Lake Ohrid. After low Ca between 121 and 100 cm depth, which would correspond to a period of ca. 200 yr based on a sedimentation rate of ca. 1 mm yr^{-1}, the increase of Ca and TIC can be correlated with the onset of the MWP, which culminated at 900–1000 AD in other cores from lakes Ohrid and Prespa (summarized in Wagner et al., 2010 and Aufgebauer et al., 2012) and between 1000 and 1200 AD in the eastern Mediterranean (Kaniewski et al., 2011). The subsequent minimum of Ca and TIC correlates well with the LIA (Wagner et al., 2009, 2010; Vogel et al., 2010a), before recent warming led to increasing Ca and TIC at the sediment surface.

5 Comparison with other sites

The patterns of geochemical fluctuations in core Co1262 suggest that the Holocene sedimentation rates at the Lini site Co1262 are varying distinctly (Fig. 4) and are relatively high compared with other sites from the northeastern or southeastern part of the lake. After subtracting the prominent mass wasting deposit in core Co1262, the Holocene sediments comprise ca. 6 m, which is twice as much as the Holocene sediment succession in the northeastern part of the lake (core Co1202, Fig. 1, Vogel et al., 2010a). In the southeastern part of the lake, the thickness of the Holocene sediment succession was similar (core Lz1120, Fig. 1, Wagner et al., 2009), but this coring location is close to an inlet. There is no significant inlet close to the site Co1262 and

Lake Ohrid is an oligotrophic lake with relatively simple basin morphology. The significant variations in sedimentation rates and the overall high sedimentation rate suggest lake internal currents (Vogel et al., 2010c) and/or contourite drift as observed in Lake Prespa nearby (Wagner et al., 2012). Another reason for the varying but high sedimentation is probably due to the tectonic activity along the western margin of the lake. The region around Lini Fault, which is one of the oldest faults in Lake Ohrid Basin and located offshore of Lini Peninsula, is one of the most active areas (Lindhorst et al., 2012a). Half-grabens were developed within the hanging wall of related fault structures, creating depocentres that are filled with redeposited material from the footwall. The Udenisht Slide is one of the biggest slides in the southwestern part of the lake, which occurred during the younger history of Lake Ohrid and was likely seismically induced (Lindhorst et al., 2012b). First age estimations suggest that the Udenisht slide is younger than 1500 yr and was also probably associated with the 518 AD (or 526 AD?) earthquake (Lindhorst et al., 2012b). However, the chronological control of this slide is hampered by high uncertainties in extrapolation of sedimentation rates of overlying sediment. These observations strongly suggest that major earthquakes in Lake Ohrid triggered lacustrine slides and are confirmed by onshore information, which indicate that the morphology of the Ohrid basin is formed by frequent earthquakes of magnitudes between $M6.0$ and 7.0 (Reicherter et al., 2011). Hence age estimation of these mass wasting deposits can be used as a proxy for estimating paleoseismicity. Lindhorst et al. (2012a) showed several slides in multichannel seismic sections suggesting that a long paleoseismic record will become available once a deep drill core will be recovered from Lake Ohrid. A deep drilling campaign is scheduled for 2013.

6 Conclusions

The Co1262 record shows the high potential of Lake Ohrid for paleoseismicity investigations, by combining seismic, sedimentological, climatic, tephrostratigraphic, and historical information. The most significant mass wasting deposit in core Co1262 was formed according to tephrostratigraphic information and climate related sediment proxies in the early 6th century AD. A better chronological framework is hampered, because the sediments of Lake Ohrid are not annually laminated and the tephra, which underlies the mass wasting deposit, cannot be clearly correlated with the 472 AD and 512 AD tephra due to their geochemical overlap. Despite these uncertainties, the lack of an erosional discordance at the base of the mass wasting deposit and the small distance to the underlying tephra imply that the period between tephra deposition and mass wasting deposit is restricted to several years or decades. This makes a correlation of the mass wasting deposit with a historical earthquake, which destroyed the city of Ohrid in the early 6th century AD, very likely. However, also the historical documents indicate different ages for a major earthquake, varying between 518 AD, 526 AD, and 527 AD. Within the framework of such uncertainties, core Co1262 is a very nice example of Holocene paleoseismicity studies. The thick mass wasting deposit, which underlies core sequence Co1262, could be a valuable example for an older mass wasting deposit triggered by an earthquake, as most existing sediment records spanning into the last glacial cycle have disturbed sedimentation at the Late Pleistocene/Holocene transition. More data from other locations of the lake and similar examples from older periods will be needed to shed more light on the earthquake history of the lake.

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Table 1. Major element glass composition of tephras and cryptotephras in core Co1262.

Tephra/Cryptotephra	Shards	SiO_2	TiO_2	Al_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	ClO	Tot. Alkali	Alk. Ratio
Co1262-320 (472/512 AD)	1	47.77	1.14	19.35	7.96	0.12	2.5	10.39	4.95	4.94	0	0.88	9.89	1.00
	2	48.04	1.13	20.2	7.72	0.38	1.44	8.19	6.39	5.42	0	1.1	11.81	0.85
	3	50.52	0.55	21.72	5.05	0.07	0.82	5.16	6.51	8.86	0	0.75	15.37	1.36
	4	50.49	0.7	21.77	5.22	0.13	0.99	5.96	4.81	9.19	0	0.75	14.00	1.91
	5	54.91	1.58	18.28	7.4	0.15	2.49	5.95	5.08	3.37	0.44	0.34	8.45	0.66
	6	47.72	1.02	20.36	7.75	0.14	2.35	9.81	5.94	3.99	0.15	0.77	9.93	0.67
	7	48.58	0.81	21.25	6.6	0.34	1.2	6.38	7.9	5.35	0.2	1.38	13.25	0.68
	8	48.48	0.8	20.91	7.33	0.17	1.19	7.72	6.48	5.68	0.09	1.16	12.16	0.88
	9	48.88	0.77	20.17	7.76	0.19	1.81	8.56	5.69	5.22	0	0.96	10.91	0.92
	10	48.06	1	20.87	7.08	0.42	1.4	7.76	6.91	5.43	0.07	0.99	12.34	0.79
Co1262-517 (FL)	1	51.87	1.94	17.78	9.86	0.15	2.69	4.89	6.01	3.77	0.67	0.36	9.78	0.63
	2	53.84	1.78	19.37	7.47	0.24	1.85	4.6	6.77	3.42	0.37	0.29	10.19	0.51
	3	54.4	1.72	18.7	6.42	0.15	2.38	4.97	5.69	4.58	0.59	0.4	10.27	0.80
	4	53.96	1.89	17.41	8.18	0.23	2.83	5.45	5.58	3.62	0.46	0.38	9.2	0.65
	5	53.4	1.82	17.69	8.53	0.24	3.07	4.97	5.46	4.01	0.52	0.29	9.47	0.73
	6	55.25	1.8	18.1	7.31	0.33	2.23	4.36	6.03	3.91	0.39	0.28	9.94	0.65
	7	53.93	1.44	18.44	7.81	0	3.4	6.36	5.28	2.86	0.31	0.17	8.14	0.54
	8	53.87	1.5	17.87	7.94	0	3.48	6.24	5.54	3.01	0.35	0.2	8.55	0.54
	9	54.01	1.91	17.46	8.17	0.3	2.75	5.55	5.4	3.68	0.45	0.31	9.08	0.68
	10	53.36	1.74	18.26	7.62	0.27	3.37	5.82	5.73	3.15	0.35	0.33	8.88	0.55
	11	54.15	1.54	18.71	7.71	0.1	3.26	5.79	5.01	3.15	0.35	0.22	8.16	0.63
Co1262-709 (Mercato)	1	51.87	1.94	17.78	9.86	0.15	2.69	4.89	6.01	3.77	0.67	0.36	9.78	0.63
	2	53.84	1.78	19.37	7.47	0.24	1.85	4.6	6.77	3.42	0.37	0.29	10.19	0.51
	3	54.4	1.72	18.7	6.42	0.15	2.38	4.97	5.69	4.58	0.59	0.4	10.27	0.80
	4	53.96	1.89	17.41	8.18	0.23	2.83	5.45	5.58	3.62	0.46	0.38	9.2	0.65
	5	53.4	1.82	17.69	8.53	0.24	3.07	4.97	5.46	4.01	0.52	0.29	9.47	0.73
	6	55.25	1.8	18.1	7.31	0.33	2.23	4.36	6.03	3.91	0.39	0.28	9.94	0.65
	7	53.93	1.44	18.44	7.81	0	3.4	6.36	5.28	2.86	0.31	0.17	8.14	0.54
	8	53.87	1.5	17.87	7.94	0	3.48	6.24	5.54	3.01	0.35	0.2	8.55	0.54
	9	54.01	1.91	17.46	8.17	0.3	2.75	5.55	5.4	3.68	0.45	0.31	9.08	0.68
	10	53.36	1.74	18.26	7.62	0.27	3.37	5.82	5.73	3.15	0.35	0.33	8.88	0.55
	11	54.15	1.54	18.71	7.71	0.1	3.26	5.79	5.01	3.15	0.35	0.22	8.16	0.63
	12	54.15	1.54	18.71	7.71	0.1	3.26	5.79	5.01	3.15	0.35	0.22	8.16	0.63

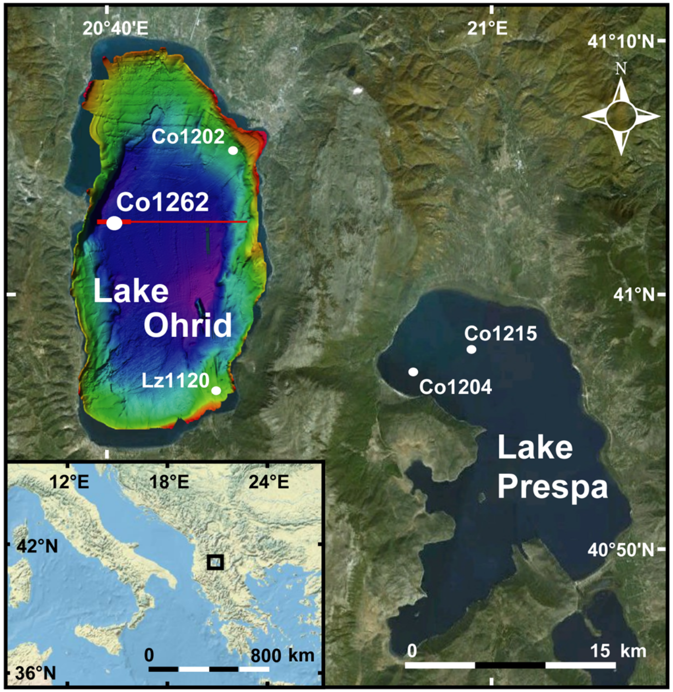

Fig. 1. Map of the northern Mediterranean region showing the location of lakes Ohrid and Prespa. The bathymetry of Lake Ohrid is adapted from Lindhorst et al. (2012a). White dots indicate coring locations Lz1120 and Co1202 from field campaigns in 2005 and 2007 in the southeastern and northeastern part of Lake Ohrid, and the new coring location Co1262 in the western part of the lake, as well as coring locations Co1204 and Co1215 from former field campaigns at Lake Prespa. The red line in Lake Ohrid indicates the location of the multichannel seismic (entire line) and hydro-acoustic (thick line) profiles shown in Figs. 2 and 3.

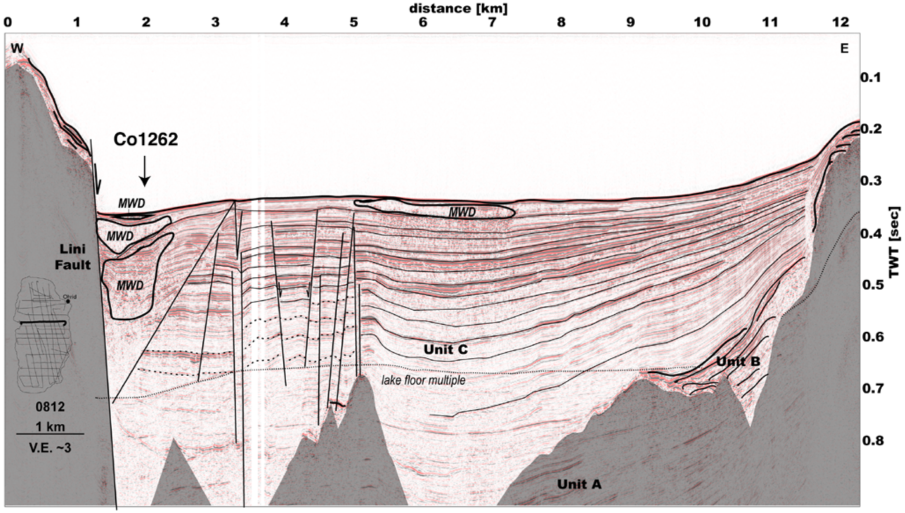

Fig. 2. Interpreted multichannel seismic profile taken by a Mini GI Gun across Lake Ohrid with the Lini Fault in the west (modified from Lindhorst et al., 2012a). Gray parts indicate bedrock. The approximate coring location Co1262 is indicated by an arrow. Transparent sediment bodies indicating mass wasting deposits (MWD).

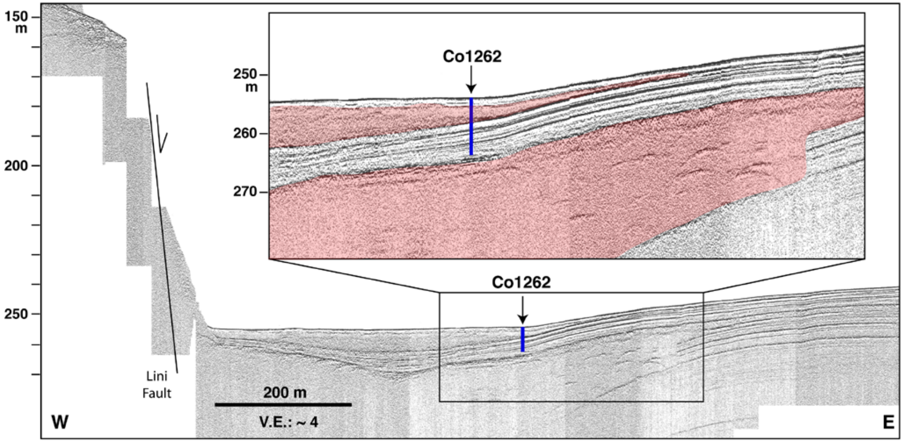

Fig. 3. Uninterpreted and interpreted (insert) hydro-acoustic profile in front of the Lini peninsula (see Fig. 1 for exact location). The profile was obtained with an Innomar transducer. The blue bar indicates the coring location Co1262 and transparent sediment bodies (red coloured in the interpreted insert) indicate mass wasting deposits.

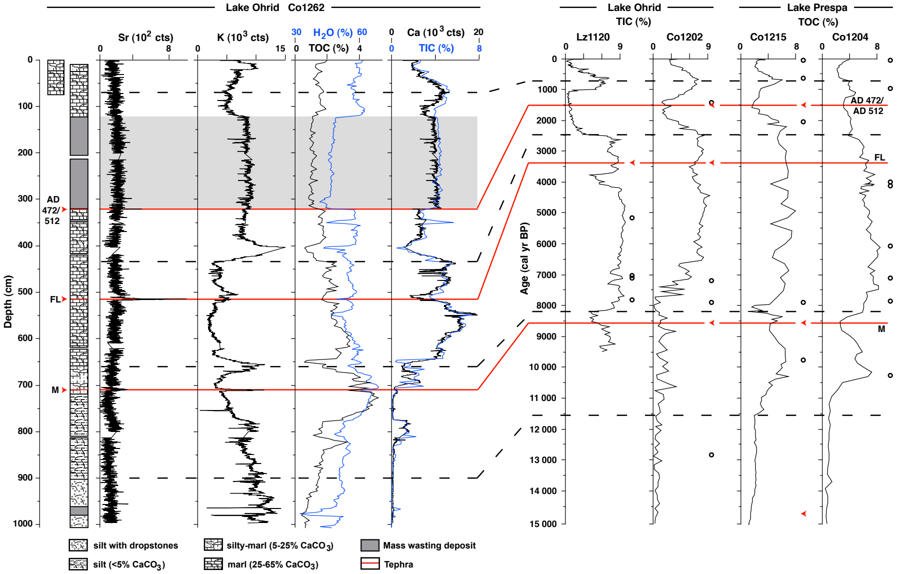

Fig. 4. Lithology, water content, and geochemical composition of core Co1262 from Lake Ohrid. Note that the entire sediment succession appears massive due to bioturbation. The gaps in XRF scanning data (Sr, K, and Ca counts) are due to non-overlapping cores. These gaps are smaller in water content, TIC, and TOC, as core catcher samples are included. The cross correlation with cores Lz1120 and Co1202 from Lake Ohrid and cores Co1215 and Co1204 from Lake Prespa (black dashed lines) can be used for an age estimation of core Co1262. Red arrows and lines indicate tephras and cryptotephras (472/512 AD, FL eruption, and M = Mercato); round circles indicate radiocarbon dated horizons in cores Lz1120 and Co1202 from Lake Ohrid and cores Co1215 and Co1204 from Lake Prespa.

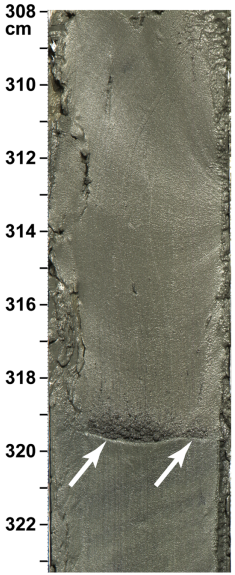

Fig. 5. Photography of the core Co1262, from ca. 308 to 322 cm depth, where the 472/512 AD tephra as thin, grayish band (arrow) underlies a mass waste deposit with a sandy basis.

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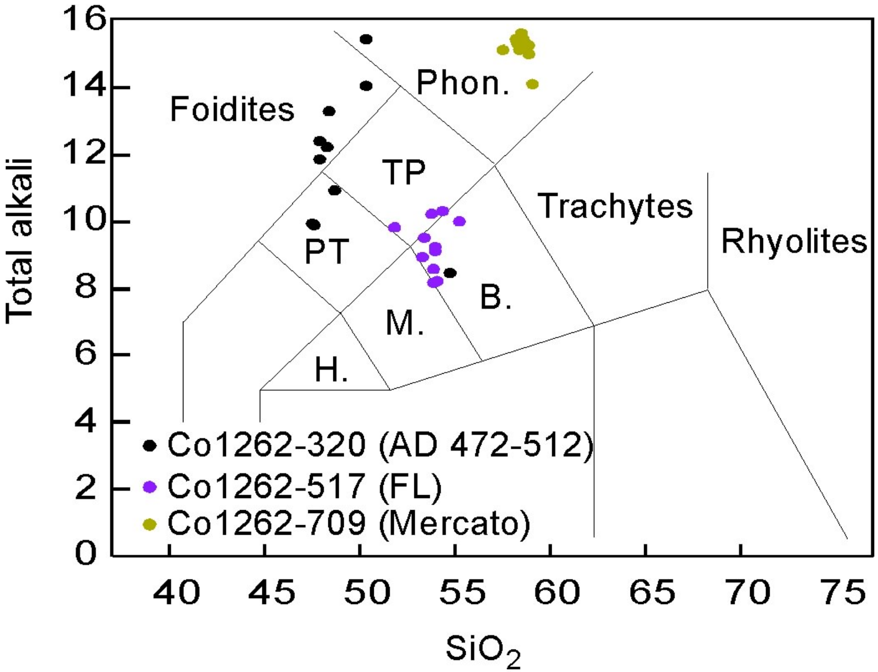

Fig. 6. Classification of tephras and cryptotephras recognised in core Co1262 from Lake Ohrid by means of the total alkali vs. silica diagram (TAS, Le Bas et al., 1986). The raw data of tephras and cryptotephras is given in Table 1.