Quaternary International 486 (2018) 44–56

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Discrimination of Holocene tephra units in Lake Van using mineral magnetic analysis

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ARTICLE INFO

Article history:
Received 15 September 2017
Received in revised form
14 March 2018
Accepted 15 March 2018
Available online 30 March 2018

Keywords:
Lake Van
Magnetic properties
Holocene
Tephra
Environmental magnetism
Geochemical

ABSTRACT

Detailed magnetic analysis of the four sediment cores from Lake Van, Eastern Turkey dating back to 9.4 cal ka BP were carried out for discriminating and correlating tephras and laminated sediments in four different cores. Six tephra units (T0, T1, T2, T3, T4 and T5) with distinct magnetic properties were identified in the cores. The tephra units are characterized by ferrimagnetic material, with a grain size in the pseudo single domain (PSD) range. There is no significant correlation between magnetic susceptibility peaks of the different tephra units except for the tephra T1 and T2. On the contrary ARM profiles show significant correlations as remanent magnetization indicators. The tephra units T1 and T2, have a higher magnetic susceptibility and a higher intensity of remanent magnetization, and finer grain size than the other tephra units. The results suggest that there is a clear difference between the magnetic properties of the different tephra units and the lake sediments. Our findings show that also differential deposition of volcanic material including magnetic mineral occurs during the transport with distance from the volcanic source.

1. Introduction

The term “tephra” comes from the ancient Greek word *τέφρα (ash)* which is the pyroclastic solid material ejected into the air by an erupting volcano and then settling down in the surrounding area. It is possible to find tephra up to thousand kilometers from its volcanic source in the case of Plinian eruptions. Tephra units are useful time markers in sedimentary sequences and are useful for stratigraphic correlation over wide regions, once their compositions are matched with the source volcanoes, and ages are ascertained by their chronostratigraphic position, or by Ar/Ar dating. Such a use of tephra in stratigraphy is called tephrochronology. Establishing the tephrochronology of depositional records is important in mapping the geographical extent of a particular volcanic ash fallouts, and studying the impact of volcanic events on natural ecosystems and human communities (Develle et al., 2009; Weiss et al., 1993; Eastwood et al., 1999, 2002; Grattan, 2006; De Klerk et al., 2008; Wulf et al., 2002, 2004; Çağatay et al., 2015).

Volcanic eruptions have always played a crucial role in the evolution of human civilizations and societies in western Anatolia, Mediterranean and Mesopotamia (Grattan, 2006; Issar and Zohar, 2007; Cullen et al., 2000; Weiss et al., 1993; Di Vito et al., 2009 Marinatos, 1939; Friedrich, 2013; Pararas-Carayannis, 1974; Mellaart, 1967). Detailed tephrochronological studies from these areas have provided important information about timing of and source of the eruptions. However, we still have insufficient knowledge of the distribution and effect of the eruptions on major civilization such as Urartu (860–590 BCE), Seljukian (1100–1400 AD), Byzantium (395–1453 AD) and Ottoman (1200–1900 AD) in the Eastern Anatolia.

Identification of tephra units in sediment core sequences and soil profiles and their assignment to their source and time of eruption allows them to be used for correlating and dating of paleoenvironmental events in the region where traditional dating methods cannot be applied because of the lack of suitable datable material and reservoir age problems in the case of the radiocarbon method. Differences in mineralogy, concentration, and grain size of the magnetic particles which control the values of the magnetic

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https://doi.org/10.1016/j.quaint.2018.03.012
1040-6182/

parameters can be used to identify and characterize different sedimentary units and their source rocks (Evens and Heller, 2003). In particular, mineral magnetic analyses which include measurements of magnetic concentrations and grain sizes have proven to be very useful in identification and differentiation of different tephra units since such units often have enhanced and different magnetic components compared to their host deposits and to each other. Therefore, it is important to find and characterize ferrimagnetic component of tephra deposits that are successfully used in dating of lacustrine and marine sediments (Brewster and Barnett, 1979; Oldfield et al., 1980, 1983; Robinson, 1986; Robertson, 1993; Lozano-Garcia and Ortega-Guerrero, 1994; Van den Bogaard et al., 1994; Pawse et al., 1998; Gonzalez et al., 1999; Dunsheng et al., 2004; Lagroix et al., 2004; Xia et al., 2007; Vogel et al., 2010).

Terminal lakes with large drainage areas, such as Lake Van in Eastern Turkey, are often characterized by high organic and inorganic carbon accumulation rates and are therefore extremely sensitive to past environmental changes (e.g., Litt et al., 2009; Litt and Anselmetti, 2014). Being located close to several Quaternary volcanic centres such as Nemrut, Suphan and Tendurek (Fig. 1), Lake Van's annually laminated (varved) sedimentary sequence is intercalated with frequent tephra units and hence provides an important archive of volcanic activity and paleoenvironmental reconstructions (Kempe and Degens, 1978; Landmann et al., 1996a, b; Wick et al., 2003; Litt et al., 2009; Sumita and Schmincke, 2013a, b; Stockhecke et al., 2012, 2014; Çağatay et al., 2014). In these studies, the chronology was mainly based on varve counting and tephrochronology. Radiocarbon dating of the lake material was an inadequate method for dating the bulk sedimentary organic carbon in Lake Van sediments because of the reservoir (hard-water) effect, which is variable between 2.5 and 3.3 ka for the last 8 ka (Makaroğlu et al., 2016), and the 50 ka upper limit of the method.

The volcanic source of the tephra units in Lake Van sediments are mainly from the Nemrut and Süphan volcanoes ejecting magma of paralkaline and calc-alkaline affinities, respectively (Landmann et al., 2011; Sumita and Schmincke, 2013a, b; Schmincke et al., 2014).

The first study on tephra units in Lake Van sediments was performed by Kempe (1977). Landmann et al. (1996a), who made the detailed geochemical analysis of 12 tephra units in two cores from the Tatvan Basin and dated them by varve chronology. Later, Landmann et al. (2011) refined the chronology of the Lake Van sediments and the tephra units, studied by Landmann et al. (1996a)

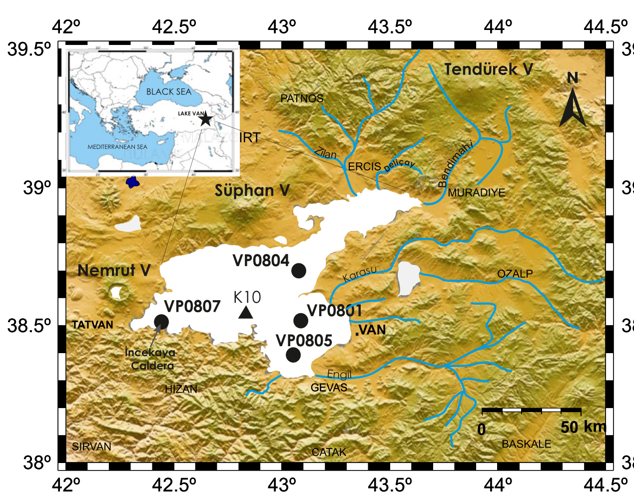

Fig. 1. Location of studied core sites VP0801, VP0804, VP0805 and VP0807 (black circles), core locations of Landmann et al. (2011) (triangle). The inset map shows location of Lake Van in eastern Turkey.

and Landmann and Kempe (2005). According to Landmann et al. (2011), over the last 15 kyr, the volcanic activity during the period from 2.6 to 7.2 kyr BP originated from Nemrut Volcano but the source for the tephra units deposited from 11.9 to 12.9 kyr BP remained unidentified. These earlier studies were followed by others covering the late Pleistocene-Holocene period (Litt et al., 2009; Makaroğlu, 2011; Schmincke et al., 2014; Vigliotti et al., 2014; Makaroğlu et al., 2016). Litt et al. (2009) documented the stratigraphy and tephra units in sediment cores from the Ahlat ridge covering the late Glacial-Holocene period. Schmincke et al. (2014) identified six peralkaline rhyolitic tephra units (V1-V6) of Nemrut Volcano origin in the Holocene Lake Van sediments. These units consist predominantly of anorthoclase, hedenbergite, and lesser amounts of augite, Fe-rich olivine and minor quartz and chevkinite. Vigliotti et al. (2014) found that the tephra units and the volcanoclastic material deposited over the last 350 ka showed the highest magnetic concentrations whereas the minimum values occurred in the laminated clayey silt. This difference in the magnetic properties was also the finding of Makaroğlu (2011), which is due to the presence of carbonate laminae in the varved Lake Van sediments with very low magnetic mineral concentrations compared to the tephra units with ferromagnetic minerals (e.g., Baumgarten et al., 2014; Landmann et al., 1996a; Stockhecke et al., 2012; Çağatay et al., 2014). This difference in the magnetic properties can be used to an advantage for detecting the tephra units in lake sediments. Makaroğlu et al. (2016) identified the tephra units previously varve-dated by Landmann et al. (2011) and determined the radiocarbon reservoir age of Lake Van over the last 8.4 ka BP, using the varve dates and radiocarbon ages obtained from total organic carbon.

In this paper, we present the first 9.4 ka-long environmental magnetic record of Lake Van sediments and use it to detect and characterize tephra units in four piston cores recovered from different parts of the lake in 2008 (Fig. 1, Table 1). We analyzed the magnetic properties (magnetic susceptibility, χ_{LF}, χ_{ARM}, and hysteresis values) and μ-XRF elemental composition (K, Zr) of the four piston cores. Two of the cores were previously studied by Makaroğlu et al. (2016) for determination of radiocarbon reservoir ages and discussion of the causal variation of the results, based on ^{14}C, elemental and isotope analyses of total organic matter. The objectives of this study are to characterize the magnetic properties of the tephra units deposited in different parts of Lake Van over the last 9.4 ka and relate the properties to the distance from the main volcanic source.

2. Regional setting

Lake Van which is located on the East Anatolian Plateau in eastern Turkey is the fourth largest soda Lake in the world and the largest lake in Turkey (Fig. 1). Lake waters have a salinity of 21.4‰ and a pH of 9.81 (Landmann et al., 1996a; Kempe et al., 2002; Reimer et al., 2009). The lake basin formed 600 ka ago, when the outflow to the Muş Basin was blocked by the growth of Nemrut Volcano (Yılmaz et al., 1998; Çukur et al., 2014; Litt et al., 2014). The lake is surrounded by Quaternary volcanoes (Nemrut, Süphan, Tendürek, etc) that appear to have been localized on north–south tensional openings formed under the north–south shortening deformation (Yılmaz et al., 1998). The volcanoes across eastern Anatolia are related to the tectonic collision (Keskin, 2007), and post-collisional volcanism at 8–6 Ma (Sumita and Schmincke, 2013a). The Nemrut volcanic center is located close to the western end of Lake Van (Fig. 1). It is the only volcano of Anatolia, which produced a historically recorded explosive eruption in 1441 CE (Oswalt, 1912). Nemrut volcano produces alkaline magma characterized by large ionic lithophile and high filed strength elements

Table 1
Details of studied cores in Lake Van.

Core name	Location	Water depth (m)	Core depth (mblf[a])	The number of samples for magnetic analysis
VP0801	N38 31 48.6 E43 09 04.7	80	4.57	238
VP0804	N38 40 15.3 E43 07 16.9	86	3.55	197
VP0805	N38 20 56.8 E43 02 57.5	70	3.10	162
VP0807	N38 30 55.2 E42 25 35.2	65	4.62	117

[a] mblf: metres below lake floor.

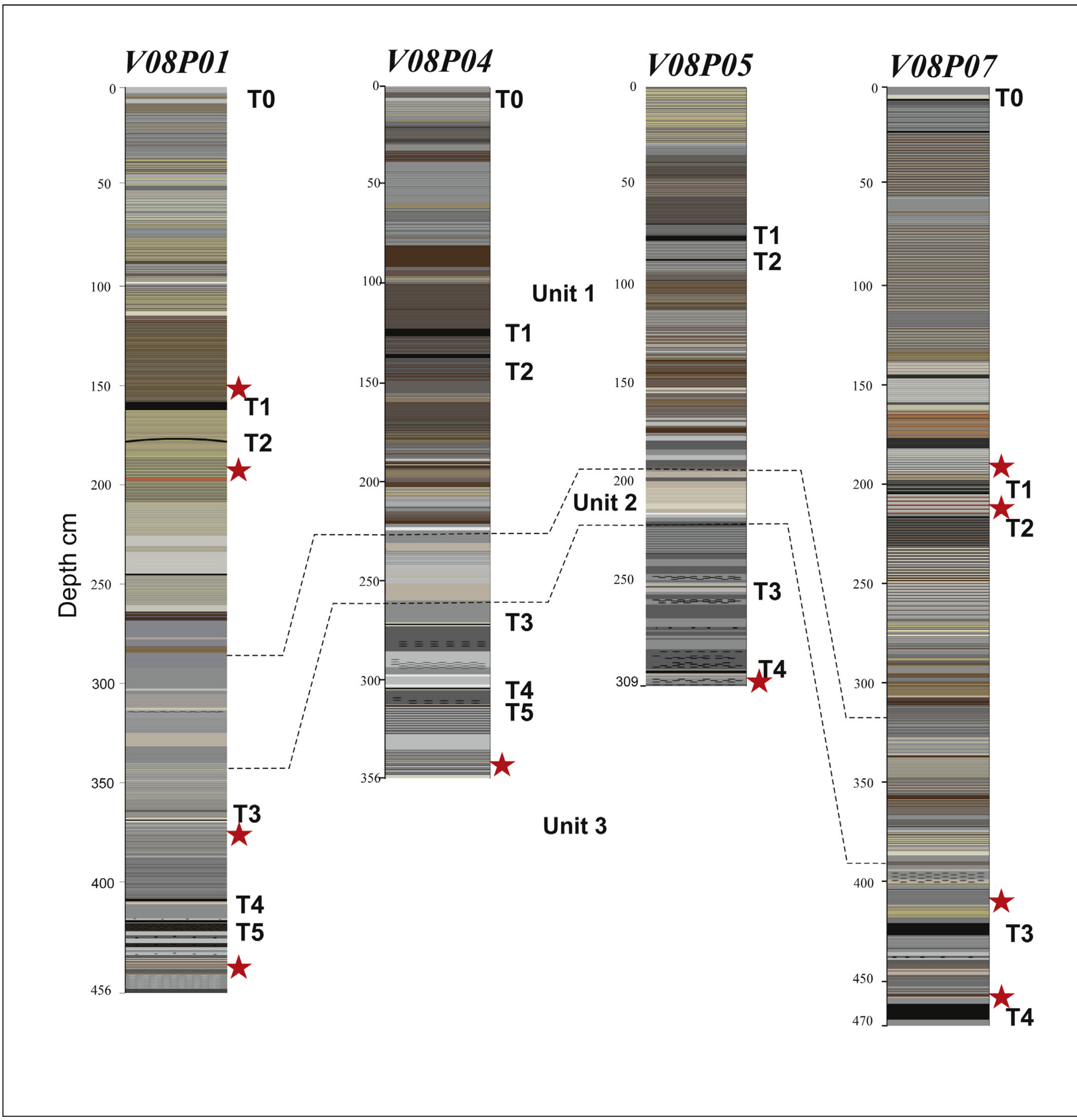

Fig. 2. Lithostratigraphic correlation of studied cores from Lake Van, showing tephra units T0-T5 (in black) and AMS ^{14}C dated samples (stars). For description of lithological units, see text and Makaroğlu et al. (2016).

such as K, Zr, and Nb (Schmincke et al., 2014; Çağatay et al., 2014). Süphan volcano is situated to the immediate north of Lake Van (Fig. 1). The volcanic center is located at the intersection of two major fault zones, trending NNE–SSW and WNW–ESW, and erupted magma of calcalkaline character (Schmincke et al., 2014). Tendürek Volcano is an isolated, low relief, volcanic center which reaches over 3500 m in height and covers an area of about 650 km^2.

The sediments under Lake Van extending back to 14,570 a, BP were previously dated by varve counting, and studied for climate variability and lake level changes (Landmann et al., 1996a, 2011; Landmann and Kempe, 2005; Reimer et al., 2009). Late Glacial-Holocene chronostratigraphy and sedimentology of Lake Van was emphasised by Makaroğlu et al. (2016). We consider the varve ages of Landmann et al. (2011) to be reliable for at least the last 8 ka, during which there was no major regression. Another varve counting on Lake Van sediments was performed by Damcı and Cağatay (2016), using an automated algorithm and digital X-ray radiographs of cores. This study showed that a 5 m long core extends back to 8500 BP, considering that the varve structure of the Lake Van sediments consists of three laminae seasonally deposited in a year (Kempe et al., 2002; Stockhecke, 2008).

3. Materials and methods

3.1. Coring and sampling

After a seismic survey conducted in 2008, four different locations were selected for coring in Lake Van. Four piston cores, VP0801, VP0804, VP0805 and VP0807 with 10 cm in diameter were recovered from water depths varying between −65 m and −80 m (Fig. 1; Table 1). After coring, the cores were cut in the field into 1.5 m sections and were then transport for the analysis in laboratory in Eastern Mediterranean Center for Oceanography and Limnology (EMCOL) of Istanbul Technical University (ITU). All cores were stored at a 4 °C in a cold room before description and various analyses. In the laboratory, the cores were split in two halves, lithologically described and sampled for mineral magnetic and geochemical analysis. For mineral magnetic analysis, total of 714 sub-samples were taken continuously along the cores into 6.0 cm^3 plastic boxes (internal dimensions 20 × 20 × 15 mm).

3.2. Magnetic analysis

Low field magnetic susceptibility (χ) of samples was measured with a Kappabridge susceptibility meter. ARM was imparted using a DTECH alternating-field demagnetizer with a peak alternating field of 100 mT and a bias DC field of 0.05 mT χ_{ARM} was calculated by dividing the ARM intensity by the used steady field strength. All remanence measurements were performed using the 2G-SQUID magnetometer. Hysteresis loops, IRM acquisition curves and back field demagnetization curves were measured for selected samples by vibrating samples magnetometer (VSM 3900) with a maximum field of 1 T. From the hysteresis loops, corrected for paramagnetic contribution, saturation magnetization (M_s), saturation remanence magnetization (M_{rs}), coercivity (B_c) and remanent coercivity (B_{cr}) were determined. All remanence measurements were performed at the Solid Earth Geophysics Laboratory of the University of Helsinki. Thermomagnetic behavior of the samples was determined using Kappabridge MFK1-FA, equipped with CS-3 temperature control system, with a maximum temperature of 700 °C, and a temperature ramping rate of 2 °C/min in argon environment to avoid samples becoming oxidized during heating. Thermomagnetic analysis was performed at the paleomagnetic laboratory of GFZ, Potsdam. After all magnetic measurements samples were dried at 40 °C and weighted to determine mass specific magnetic parameters.

χ is roughly proportional to the concentration of ferrimagnetic and paramagnetic minerals within the sample. ARM is interpreted principally in terms of variations in the overall concentration of ferrimagnetic minerals, but it also reflects changes in grain size distribution and changes in the relative amounts of different ferrimagnetic minerals (Thompson and Oldfield, 1986). The intensity of ARM responds sensitively to fine grained ferromagnetic particles of stable single domain size (King et al., 1982; Maher, 1988). Thus, χ_{ARM} indicates the concentration of fine ferrimagnetic grains (King et al., 1982). The ratio, χ_{ARM}/χ generally increases with decreasing grain size and indicates changes in magnetite grain size if the magnetic mineralogy is dominantly magnetite and significant amounts of very fine SP grains are absent (King et al., 1982; Evens and Heller, 2003). The hysteresis parameters (Hcr/Hc and Msr/Ms), calculated after removal of the paramagnetic component of the magnetization, are plotted on a Day plot which has been widely used to determine the domain state of magnetic minerals (Day et al., 1977; Dunlop, 2002). The thermomagnetic measurement aids the identification of the magnetic mineralogy present in a sample, because the mineral composition controls the Curie temperature.

3.3. Geochemical analysis

μ-XRF analysis was made on half cores at 200 μm resolution using an Itrax XRF Core scanner equipped with XRF-EDS at the Core Analysis Laboratory of EMCOL (Thomson et al., 2006). A fine focus Mo X-ray tube was used as the source. The X-ray generator was operated at 40 kV and 50 mA, and a counting time of 10 s. Elemental concentrations were recorded as counts per second (cps).

3.4. Radiocarbon analysis

Samples for the AMS radiocarbon dating were collected close to the tephra units. A total of 10 samples with total organic carbon (TOC) contents higher than 1.5 wt % were used for AMS radiocarbon analyses of the TOC fractions at the Radiocarbon Dating Laboratory of Illinois State Geological Survey. The results were compared with the varve dates of Landmann et al. (2011) and the radiocarbon reservoir ages were calculated, using the procedures explained by Makaroğlu et al. (2016).

4. Results

4.1. Lithology

All cores visually consist of three lithological units labelled as 1, 2, and 3 from top to the bottom based on their color and

Table 2
Lake Van AMS radiocarbon data.

Lab Code ISGS#	Depth (mblf)	Uncal. AMS ^{14}C age (yr BP)
Core VP0801 (80 m water depth)		
A1576	1.54	5185 ± 30
A1574	1.94	5540 ± 25
A1575	3.77	8400 ± 35
A1577	4.44	10430 ± 45
Core VP0804 (86 m water depth)		
A1578	3.53	11825 ± 50
Core VP0805 (70 m water depth)		
A1579	3.08	9360 ± 45
Core VP0807 (65 m water depth)		
A1580	1.92	4980 ± 25
A1581	2.17	5400 ± 25
A1582	4.18	7920 ± 35
A1583	4.64	9270 ± 35

Table 3
Tephra units in the studied cores and their correlation with the tephra units dated by varve-counting by Landmann et al. (2011) (mblf: meters below lake floor).

Core location of tephra units					Tephra Age	
Tephra unit	VP0801 mblf	VP0804 mblf	VP0805 mblf	VP0807 mblf	Tephra unit	Varve age (yr BP)
T0	0.38	0.33	–	5.8	**V-1**	700 [a]
T1	1.61	1.27	0.81	2.05	**A**	2607 [b]
T2	1.78	1.40	0.92	2.18	**B**	2737 [b]
T3	3.72	2.78	2.62	4.25	**C**	6005 [b]
T4	4.13	3.03	3.04	4.68	**D**	6888 [b]
T5	4.22	3.11	–	–	**E**	7192 [b]

[a] Stockhecke et al., 2014.
[b] Landmann et al., 2011.

sedimentary structures (Fig. 2). The uppermost unit 1 is composed of reddish brown, yellow to grey, finely and distinctly laminated mud. Unit 2 is a predominantly beige, with some intervening grey laminations and bands, and unit 3 is commonly grey to dark grey with less distinctly laminated and banded structure (Fig. 2). The cores also include tephra units labelled T0-T5, which are describe separately in section 4.2.

Cores VP0801 and VP0807 were described by Makaroğlu et al. (2016). The 3.56 m long Core VP0804 was recovered at 86 m water depth in Erciş Gulf, 4 km offshore from the eastern coast of the lake (Fig. 1). Its location is influenced by the Zilan, Deliçay and Bendimahi rivers near Erciş. The core consists of unit 1 with 2.2 m thickness, unit 2 with 0.4 m thickness and Unit 3 is 0.96 m thick (Fig. 2). The 3.09 m long Core VP0805 was recovered from ~70 m-deep, in the same basin with core VP0801. Its location is influenced by Engil river, close to Gevaş, 5 km offshore in southern coast of the lake. The core consists of lithological units from top to the base 1.7 m thick unit 1, 0.55 m is Unit 2 and 0.84 m thick unit 3. Core VP0807 was recovered from a ~65 m-deep, rounded volcanic edifice, Incekaya Crater with ~800 m in diameter in the southwest of the lake, 20 km east of the Nemrut Volcano (Fig. 1). Compared to other cores, this 4.7 m long core consists mainly of reddish brown, dark brown to beige muds with minor grey laminated intervals, having more distinct and thin (sub-mm) laminated structure (Fig. 2). The lithology of all cores indicates continuous sedimentation without any disconformities.

4.2. Tephra units

We identified a total of six tephra units (T0, T1, T2, T3, T4, and

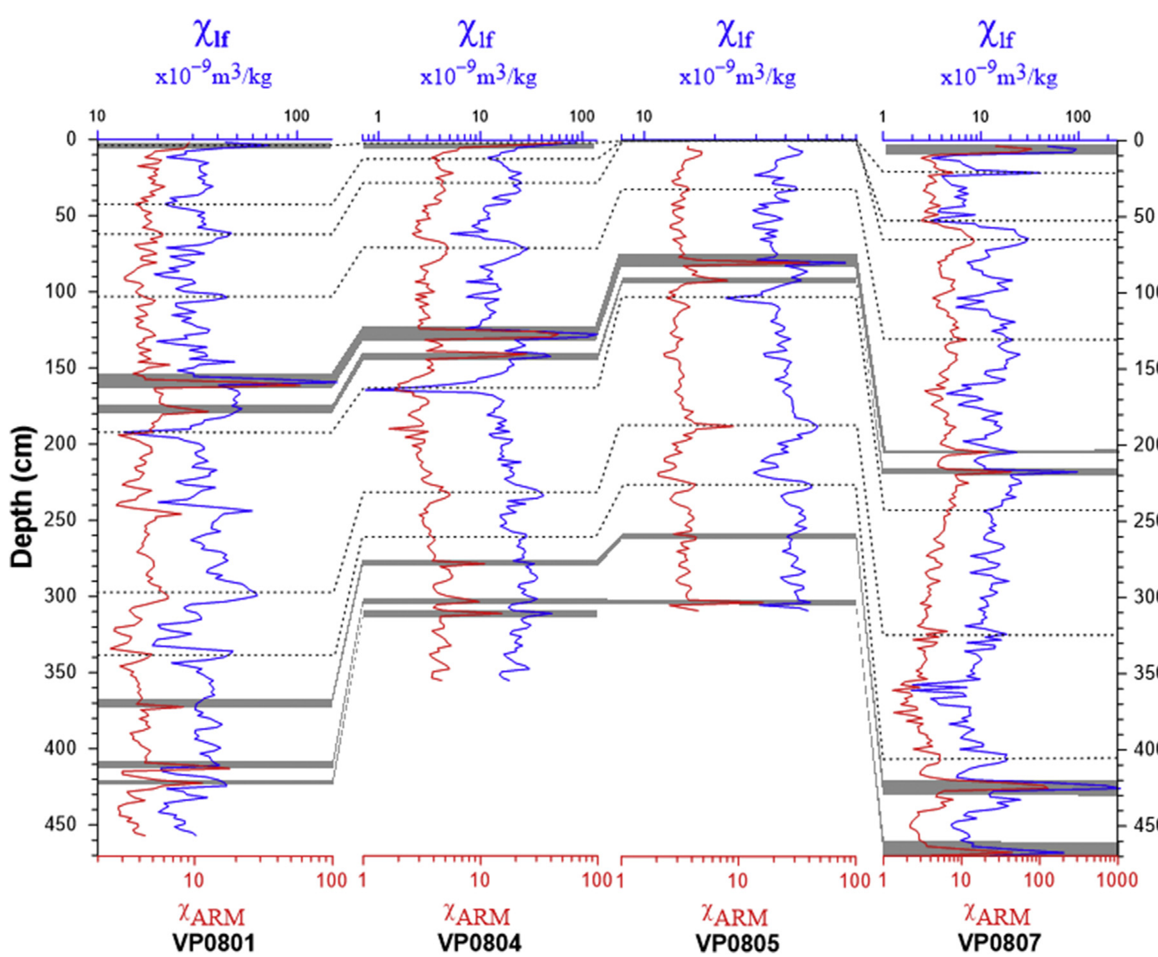

Fig. 3. Comparison χ_{LF} and χ_{ARM} values of the cores VP0801, VP0804, VP0805 and VP0807. Dashed lines indicate correlative features. Grey lines indicate the tephra units.

T5) in the cores, using μ-XRF core scanner elemental analysis, magnetic mineral analysis, and microscopic smear-slide examination (Table 3; Figs. 2–5). The tephra units were recognized by their distinct magnetic properties, μ-XRF elemental composition (Fig. 4), and the presence of volcanic glass. Tephra unit T0 is not visible to the eye and it is missing in core VP0805. Tephra units T1, T2, and T3 are visible in all cores, whereas tephra T4 is visible only in core VP0807. Tephra units T4 and T5 are present as cryptotephra (non-visible) in the lowermost part of cores VP0801, VP0804 and VP0805. Unit T5 is missing in Core VP0807 that fails to intercept it due to the high sedimentation rate at this core site. Tephra units T1 and T2 are thicker (4 cm and 1 cm, respectively) and coarser (granule to coarse sand size) in Core VP0801 than in the other cores. They are brown in color. The 3.6 cm-thick T3 tephra is brown, granule to coarse sand size in Core VP0807, whereas in the other cores it is about 1 cm-thick, dark grey, medium-grained sand size and sandwiched between beige laminated sediments. Units T4 and T5 are 2 cm thick, dark grey in all cores and finer grained (medium-grained sand size) than the younger tephra units.

4.3. Chronology

A total of ten radiocarbon ages from the bulk organic matter, mostly picked around tephra units, are listed in Table 2. The radiocarbon chronology and the reservoir ages for Cores VP0801 and VP0807 were reported by Makaroğlu et al. (2016). In cores VP0804 and VP0805, one radiocarbon date each was obtained from the core bottoms (Fig. 2). In cores VP0801 and VP0807, the radiocarbon ages linearly increase in age with depth, without any age reversals (Table 2). The radiocarbon dates from cores VP0804 and VP0805 are also consistent with the other cores according to their lithologies and tephra depths.

The tephra unit T0 in cores VP0801, VP0804 and VP0807 is correlated with the tephra units “tephra 1” of Litt et al. (2009) and the tephra unit V1 of Stockhecke et al. (2014). The tephra units T1 to T5 in our cores are correlated with the previously varve-dated tephra units A to E of Landmann et al. (2011) (Table 3). According to the published data, the tephra units T0-T5 have ages of 700, 2607, 2737, 6005, 6888, and 7192 yr BP, respectively (Landmann et al., 2011; Stockhecke et al., 2014) (Table 3).

4.4. Magnetic properties

The depth profiles of magnetic parameters associated with magnetic grain size parameter (χ_{ARM}/χ_{LF}) and concentration of ferrimagnetics-bearing minerals (χ_{LF}, ARM) in Lake Van cores VP0801, VP0804, VP0805 and VP0807 are shown in Fig. 4. The sediments from Lake Van are characterized by low χ_{LF} values ranging from ~1 to ~250×10^{-9} m^3/kg. Mean susceptibility (χ_{LF}) value of Lake Van sediments is 30×10^{-9} m^3/kg except for the tephra units which reveal clearly enhanced susceptibilities of 50 and 250×10^{-9} m^3/kg (Figs. 3 and 4). According to correlation of the cores as based of χ_{LF}, the sedimentation rates from slowest to fastest occur in cores VP0804, VP0805, VP0801 and VP0807, respectively. All cores contain distinctive and similar variations in χ_{LF} and χ_{ARM} (Fig. 3). A number of peaks on magnetic parameters are observed at variable depths that are related to the tephra units (Fig. 4). In particular, there are distinct ARM and χ_{ARM}/χ peaks observed in all cores. The tephra unit T0 has high magnetic susceptibility and ARM value in all cores except for core VP0805. Tephra units T1 and T2 roughly coincide with the visible tephra units in the cores. χ_{ARM}/χ profiles are highly correlated between the cores compared to those of χ_{LF} (Fig. 4). The magnetic parameters of cores VP0801, VP0804, VP0805 are highly comparable with very similar χ_{LF} variations. Core VP0807, located in the central of the

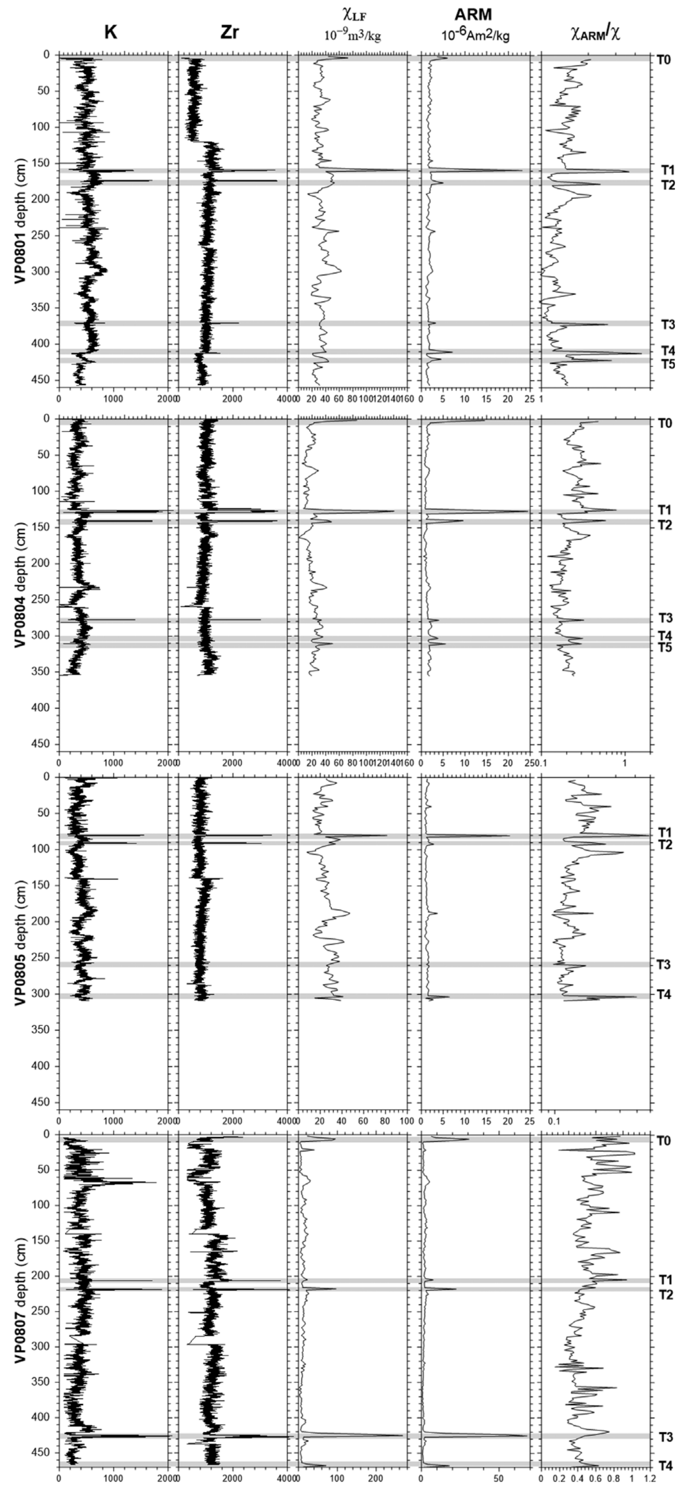

Fig. 4. Profiles of μ-XRF K and Zr and magnetic properties of studied cores. Grey bars show the tephra units (T0-T5).

İncekaya Crater (Fig. 1), show slightly higher χ_{LF} values in both the laminated sediments and the tephra layers compared to the those in the other cores (Fig. 3).

Bivariate plots of magnetic parameters are used to qualitatively identify magnetic mixtures. On a biplot of χ_{ARM} against χ_{LF} (King et al., 1982), the tephra and laminated sediments in Lake Van are separated in two different clusters (Fig. 5).

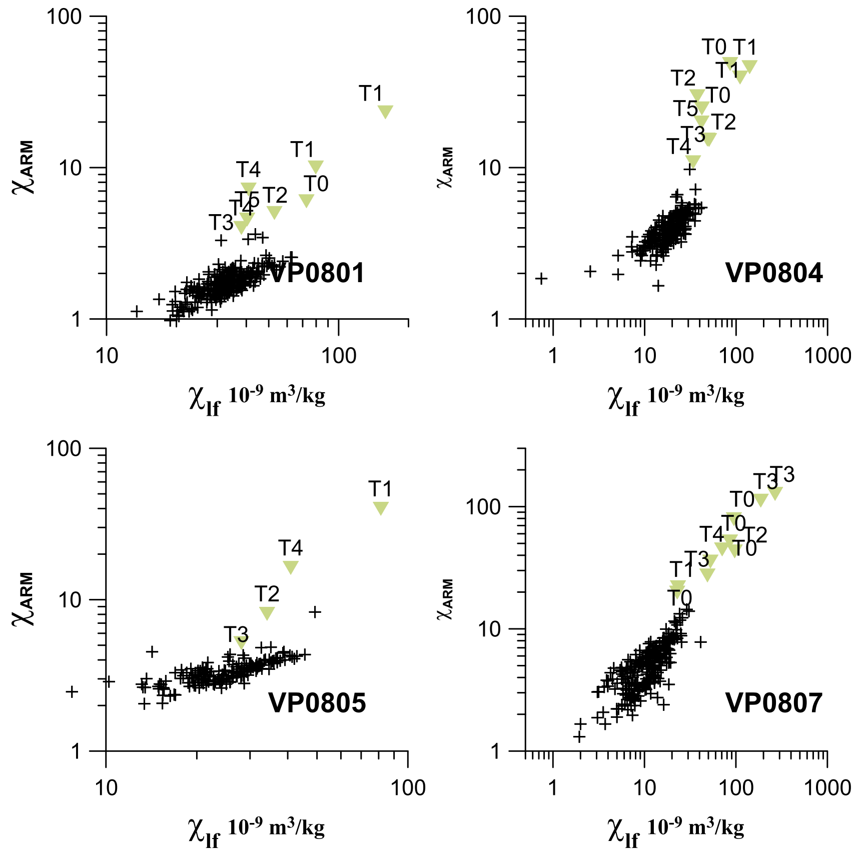

Fig. 5. Bivariate plots of the χ versus χ_{ARM}. Triangles show tephras, pluses show laminated sediments.

Table 4
Hysteresis parameters of Lake Van sediments.

	sample name	core depth (cm)	H_C (mT)	M_{rs} (mAm^2/kg)	M_S (mAm^2/kg)	Hc_R (mT)	Hr/Hcr	Mrs/Ms
Laminated sediments	VP1.1.54	101.76	14.18	0.178	0.0001	34.542	2.44	0.15
	VP1.3.17	297.6	14.77	0.152	0.999	36.483	2.47	0.15
	VP1.3.25	312.96	17.02	0.151	0.431	35.269	2.07	0.35
	VP1.3.37	336	14.53	0.115	0.701	34.525	2.38	0.16
	VP1.4.15	439.68	14.05	0.091	0.576	28.510	2.03	0.16
	VP4.1.31	51.46	9.66	0.212	1.525	29.985	3.10	0.14
	VP4.2.75	136.87	15.21	0.104	0.576	30.165	1.98	0.18
	VP4.3.7	272.32	14.14	0.106	0.655	25.553	1.81	0.16
	VP5.1.15	28.8	14.64	0.171	1.086	33.903	2.32	0.16
	VP5.2.23	186.01	17.31	0.336	1.188	34.341	1.98	0.28
	VP5.2.43	224.21	14.23	0.094	0.617	30.323	2.13	0.15
	VP7.1.35	68.49	12.61	0.652	4.197	61.625	4.89	0.16
	VP7.2.27	186.5	10.96	0.353	2.633	52.014	4.75	0.13
	VP7.3.15	311.5	15.89	0.203	0.829	53.430	3.36	0.24
	VP7.3.67	407	31.13	0.154	0.746	80.258	2.58	0.21
	Mean		**15.35**	**0.33**	**0.568**	**40.06**	**2.68**	**0.18**
Tephra	VP1.1.2	3.84	7.88	0.574	5.046	28.941	3.67	0.11
	VP1.2.21	159.36	14.11	2.696	15.69	43.230	3.06	0.17
	VP4.1.2	3.32	10.8	0.905	5.901	32.32	2.99	0.15
	VP4.2.15	140	20.74	1.044	4.788	59.181	2.85	0.22
	VP4.3.27	310.72	14.31	0.908	4.416	39.545	2.76	0.21
	VP5.1.42	80.64	24.82	4.846	18.93	58.095	2.34	0.26
	VP7.1.3	5.871	11	3.211	20.5	33.111	3.01	0.16
	VP7.2.44	217.8	15.73	5.581	31.01	42.725	2.72	0.18
	VP7.3.77	426	14.41	14.21	84.85	42.924	2.98	0.17
	VP7.4.17	467.8	14.89	3.924	22.96	42.962	2.89	0.17
	Mean		**14.86**	**3.59**	**20.08**	**42.30**	**2.92**	**0.17**

The room temperature hysteresis properties of 25 selected samples are summarized in Table 4, and plotted in Figs. 6 and 7. The average values of M_{rs} and M_s for the tephra samples (n = 10) are 3.59 mAm^2/kg and 20.08 mAm^2/kg whereas for the laminated samples (n = 15) are 0.33 mAm^2/kg and 0.56 mAm^2/kg, respectively (Table 4). The values of M_{rs}/M_s and H_{cr}/H_c plotted on a Day diagram (Day et al., 1977), showing the pseudo single-domain (PSD) range of minerals, are shown in Fig. 7.

Thermomagnetic curves for both heating and cooling are given in Fig. 8. All samples heating and cooling curves are not reversible during cycling to 700 °C. All of the thermomagnetic curves document increased magnetic susceptibility upon heating above 400 °C. On cooling curves, the susceptibility increases steeply or gradually from around 580 to 300 °C for most specimens.

5. Discussion and conclusions

Four laminated sediment cores VP0801, VP0804, VP0805, and VP0807 from Lake Van provide the continuous records of volcanic activity in the region during the Holocene. The volcanic activity in the cores is represented by six tephra units T0-T5 (Table 3).

The tephra unit T0 occurs in all cores except in core VP0805, in which the core top is missing according to the correlation of magnetic parameters (Fig. 3). It is most likely deposited from the

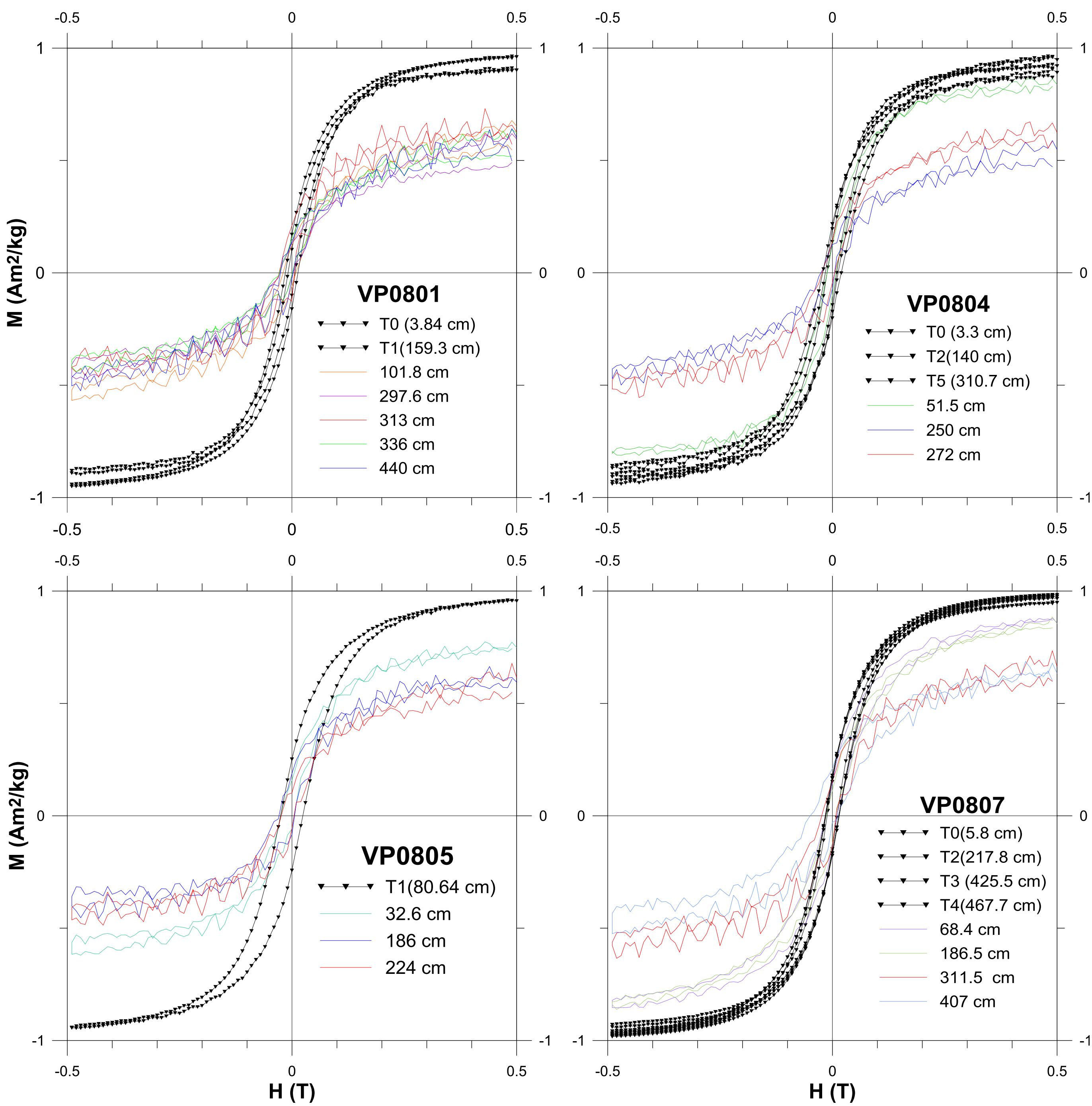

Fig. 6. Hysteresis properties of the sediment from Lake Van.

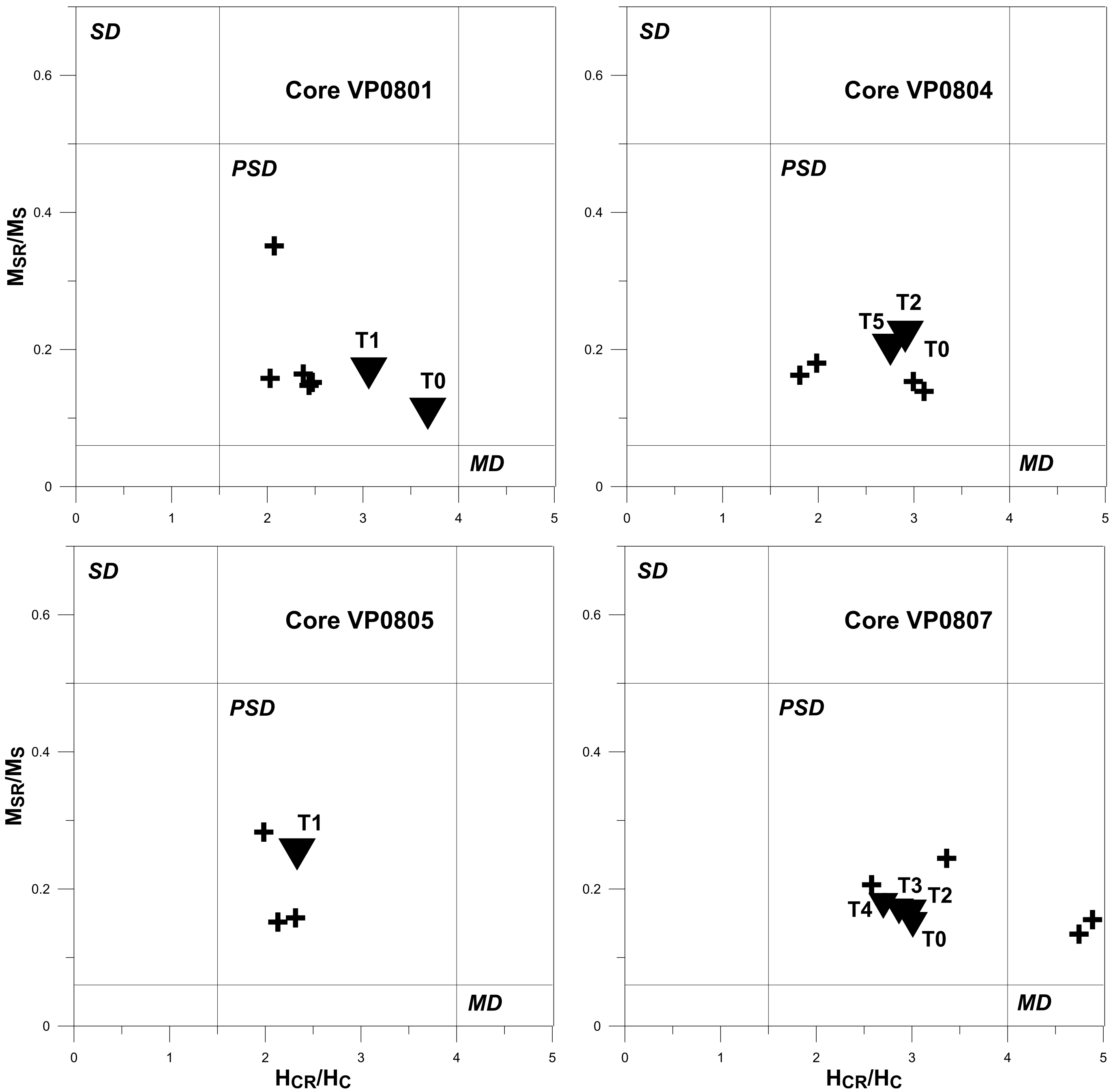

Fig. 7. Day Plot of the sediments samples from Lake Van.

historical (1441 CE) eruption of the Nemrut volcano (Oswalt, 1912). Because of its close vicinity to the volcanic center, Tephra T0 unit is best represented in core VP0807 with distinct magnetic properties and marked enrichment in Zr (Figs. 4 and 9). This tephra unit coincides with "Tephra 1" of Litt et al. (2009) and V-1 of Stockhecke et al. (2014) (Fig. 1; Table 3).

The tephra units T1 and T2 in all cores are enriched in incompatible and high field strength elements (e.g., K and Zr), indicating their alkaline affinity and suggesting their source as the Nemrut volcano. Tephra unit T3 is enriched in K, Zr in all cores except in core VP0805, probably because of the differential wind transport of minerals with the distal and relatively southerly location of the core. Tephra unit T4 has less distinctly anomalous K and Zr contents, but high ARM intensities (Fig. 4). Tephra unit T4 has high K and Zr concentrations only in core VP0807 located near to Nemrut Volcano, suggesting differential deposition of minerals such as coarse-grained alkali feldspars and high density mineral zircon near the volcanic source. The tephra unit T5 in all cores shows no distinct anomalies of K and Zr counts, but reasonably high remanent intensities as in tephra unit T4 (Fig. 4).

The magnetic susceptibility and χ_{ARM} logs of the cores provide a rapid means of stratigraphic correlation even though the coring sites are far away from each other and from the source with distances varying between 15 and 60 km (Fig. 3). Therefore, all the magnetic properties together, suggest that they relate to basin-wide environmental changes rather than to local effects. The

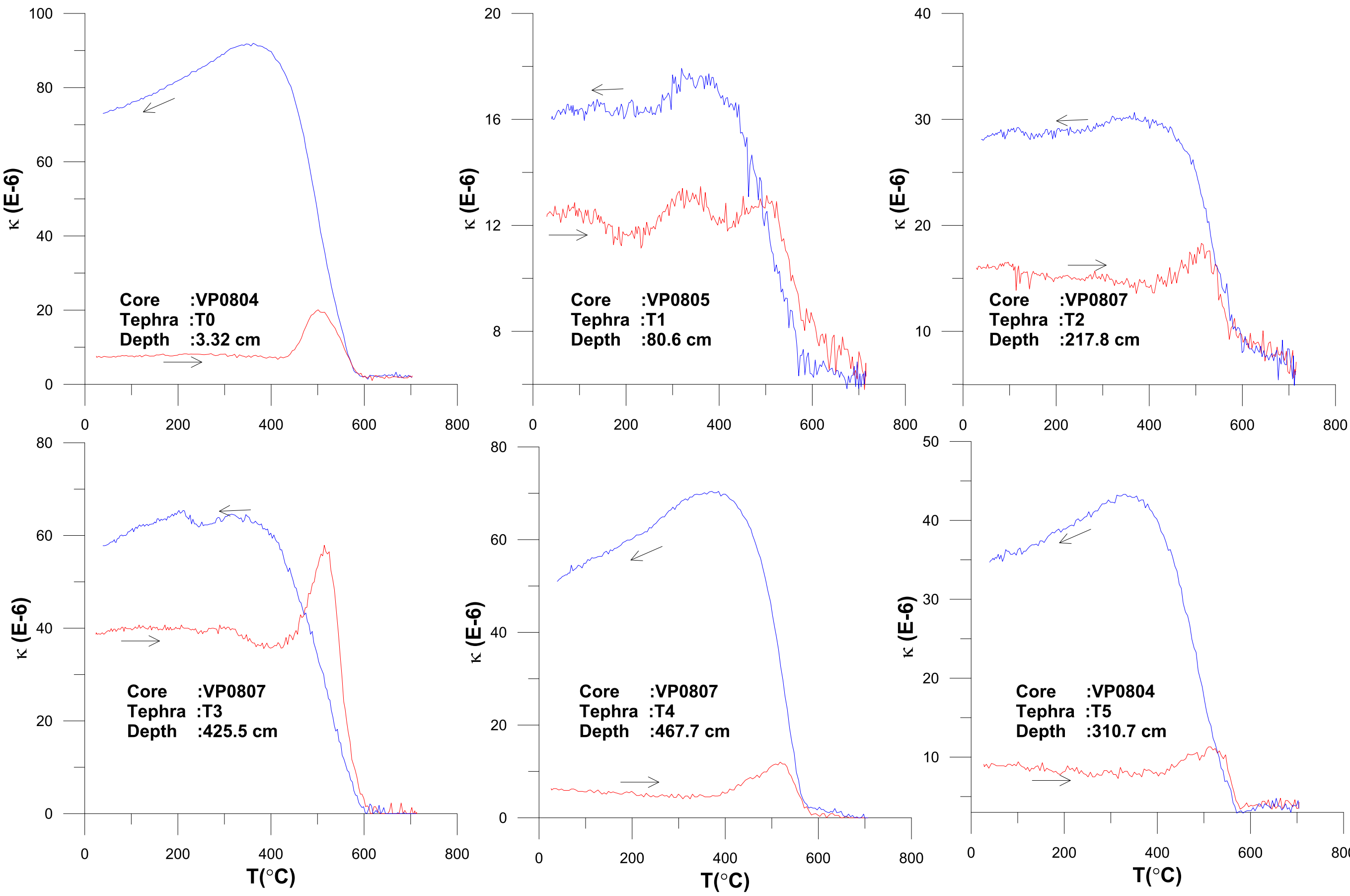

Fig. 8. Thermomagnetic analysis of the tephra samples from Lake Van sediments. Red line shows heating, blue shows cooling. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

magnetic susceptibility in the cores are predominantly controlled by detrital paramagnetic minerals, with some contribution from small amount of ferrimagnetic minerals indicated by low ARM intensities, all of which are derived from the catchment area. Relatively low magnetic mineral concentration of the all tephra units in Lake Van support the rhyolitic composition and its source as the Nemrut volcano. High paramagnetic (i.e., carbonate) content of the laminated sediments of Lake Van make the magnetic parameters an effective discriminator to detect the intercalated tephra units with significant ferromagnetic components. Down-core magnetic susceptibility appears not to be a useful indicator to detect all tephra units because it identifies just few tephra units except the tephra units in the core VP0807, located close to the volcanic source (Fig. 4). However, it is useful for the general stratigraphic correlation of the cores (Fig. 3) and interpretation of Holocene paleoenvironmental changes, in cores located as far away as 30 km from each other (Çağatay et al., 2014; Makaroğlu et al., 2016). Unlike magnetic susceptibility, remanent properties such the ARM are not sensitive to the variations in the paramagnetic component (Lean and Mc Cave, 1998). ARM is particularly sensitive to the single domain (SD) and small pseudo-single domain (PSD) grains of the finer magnetite fraction whereas magnetic susceptibility depends to magnetic mineral concentration and is relatively more sensitive to the coarser magnetite fraction (larger PSD and smaller multi-domain grains) (King et al., 1982). The grain size of tephra units consists of small PSD grains (Figs. 5 and 7). Thus, the remanent properties are more useful when used with magnetic susceptibility for the identification and correlation of different tephra units in Lake Van, instead of using the magnetic susceptibility alone (Fig. 9). Especially, the ARM intensity was found to be the best parameter for correlating the tephra units in the Lake Van sediments.

According to hysteresis analysis, the tephra units are characterized by PSD grain size (Figs. 6 and 7). Fig. 6 shows the hysteresis loops for the tephra and the laminated sediment samples. The tephra and laminated sediments can be distinguished clearly by their hysteresis loops. The hysteresis loops of the tephra samples are closed below 500 mT, suggesting the predominance of low-coercivity and high concentration ferrimagnetic minerals whereas hysteresis loops of the laminated sediment indicate consisting of low concentration of ferromagnetic minerals (Fig. 6). The values of M_{rs}/M_s and H_{cr}/H_c plotted on a Day diagram indicate that the magnetic mineralogy of tephras and laminated sediments are dominated by pseudo single-domain (PSD) range (Fig. 7). It is, however, noteworthy that, in the Day plot, there are no clear differences in magnetic grain size between tephras and laminated sediments (Table 4; Fig. 7). PSD grain size range was also obtained by Vigliotti et al. (2014) for the laminated sediments from Lake Van for the last 350 ka by hysteresis parameters measured.

The King plot indicate that smaller grains yield steeper slopes (King et al., 1982). According to the King plot of tephra samples characterize smaller grain size than the normal laminated sediments (Fig. 5). This is probably because of the reductive diagenesis (i.e., sulphate reduction) in the Lake Van Holocene sediments, which are characterized by high organic carbon and iron sulphides (Landmann et al., 1996b; Makaroğlu, 2011; Stockhecke et al., 2014). Such diagenetic effects on the magnetic properties are commonly

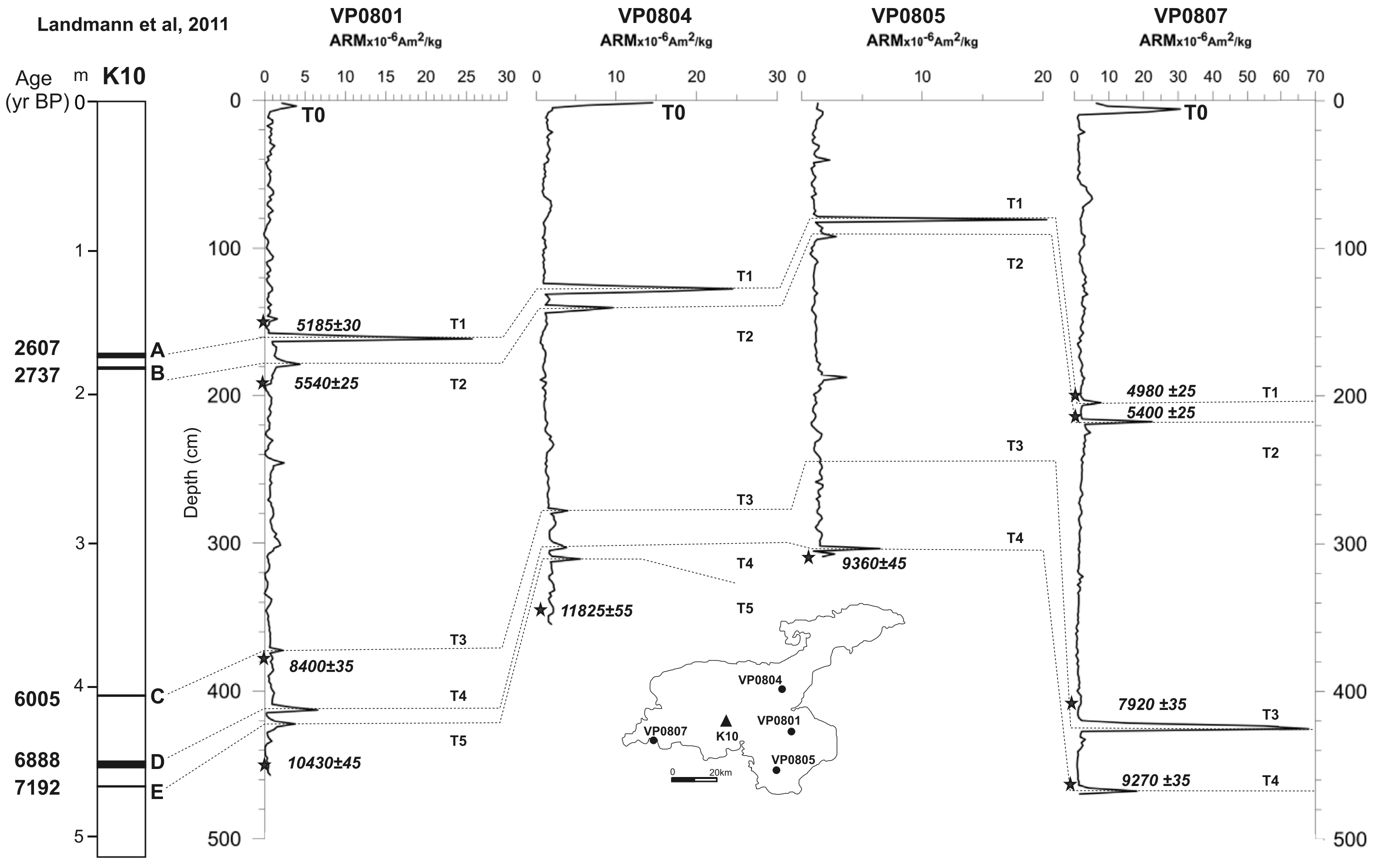

Fig. 9. Inter-core correlation using ARM and comparing the tephra units found in core VP0801, VP0804, VP0805 and VP0807 with the tephra units previously varve-dated by Landmann et al. (2011). Stars show that the depths of radiocarbon dates which are uncalibrated age before present. Tephra units were showed as T0-T5 from top to bottom, respectively.

observed in lakes with sulfate-rich waters and organic-rich sediments (e.g., Snowball, 1996; Stockhausen and Zolitschka, 1999; Demory et al., 2005; Nowaczyk, 2011; Su et al., 2013; Fu et al., 2015; Roberts, 2015). The organic rich nature of the Lake Van sediments is supported by the irreversible behavior of thermomagnetic curves (Fig. 8). The heating curves also indicate the chemical transformation of paramagnetic or clay minerals into magnetite (Roberts, 2015). The formation of new magnetite is supported by the cooling curves; the steep increase in susceptibility from 580 to 300 °C shows the mineralogical transformation of the paramagnetic minerals during the heating stage (Hrouda, 1994; Sagnotti et al., 1998).

The tephra found in Lake Van sediment over the Holocene originated from Nemrut Volcano that produced alkaline magma characterized by high K and Zr concentrations (Landmann et al., 2011; Schmincke et al., 2014; Makaroğlu et al., 2016, Fig. 4). It is clear that the tephra thickness and the intensities of geochemical elements and magnetic parameters are not same for all cores. In core VP0807, located only 20 km from the Nemrut Volcano, the ferrimagnetic component is rich and the tephra units (except for T1) are thicker and better expressed in the geochemical and magnetic profiles than other cores. This supports the hypothesis that differential deposition of minerals and other volcanic material occurs during the transport with distance from the volcanic source, according to the density and size of the material. Cores VP0801, VP0804 and VP0805 are as much as 80 km away and characterized by lower magnetic mineral contents than that in core VP0807 (Fig. 1). Unexpectedly, tephra unit T1 in core VP0807 is thinner and has low magnetic concentration than others cores. This is likely due to the force of eruption and wind speed direction that could have promoted a long-distance transport and deposition of the fall out material. Present wind directions for the Lake Van area are WSW to WNW. These directions have been fairly stable since 400 ka (Sumita and Schmincke, 2013a).

In summary, we conclude that the ARM is the most useful magnetic parameter for identification of the different tephra units in Lake Van sedimentary sequence because of its sensitivity to grain size differences between the laminated sediments and the intervening tephra units. It is also useful for correlation of the tephra units in different cores. Hence, analyses of magnetic properties provide a fast, economical and powerful method of discriminating and correlating between different tephra units, and thus, stratigraphic correlation between cores located in different parts of Lake Van.

Acknowledgements

This research was supported by the Scientific Research Projects Coordination Unit of Istanbul University with the projects numbers 2347, 1228. We thank Sena Akçer Ön and Umut Bariş Ülgen for their help during the coring campaign in Lake Van and Dursun Acar for core handling and μ-XRF analyses in ITU-EMCOL. We would like to acknowledge the two anonymous reviewers for their constructive comments, which helped us to improve the manuscript.

References

Baumgarten, H., Wonik, T., Kwiecien, O., 2014. Facies characterization based on physical properties from downhole logging for the sediment record of Lake Van, Turkey. Quat. Sci. Rev. 104, 85–96.

Brewster, G.R., Barnett, R.L., 1979. Magnetites from a new unidentified tephra source, banff national park, alberta. Can. J. Earth Sci. 16, 1294–1297.

Çağatay, M.N., Öğretmen, N., Damcı, E., Stockhecke, M., Sancar, Ü., Eris, K.K., Ozeren, S., 2014. Lake level and climate records of the last 90 ka from the Northern Basis of Lake Van, eastern Turkey. Quat. Sci. Rev. 104, 97–116.

Çağatay, M.N., Wulf, S., Sancar, Ü., Özmaral, A., Vidal, L., Henry, P., Appelt, O., Gasperinni, L., 2015. The tephra record from the Sea of Marmara for the last ca. 70 ka and its palaeoceanographic implications. Mar. Geol. 361, 96–110.

Çukur, D., Krastel, S., Schmincke, H Ui, Sumita, M., Çağatay, M.N., Feray, Meydan A., DAmcı, E., Stockhecke, 2014. Seismic stratigraphy of Lake Van, eastern Turkey. Quat. Sci. Rev. 104, 63–84.

Cullen, H.M., de Menocal, P.D., Hemming, S., Hemming, G., Brown, F.H., Guilderson, T., Sirocko, F., 2000. Climate change and the collapse of the Akkadian empire: evidence from the deep-sea. Geology 28, 379–382.

Damcı, E., Cağatay, M.N., 2016. An automated algorithm for dating annually laminated sediments using X-ray radiographic images, with applications to Lake Van (Turkey), Lake Nautajarvi (Finland) and Byfjorden (Sweden). Quat. Int. 401, 174–183.

Day, R., Fuller, M., Schmidt, A.V., 1977. Hysteresis properties of titanomagnetites: grain-size and compositional dependence. Phys. Earth Plenatary Interiors 13, 260–267.

De Klerk, P., Janke, W., Kühn, P., Theuerkauf, M., 2008. Environmental impact of the Laacher See eruption at a large distance from the volcano: integrated palaeoecological studies from Vorpommern (NE Germany). Palaeogeogr. Palaeoclimatol. Palaeoecol. 270 (1–2), 196–214.

Demory, F., Oberhänsli, H., Nowaczyk, N.R., Gottschalk, M., Wirth, R., Naumann, R., 2005. Detrital input and early diagenesis in sediments from Lake Baikal revealed by rock magnetism. Glob. Planet. Change 46, 145–166.

Develle, A.L., Williamsona, D., Gassea, F., Walter-Simonnet, A.V., 2009. Early Holocene volcanic ash fallout in the Yammoûneh lacustrine basin (Lebanon):Tephrochronological implications for the Near East. J. Volcanol. Geotherm. Res. 18, 416–425.

Di Vito, M.A., Zanella, E., Gurioli, L., Lanza, R., Sulpizio, R., Bishop, J.J., Laforgia, E., 2009. The Afragola settlement near Vesuvius, Italy: the destruction and abandonment of a Bronze Age village revealed by archaeology, volcanology and rock-magnetism. Earth Planet. Sci. Lett. 277, 408–421.

Dunlop, D.J., 2002. Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc) 2. Application to data for rocks, sediments, and soils. J. Geophys. Res. 107 (B3). EPM 5-1–EPM 5–15.

Dunsheng, X.I.A., Bloemendal, J., Chiverrell, R.C., Dearing, J.A., Ming, J.I.N., 2004. Use of environmental magnetic measurements to characterize and correlate tephra. A case study in Iceland. Chin. Sci. Bull. 49 (3), 286ü294.

Eastwood, W.J., Pearce, N.J.G., Westgate, J.A., Perkins, W.T., Lamb, H.F., Roberts, N., 1999. Geochemistry of Santorini tephras in lake sediments from southwest Turkey. Glob. Planet. Change 21, 17–29.

Eastwood, W.J., Tibby, J., Roberts, N., Birks, H.J.B., Lamb, H.F., 2002. The environmental impact of the Minoan eruption of Santorini (Thera): statistical analysis of palaeoecological data from Golbisar, southwest Turkey. Holocene 12 (4), 431–444.

Evens, M.E., Heller, F., 2003. Environmental Magnetism: Principles and Applications of Enviromagnetics. Academic Press, 299 pp.

Friedrich, W.L., 2013. The Minoan eruption of Santorini around 1613 BC and its consequences. In: Tagungen des Landesmuseums für Vorgeschichte Halle. Band 9.

Fu, C.F., Bloemendal, J., Qiang, X.K., Hill, M.J., An, Z.S., 2015. Occurrence of greigite in the Pliocene sediments of Lake Qinghai, China, and its paleoenvironmental and paleomagnetic implications. Geochem. Geophys. Geosyst 16, 1293–1306.

Gonzalez, S., Jones, J.M., Williams, D.L., 1999. Characterization of tephras using magnetic properties: an example from SE Iceland. In: Firth, C., McGuire, W.J. (Eds.), Volcanoes in the Quaternary. Geological Society of London Special Publication 161. Geological Society Publishing House, Bath, pp. 125–145.

Grattan, J., 2006. Aspects of Armageddon: an exploration of the role of volcanic eruptions in human history and civilization. Quat. Int. 151, 10–18.

Hrouda, F., 1994. A technique for the measurement of thermal changes of magnetic susceptibility of weakly magnetic rocks by the CS-2 apparatus and KLY-2 Kappabridge. Geophys. J. Int. 118, 604–612.

Issar, A.S., Zohar, M., 2007. Climate Change – Environment and History of the Near East. Springer-Verlag Berlin Heidelberg.

Kempe, S., 1977. Disseration. Hydrographic, Warvenchronologie und organische Geochemie des an Sees, Ost-Türkei, vol. 47. Mitt.Geol.-Palaont.Inst.Unv, Hamburg, pp. 125–228.

Kempe, S., Landmann, G., Müller, G., 2002. A floating varve chronology from the last glacial maximum terrace of Lake Van/Turkey. Z Geomorph N. F. 126, 97–114.

Kempe, S., Degens, E.T., 1978. Lake Van varve record: the last 10.420 years. In: Degens, E.T., Kurtman, F. (Eds.), Geology of Lake Van. MTA Press, Ankara, pp. 56–63.

Keskin, M., 2007. Eastern Anatolia: a Hotspot in a Collision Zone without a Mantle Plume. The Geological Society of America. Special Paper 430.

King, J., Banerjee, S.K., Marvin, J., Özdemir, Ö., 1982. A comparison of different magnetic methods for determining the relative grain size of magnetite in natural materials: some results from lake sediments. Earth Planet. Sci. Lett. 59, 404–419.

Lagroix, F., Banerjee, S.K., Jackson, M., 2004. Magnetic properties of the Old Crow tephra: identification of a complex iron titanium oxide mineralogy. J. Geophys. Res.: Solid Earth. American Geophysical Union.

Landmann, G., Reimer, A., Lemcke, G., Kempe, S., 1996a. Dating Late Glacial abrupt climate changes in the 14, 570 years long continuous varve record of Lake Van/Turkey. Paleogeogr. Paleocl Paleoecol. 2, 107–118.

Landmann, G., Reimer, A., Kempe, S., 1996b. Climatic induced lake level changes of Lake Van/Turkey during the transition Pleistocene/Holocene. Glob. Biogeochem. Cycles 10 (4), 797–808.

Landmann, G., Kempe, S., 2005. Annual deposition signal versus lake dynamics: microprobe analysis of Lake Van (Turkey) sediments reveals missing varves in the period 11.2–10.2 ka BP. Facies 51, 135–145.

Landmann, G., Steinhauser, G., Sterba, J.H, Kempe, S., Bichler, M., 2011. Geochemical fingerprints by activation analysis of tephra layers in Lake Van sediments, Turkey. Appl. Radiat. Isotopes 69, 929–935.

Litt, T., Anselmetti, F.S., 2014. Lake Van drilling project “PALEOVAN”, scientific goals and perspectives. Quat. Sci. Rev. 104, 1–7.

Litt, T., Krastel, S., Sturm, M., Kipfer, R., Orcen, S., Heumann, G., Franz, S.O., Ulgen, U.B., Niessen, F., 2009. ‘Paleovan’, international continental scientific drilling program (ICDP): site survey results and perspectives. Quat. Sci. Rev. 28, 1555–1567.

Litt, T., Pickarski, N., Heumann, G., Stockhecke, M., Tzedakis, P.C., 2014. A 600,000 year long continental pollen record from Lake Van, eastern Anatolia (Turkey). Quat. Sci. Rev. 104, 30–41.

Lean, C.M.B., Mc Cave, I.N., 1998. Glacial to interglacial mineral magnetic and palaeoceanographic changes at catham rise, SW pacific ocean. Earth Planet. Sci. Lett. 163, 247–260.

Lozano-Garcia, M.S., Ortega-Guerrero, B., 1994. Palynological and magnetic susceptibility records of Lake Chalco, central Mexico. Palaeogeogr. Palaeoclim. Palaeoecol. 109, 177–191.

Maher, B., 1988. Magnetic properties of some synthetic sub-micron magnetites. Geophys. J. Int. 94, 83–96.

Makaroğlu, Ö., 2011. Van Gölü Sedimanlarının Çevre Mağnetizması Ve Paleomağnetik Kayıtları. Ph.D. thesis. İstanbul Üniversitesi, Fen Bilimleri Enstitüsü.

Makaroğlu, Ö., Çağatay, N., Orbay, N., Pesonen, L., 2016. The radiocarbon reservoir age of Lake Van, eastern Turkey. Quat. Int. 113–122.

Marinatos, S., 1939. The volcanic destruction of Minoan Crete. Antiquity 13, 425–439.

Mellaart, J., 1967. Catal Hüyük: a Neolithic Town in Anatolia. Thames & Hudson.

Nowaczyk, N.R., 2011. Dissolution of titanomagnetite and sulphidization in sediments from Lake Kinneret. Isr. Geophys. J. Int. 187, 34–44.

Oldfield, F., Appleby, P.G., Thompson, R., 1980. Paleoecological studies of lakes in the Highlands of Papua New Guinea, I: the chronology of sedimentation. J. Ecol. 68, 457–477.

Oldfield, F., Barnosky, C., Leopold, E.B., Smith, J.P., 1983. Mineral magnetic studies of Lake sediments. Hydrobiologia 103, 37–44.

Oswalt, F., 1912. Armenian Handbuch der regionalen Geologie, vol. 10 (Heidelberg).

Pararas-Carayannis, G., 1974. The destruction of the Minoan civilization. Encyclopaedia grollier. Sci. Suppl. 314–321.

Pawse, A., Beske-Diehl, S., Marshall, S.A., 1998. Use of magnetic hysteresis properties and electron spin resonance spectroscopy for the identification of volcanic ash: a preliminary study. Geophys. J. Int. 132, 712–720.

Reimer, A., Landmann, G., Kempe, S., 2009. Lake Van eastern Anatolia hydrochemistry and history. Aquat. Geochem 15, 195–222.

Roberts, A.P., 2015. Magnetic mineral diagenesis. Earth-Science Rev. 151, 1–47.

Robertson, D.J., 1993. Discrimination of tephra using rockmagnetic characteristics. J. Geomagnetism Geoelectr. 82, 223–234.

Robinson, S.G., 1986. The late Pleistocene palaeoclimatic record of North Atlantic deep-sea sediments revealed by mineral-magnetic measurements. Phys. Earth Planet. Interiors 42, 22–47.

Sagnotti, L., Speranza, F., Winkler, A., Mattei, M., Funiciello, R., 1998. Magnetic fabric of clay sediments from the external northern Apennines (Italy). Phys. Earth Planet. Inter 105, 73–93.

Schmincke, H.U., Sumita, M., Paleovan scientific team, 2014. Impact of volcanism on the evolution of Lake Van (eastern Anatolia) III: periodic (Nemrut) vs. episodic (Süphan) explosive eruptions and climate forcing reflected in a tephra gap between ca. 14 ka and ca. 30 ka. J. Volcanol. Geotherm. Res. 285, 195–213.

Snowball, I.F., 1996. Holocene environmental change in the Abisko region of northern Sweden recorded by the mineral magnetic stratigraphy of lake sediments. GFF 118, 9–17.

Stockhecke, M., 2008. The Annual Particle Cycle of Lake Van: Insights from Space, Sediments and the Water Column. M.S. Thesis. University of Zurich.

Stockhecke, M., Anselmetti, F.S., Meydan, A.F., Odermatt, D., Sturm, M., 2012. The annual particle cycle in Lake Van (Turkey). Palaeogeogr. Palaeoclimatol. Palaeoecol. 333–334, 148–159.

Stockhecke, M., Kwiecien, O., Vigliotti, L., Anselmetti, F.S., Beer, J., Çağatay, M.N., Channell, J.E.T., Kipfer, R., Lachner, J., Litt, T., Pickarski, N., Sturm, M., 2014. Chronostratigraphy of the 600,000 year old continental record of Lake Van (Turkey). Quat. Sci. Rev. 104, 8–17.

Stockhausen, H., Zolitschka, B., 1999. Environmental changes since 13,000 cal. BP reflected in magnetic and sedimentological properties of sediments from Lake Holzmaar (Germany). Quat. Sci. Rev. 18, 913–925.

Su, Y.L., Gao, X., Liu, Q.S., Wang, J.B., Haberzetti, T., Zhu, L.P., Li, J.H., Duan, Z.Q., Tian, L.D., 2013. Mineral magnetic study of lacustrine sediments from Lake Pumoyum Co, southern Tibet, over the last 19 ka and paleoenvironmental significance. Tectonophysics 588, 209–221.
Sumita, M., Schmincke, H.U., 2013a. Impact of volcanism on the evolution of Lake Van I: evolution of explosive volcanism of Nemrut Volcano (eastern Anatolia) during the past >400,000 years. Bull. Volcanol. 75 (5), 1–32.
Sumita, M., Schmincke, H.-U., 2013b. Impact of volcanism on the evolution of Lake Van II: temporal evolution of explosive volcanism of Nemrut Volcano (eastern Anatolia) during the past ca. 0.4 Ma. J. Volcanol. Geotherm. Res. 253, 15–34.
Thompson, Oldfield, 1986. Environmental Magnetism. Allen and Unwin, London.
Thomson, J., Croudace, I.W., Rothwell, R.G., 2006. A geochemical application of the ITRAX scanner to a sediment core containing eastern Mediterranean sapropel units. In: Rothwell, R.G. (Ed.), New Techniques in Sediment Core Analysis. Geological Society, London, Special Publications 267.
Van den Bogaard, C., Dörfler, W., Sandgren, P., Schmincke, H.U., 1994. Correlating the Holocene records: Icelandic tephra found in Schleswig-Holstein (Northern Germany). Naturwissenschaften 81, 554–556.
Vigliotti, L., Channell, J.E.T., Stockhecke, M., 2014. Paleomagnetism of Lake Van sediments: chronology and paleoenvironment since 350 ka. Quat. Sci. Rev. 104, 18e29.
Vogel, H., Zanchetta, G., Sulpizio, R., Wagner, B., Nowaczyk, N., 2010. A tephrostratigraphic record for the last glacial–interglacial cycle from Lake Ohrid, Albaniaand Macedonia. J. Quat. Sci. ISSN: 0267-8179 25, 320–338.
Weiss, H., Courty, M.A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., Curnow, A., 1993. The genesis and collapse of third millennium north Mesopotamian civilization. Science 261 (5124), 995–1004.
Wick, L., Lemcke, G., Sturm, M., 2003. Evidence of Lateglacial and Holocene climatic change and human impact in Eastern Anatolia: high resolution pollen, charcoal, isotopic and geochemical records from the laminated sediments of Lake Van, Turkey. Holocene 13, 665–675.
Wulf, S., Kraml, M., Kuhn, T., Schwarz, M., Inthorn, M., Keller, J., Kuscu, I., Halbach, P., 2002. Marine tephra from the Cape Riva eruption (22 ka) of Santorini in the Sea of Marmara. Mar. Geol. 183, 131–141.
Wulf, S., Brauer, A., Kraml, M., Keller, J., Negendank, J.F.W., 2004. Tephrochronology of the 100 ka lacustrine sediment record of Lago Grande di Monticchio (southern Italy). Quat. Int. 122, 7–30.
Xia, D.S., Chun, X., Bloemendal, J., Chiverrell, R.C., Chen, F., 2007. Use of magnetic signatures to correlate tephra layers in Holocene loessial soil profiles from a small region, SE Iceland. Environ. Geol. 51 (8), 1425–1437.
Yılmaz, Y., Güner, Y., Saroglu, F., 1998. Geology of the Quaternary volcanic centers of the east Anatolia. J. Volcanol. Geotherm. Res. 85 (1–4), 173–210.