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Seismogenic structures in Quaternary lacustrine deposits of Lake Van (eastern Turkey)

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Abstract

Soft-sediment deformation structures formed by liquefaction and/or fluidisation of unconsolidated sediments due to seismic shocks are frequent in the Quaternary sandy, silty and clayey deposits of Lake Van. They are present in both marginal and deep lacustrine facies. Their morphology and interpreted genesis imply that they should be considered as fluid-escape structures (dish and pillar structures, flame structures and sand volcanoes), contorted structures (simple and complex convolutions and ball-and-pillow structures) and other structures (disturbed layers and slump structures). The most recently formed structures are related to the October 23rd, 2011 Van-Tabanlı (M_w 7.2) earthquake. The existence of seismites at various stratigraphic levels in the lacustrine deposits is indicative of tectonic activity that frequently triggered earthquakes with magnitudes of 5 or more, affecting the Lake Van Basin.

Keywords: Seismites, soft-sediment deformation structures, earthquake, Lake Van, Turkey

1. Introduction

Seismic events can be recorded in sedimentary successions as seismites, layers characterised by earthquake-induced soft-sediment deformation structures, including convolutions, dish and pillars, flame structures, and sand volcanoes (see, for instance, Valente et al., 2014, this issue). Seismites are formed by liquefaction and/or fluidisation of water-saturated, unconsolidated, and non-cohesive sediments due to seismic shocks (Seilacher, 1969; Lowe, 1975; Van Loon, 2014a, this issue). Seismites exist in many sedimentary environments such as lacustrine, fluvial, transitional, and marine environments (Seilacher, 1969; Seed & Idriss, 1982; Obermeier et al., 1989; Ringrose, 1989; Moretti et al., 1995). Inner basins and lakes are the most suitable environments for the formation of seismites as the various depositional subenvironments and sedimentary facies are commonly highly susceptible to deformations (Sims, 1975; Hempton et al., 1983; Seilacher, 1984; Ringrose, 1989; Ricci Lucchi, 1995; Alfaro et al., 1997; Rodriguez-Pascua et al., 2000; Bowman et al., 2004; Moretti & Sabato, 2007; Taşgın & Türkmen, 2009). Seismites resulting from earthquakes with a magnitude M≥5 (Fukuoka, 1971; Atkinson, 1984; Ambraseys, 1988) can sometimes be used to determine the location and frequency of the seismic activity in a region (Allen, 1975; Sims, 1975; Hempton et al., 1983; Scott & Price, 1988; Ringrose, 1989).

Seismites occur frequently in the Quaternary lacustrine deposits of the Lake Van Basin in eastern Turkey. The most recent seismogenic structures (sand volcanoes) formed during the Van-Tabanlı earthquake (M_w 7.2), which seriously damaged Van City and its close vicinity on October 23rd, 2011.

The purpose of the present contribution is to define and classify the seismogenic structures in the lacustrine deposits of the Lake Van Basin and to discuss the importance of these structures with respect to regional tectonics.

2. Geological setting

Lake Van Basin is located on the East Anatolian Plateau that was formed by a collision between the Eurasian and Arabian Plates in the eastern Mediterranean region (including Turkey) (Şengör & Yılmaz, 1981) (Fig. 1A). The basin developed in the Late Pliocene and took its recent shape by the volcanism that was active during the Quaternary (Degens et al., 1984). The basement, consisting of Bitlis metamorphic rocks, Late Cretaceous ophiolites, and Tertiary deep-marine sediments (Van Formation), is unconformably overlain by Quaternary volcanics and lacustrine sediments of the same age (Lake Van Formation). The basin infilling ends with Late Quaternary travertines and recent unconsolidated fluvial sediments (Acarlar et al., 1991).

Lake Van is the largest sodic lake in the world (Kempe et al., 1978). It originated 500 ka ago (Litt et al., 2009). The water level of Lake Van experienced significant fluctuations since its formation (Degens et al., 1978; Kuzucuoğlu et al., 2010). Ancient deposits of the lake occur also east of the lake, proving that it was previously larger than nowadays (Üner et al., 2010) (Fig. 1B).

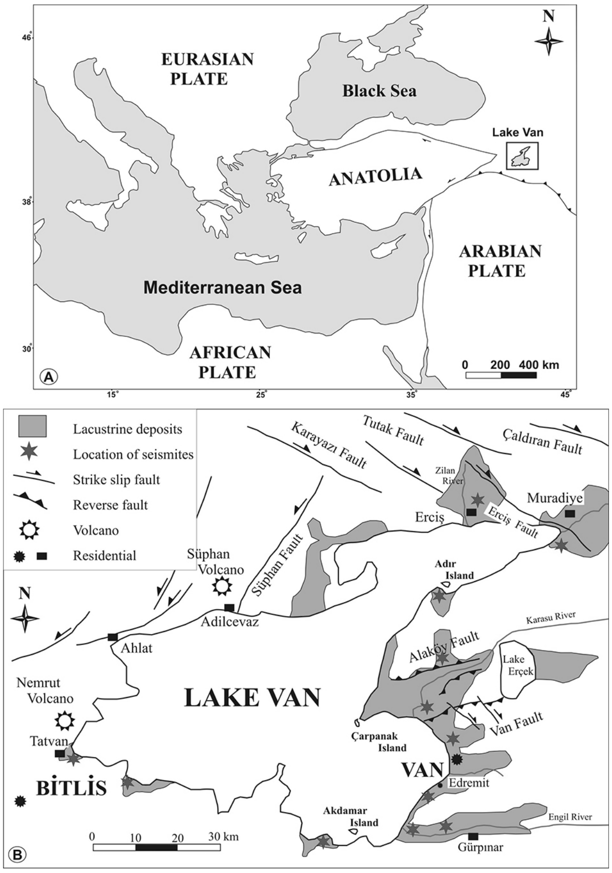

Fig. 1. Setting of the study area.
A: Location map of Lake Van and study area; **B:** Simplified geological map showing the active faults and lacustrine deposits in the Lake Van Basin (modified from Acarlar et al., 1991; Koçyiğit et al., 2001; Üner et al., 2010; Koçyiğit, 2013).

The Lake Van Basin experienced tectonics during the Plio-Quaternary (Koçyiğit et al., 2001). A N-S trending compressional regime, due to collision between Arabian and Eurasian plates, is represented by E-W trending reverse faults, NW-SE trending dextral and NE-SW trending sinistral strike-slip faults, and by N-S trending extensional structures (Şaroğlu & Yılmaz, 1986; Özkaymak et al., 2011; Koçyiğit, 2013). Several earthquakes with magnitudes of $M_w \geq 5$ have been recorded in the region during historical times, and also since they can be monitored, such as the Çaldıran Earthquake in 1976 ($M_s = 7.2$) and the Van-Tabanlı Earthquake in 2011 ($M_w = 7.2$), which are the best known.

3. Types of seismogenic deformation structures

The seismogenic deformation structures dealt with in the present contribution have been investigated for their genesis and morphological features; on this basis they are divided into three major groups, viz. fluid-escape structures, contorted structures, and other structures (such as disturbed layers and slump structures).

3.1. Fluid-escape structures

Fluid-escape structures are formed by upward movement of pore water and/or fluidised unconsolidated sediment. Layers with laterally ongoing deformation structures of this type, intercalated between non-deformed beds, point at fluidisation due to earthquake-induced shock waves of sufficient magnitude. These structures are subdivided here on the basis of their morphology into dish and pillar structures, flame structures and associated load-casts, and sand volcanoes.

3.1.1. Dish and pillar structures

Dish and pillar structures occur in both sandy and silty lacustrine deposits around Lake Van. Dish structures are present as concave-upwards bent layers (Fig. 2A). The individual dishes vary in width from 10 cm to 1 m. The dishes are separated from each other by pillars. These pillars can reach a height of 50 cm. They may be vertical or somewhat inclined (Fig. 2B).

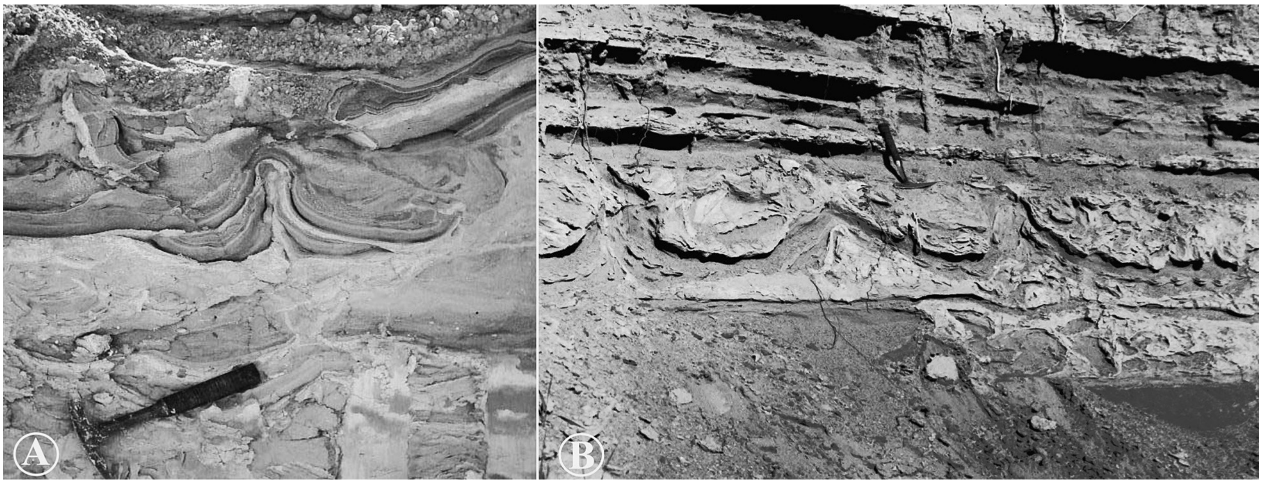

Fig. 2. Dish and pillar structures in lacustrine deposits of Lake Van.
A: Dish structures with a clear concave-upward geometry; **B:** Dish structures separated by pillar structures.

The dish structures originated because of the local upward movement of pore water; this upward movement resulted in upward bending of the sediment at both sides (cf. Van Loon & Mazumder, 2011). In between the dishes, pillar structures were formed (Lowe 1975). The variable shape of the dish structures must be ascribed to differences in the velocity of the upward flowing water/sediment mixture and/or the degree of consolidation. Dish and pillar structures have commonly been described from seismites (Plaziat & Ahmamou, 1998; Moretti et al., 1999; see also Perucca et al., 2014, this issue).

3.1.2. Flame structures and associated loadcasts

Flame structures also occur in both sandy and silty sediments of Lake Van. These structures occur most commonly at the boundary between silty and sandy layers (see also He et al., 2014, this issue). The flames are separated from one another by loadcasts, which may show a lateral component, which consequently also holds for the flame structures in between (Fig. 3). The flames tend to have a relatively wide basal part, from where the thickness diminishes upwards (Fig. 3A). The structures vary in size from a few to 30 cm.

The flame structures are genetically closely related to the adjacent loadcasts, as loadcasts are commonly ascribed to conditions (e.g. reversed density gradients) that favour sagging, the most common explanation for flames is that they are formed because sediment is pushed upwards between sagging loadcasts. The flames then are a 'byproduct' of the loadcasts. In the sediments under study here, however, it seems that the loadcasts are the 'byproduct' of the flames, which originated because of an upward injection of silty sediments into

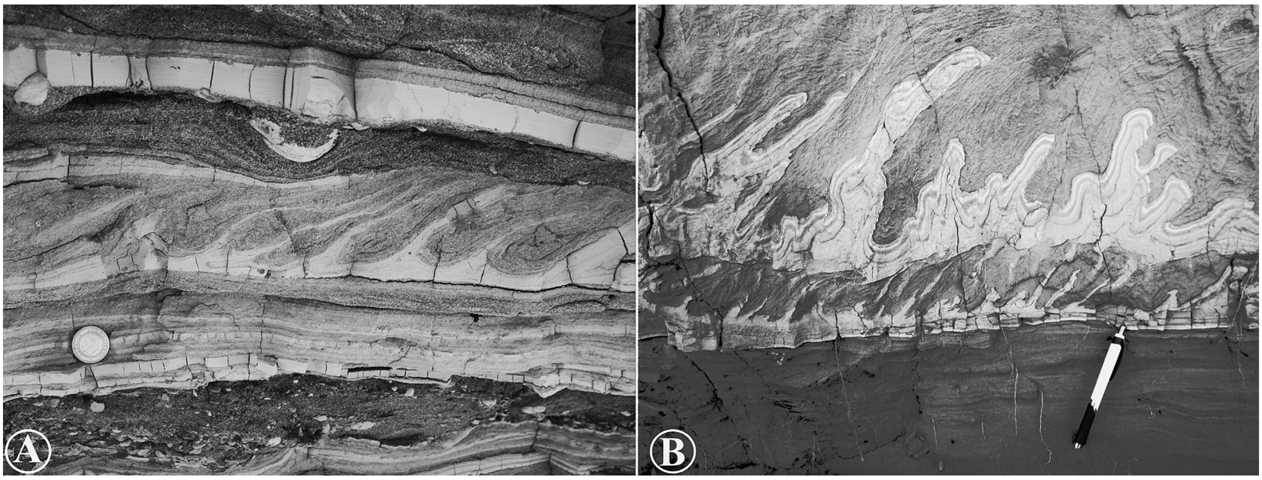

Fig. 3. Flame structures in sandy and silty lacustrine deposits.
A: Thin, simple flame structures separating load casts from each other. Note the horizontal component; **B:** Complex flame structures bent into the same direction.

fine-grained sandy sediments as a result of liquefaction due to an earthquake-induced shockwave. This has been described from numerous seismites (e.g. Visher & Cunningham, 1981; Dasgupta, 1998; Rodríguez-Lopez et al., 2007; Van Loon & Pisarska-Jamroży, 2014).

3.1.3. Sand volcanoes

Sand volcanoes are present in modern lacustrine and flood-plain deposits of the Karasu River bed, due to the Van-Tabanlı earthquake (M_w = 7.2) which took place on October 23rd, 2011 (Fig. 4A). These structures occur along a line and consist of coarse to fine-grained sand deposits. These cone-shaped structures are about a metre wide and 15 cm in height. A craterpipe-like depression of about 5 cm in diameter is located on the top of structure (Fig. 4B).

Sand volcanoes are commonly formed by upward extrusion of liquefied sands during an earthquake (Obermeier, 1996, 1998; Van Loon & Maulik, 2011). The direction of the line of the sand volcanoes can, however, not be associated with the fault direction that generated to Van-Tabanlı earthquake. The positions of the sand extrusions are therefore interpreted as resulting from the failure of a weak zone failure due to a seismic shock coming from somewhere near the Karasu River.

3.2. Contorted structures

The contorted structures are subdivided here in two categories: simple and complex convolutions, and ball-and-pillow structures.

3.2.1. Simple and complex convolutions

Contorted structures are present in silty and in coarse to fine-grained sandy lacustrine deposits, in the form of syncline-shaped structures (Fig. 5A, B). These structures sometimes form simple convolutions and in other cases complex convolutions (see also Sarkar et al., 2014, this issue). The simple convolutions have a simple geometry (Fig. 5A), whereas complex convolutions are characterised by disorganised internal lamination (Fig. 5B). The structures are up to 130 cm wide and 70 cm high.

The complex convolutions with their large trough-like outer boundary and their circular to semi-circular laminae inside are interpreted to have formed by plastic deformation due to liquefaction. The presence of undisturbed layers above and below the convoluted structures indicates a seismic origin for these structures (cf. Rossetti, 1999; Rodriguez-Pascua et al., 2000). Furthermore, the existence of more than one bend in the central part of the contorted structures suggests that this layer was affected by more than one earthquake (cf. Bhattacharya & Bandyopadhyay, 1998).

3.2.2. Ball-and-pillow structures

The ball-and-pillow structures under study are characterised by spherical or semi-spherical sand bodies within silt-sized sediments (Fig. 6). Some of the structures are connected with each other, whereas others are isolated. The structures show internal lamination and have often an outermost layer of silt. The structures are up to 26 cm wide and 12 cm thick.

The structures are interpreted to have formed by partial liquefaction as the result of the aggregation

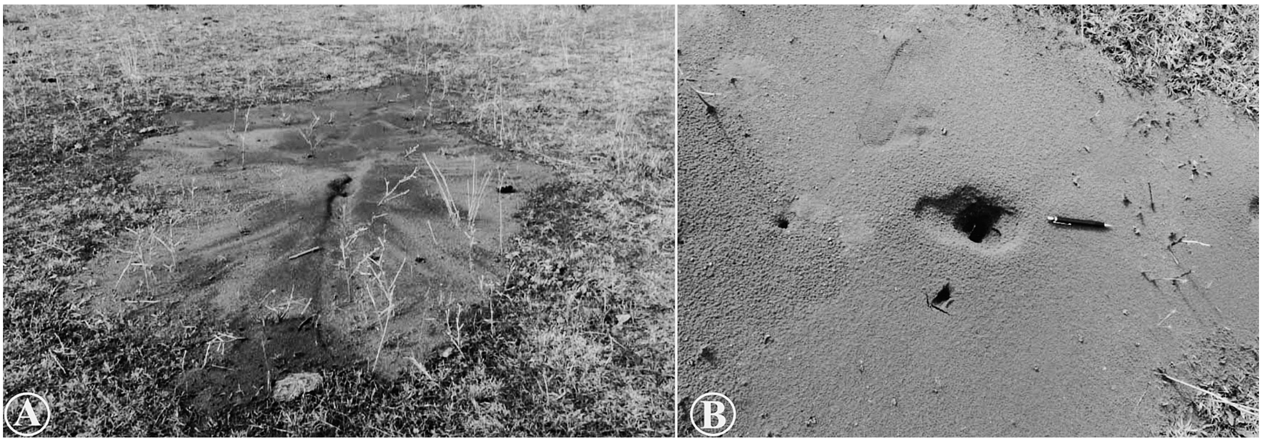

Fig. 4. The sand volcano that formed due to the Van-Tabanlı earthquake (M_w = 7.2) on October 23rd, 2011 (from Alan et al., 2011).
A: overview; **B:** Detail with the crater on top of structure.

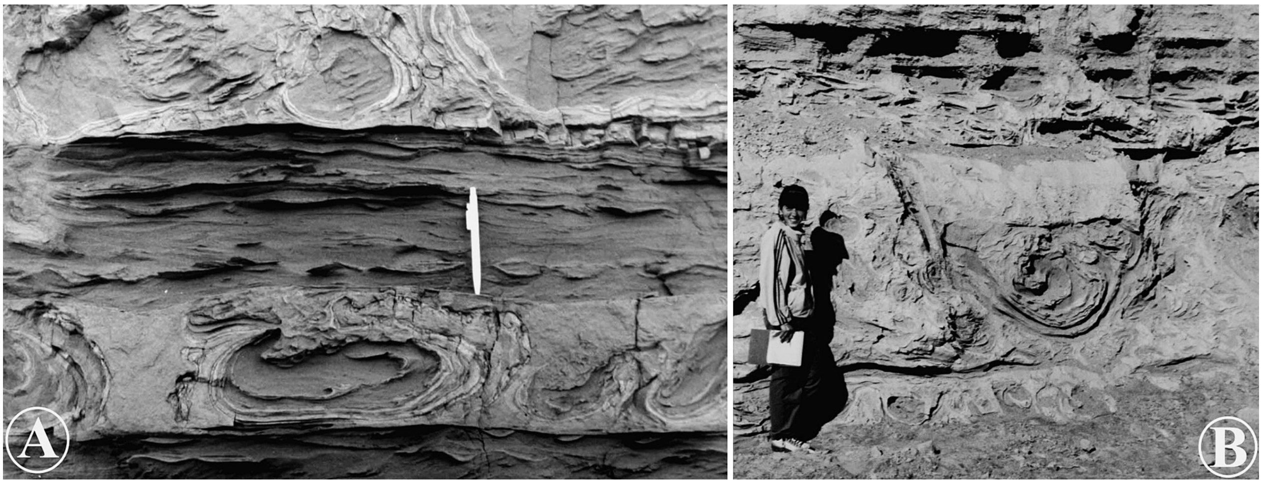

Fig. 5. Convolutions in the lacustrine deposits of Lake Van. **A:** Simple convolutions; **B:** Complex convolutions.

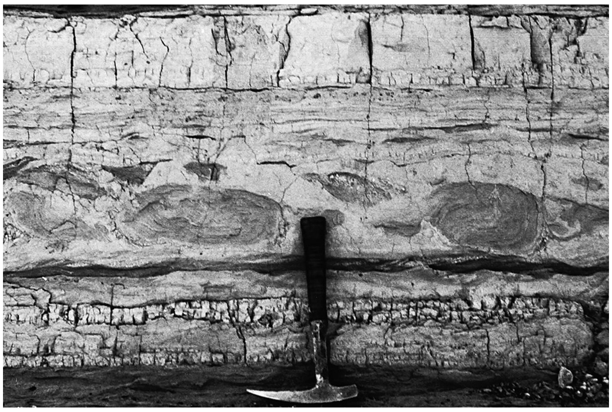

Fig. 6. Spherical and semi-spherical ball-and-pillow structures in a silty lacustrine seismite of Lake Van. Note the undisturbed under- and overlying layers.

of unconsolidated sands during a seismic shock (cf. Hempton et al., 1983; Ringrose, 1989; Rossetti, 1999; Rodriguez-Pascua et al., 2000).

3.3. Other structures

The disturbed structures occur in the lacustrine facies where fine sand and silt alternate. The thickness of these layers, which are sandwiched between undeformed layers, ranges from 2 to 10 cm. Laterally these layers pass into undeformed beds (Fig. 7). The structures are interpreted to have formed by ductile deformation induced by seismic shocks shortly after deposition (cf. Rossetti, 1999); brecciation, a process that is commonly associated with earthquakes (see Van Loon, 2014b, this issue) has, however, not been observed. The alternation of disturbed layers with undeformed strata is characteristic for deformation-susceptible sediments in areas where seismic shocks are not exceptional events.

Slump structures occur in the silty and clayey distal parts of the delta prograding into Lake Van. The slumped sediments rest unconformably on horizontal layers and the upper part of the slumped layer overlain by undeformed clay and silts. The maximum thickness of the slumps is 45 cm (Fig. 8). Slump structures can originate on oversteepened slopes or due to overload-induced failure or by plastic deformation as a result of seismic shakes (Rodriguez-Pascua et al., 2000). They can occur on very slightly inclined slopes, and the presence of slumps on low-gradient slopes has been attributed to seismic activity by several researchers (e.g. Moretti & Sabato, 2007).

4. Discussion

The deformation of unconsolidated sediments requires a trigger. Well documented triggers include overpressure due to the accumulation of sediment (Lowe, 1975; Van Loon et al., 2013), storm waves (Molina et al., 1998; Chen et al., 2009a, 2009b; Chen & Lee, 2013), water-level fluctuations (Spence & Tucker, 1997; Chen et al., 2011) and seismic shocks (Seilacher, 1969; Lowe, 1975; Sims, 1975; Rossetti, 1999; Rodriguez-Pascua et al., 2000; Bowman et al., 2004). Deformation structures in the lacustrine deposits of Lake Van were most probably not induced by water-level fluctuation, sediment load or storm waves, because there is no sedimentological or stratigraphical evidence for such processes such as hummocky cross-lamination, disorganised gravel or uncommon event deposition.

The deformation structures under study satisfy all regional, sedimentological and tectonic criteria

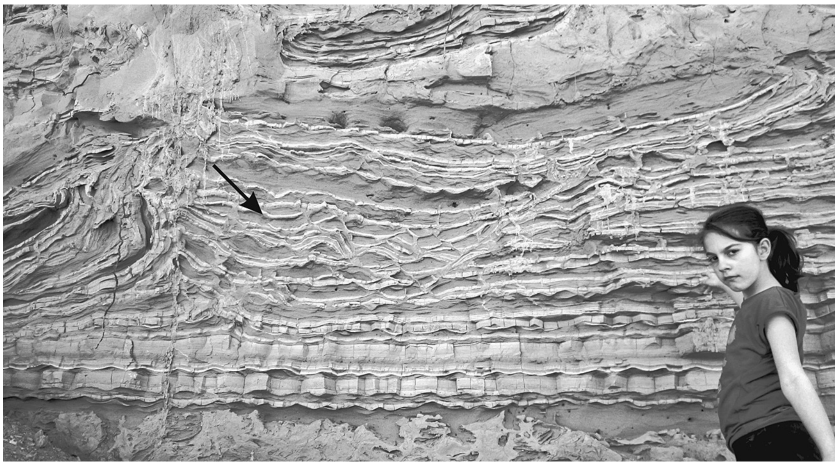

Fig. 7. Disturbed layers laterally passing into undeformed layers. Black arrow indicates the undeformed parts.

Fig. 8. General view of the slump structure in very slightly inclined prodelta sediments.

of seismites (Sims, 1975; Obermeier, 1998; Bowman et al., 2004). These are: (1) the deformation structures form within a seismically active basin, (2) deposits are susceptible to liquefaction, (3) layers with deformation structures show lateral continuity, (4) cyclic repetitions of deformation structures (Fig. 9A, B), (5) the deformed beds are separated by undeformed levels, (6) there is no evidence for slope failure, (7) the deformation structures show many similarities to those recognised as seismites in modern deposits or in 'seismic' experiments. Although general agreement exists regarding the usefulness of these criteria, it should be kept in mind that they should be applied only if the geological context

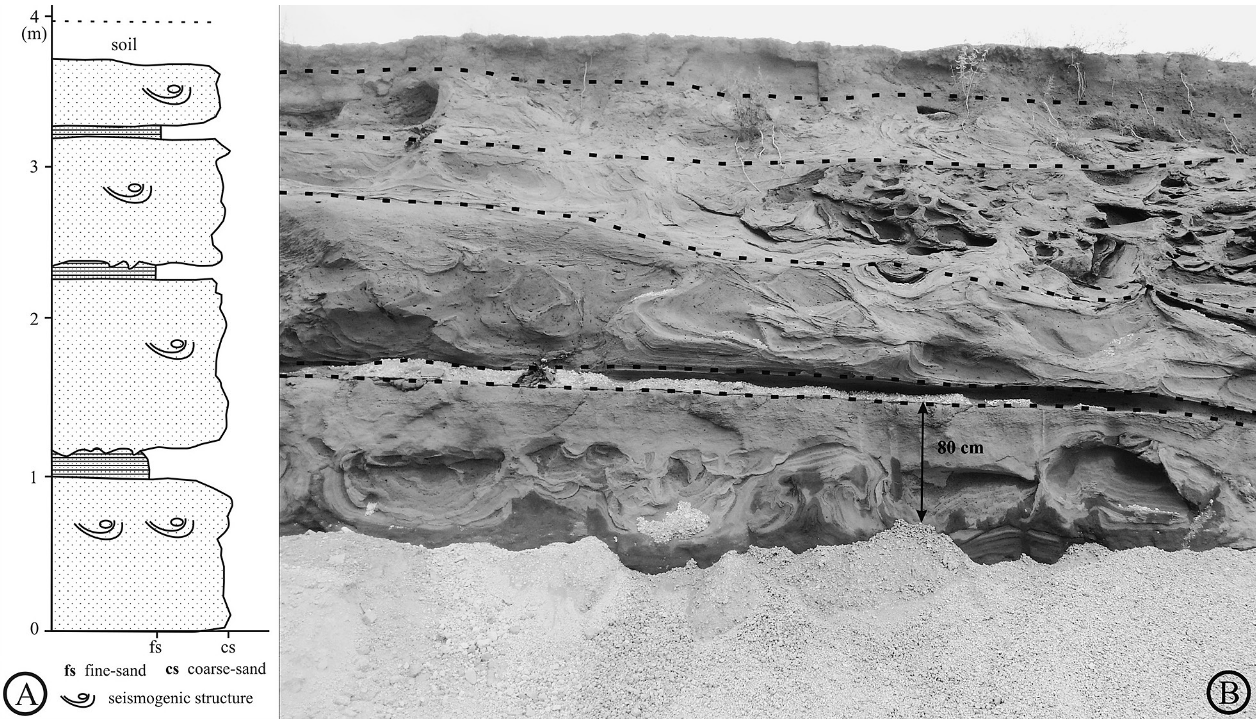

Fig. 9. Cyclic repetitions of seismogenic deformation structures in lacustrine deposits of Lake Van. **A:** Schematic log; **B:** Exposure in the field.

does not provide counter-arguments (Moretti & Van Loon, 2014)

Soft-sediment deformation structures have been classified in various ways (Lowe, 1975; Rossetti, 1999; Rodriguez-Pascua et al., 2000; Van Loon, 2002, 2009). Most of these classifications were prepared by evaluating the origin, formative mechanisms and morphological features. In this study, the soft-sediment deformations in the seismites are classified into three categories based on morphological features and the interpreted deformation processes (fluid-escape structures, contorted structures, and other structures).

Several studies deal with the question at which magnitude of an earthquake and at what distance from the epicentre seismites can originate. The commonly accepted opinion is that liquefaction can be induced by earthquakes with magnitudes > 5 and that seismites then can come into being (Allen, 1986; Scott & Price, 1988). How far away from the epicentre seismites can still originate has been the subject of only few studies, however. Scott & Price (1988) came to the conclusion that an earthquake with a magnitude of 7 can cause liquefaction in an area with a distance of 20 km from the epicentre. A maximum distance of 100 km would, however, be possible for earthquakes with magnitudes >8 according to other studies (Galli & Meloni, 1993; Moretti et al., 1995). The influence of the depth of the earthquake is, however, usually overlooked in such investigations: a deep earthquake will not have the same effect as a shallower one. Sand volcanoes formed due to the Van-Tabanlı Earthquake ($M_w = 7.2$) on October 23rd, 2011 up to 21 km away from the epicentre.

5. Conclusions

Based on their shapes, sizes, and locations the soft-sediment deformation structures in the lacustrine seismites of Lake Van Basin were divided into three groups: fluid-escape structures, contorted structures, and other structures.

Lake Van Basin formed in a tectonically active region. Seismites formed within sandy, silty and clayey lacustrine deposits are present at different levels west and north of the basin. The widespread occurrence of seismites at different levels indicates that the Lake Van Basin and its close vicinity were subject to frequent earthquakes with magnitudes ≥5 during the Late Quaternary. Taking the locations of these seismites and faults in the region into consideration, it must be deduced that several faults caused the shocks that led to the origin of the seismites.

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References

Acarlar, M., Bilgin, A.Z., Elibol, E., Erkan, T., Gedik, İ., Güner, E., Hakyemez, Y., Şen, A.M., Uğuz, M.F. & Umut, M., 1991. *Van Gölü doğusu ve kuzeyinin jeolojisi* [Geology of the eastern and northern part of Lake Van]. The Mineral Research and Exploration Institute of Turkey (MTA) Rept. 9469, 94 pp. (in Turkish).

Alan, H., Bozkurt, E., Çağlan, D., Dirik, K., Özkaymak, Ç., Sözbilir, H. & Topal, T., 2011. Van earthquakes report (Tabanlı and Edremit). *Chamber of Turkish Geological Engineers Report* 110, 48 pp.

Alfaro, P., Moretti, M. & Soria, J.M., 1997. Soft-sediment deformation structures induced by earthquakes (seismites) in Pliocene lacustrine deposits (Guadix-Baza Basin, central Betic Cordillera). *Eclogae Geologicae Helvetiae* 90, 531–540.

Allen, C.R., 1975. Geological criteria for evaluating seismicity. *Geological Society of American Bulletin* 86, 1041–1057.

Allen, J.R.L., 1986. Earthquake magnitude-frequency, epicentral distance and soft-sediment deformation in sedimentary basins. *Sedimentary Geology* 46, 67–75.

Ambraseys, N.N., 1988. Engineering seismology. *Earthquake Engineering and Structural Dynamics* 17, 1–105.

Atkinson, G., 1984. Simple computation of liquefaction probability for seismic hazard applications. *Earthquake Spectra* 1, 107–123.

Bhattacharya, H.N. & Bandyopadhyay, S., 1998. Seismites in a Proterozoic tidal succession, Singhbhum, Bihar, India. *Sedimentary Geology* 119, 239–252.

Bowman, D., Korjenkov, A. & Porat, N., 2004. Late-Pleistocene seismites from Lake Issyk-Kul, The Tien Shan range, Kyrghyztan. *Sedimentary Geology* 163, 211–228.

Chen, J. & Lee, H.S., 2013. Soft-sediment deformation structures in Cambrian siliciclastic and carbonate storm deposits (Shandong Province, China): differential liquefaction and fluidization triggered by storm-wave loading. *Sedimentary Geology* 288, 81–94.

Chen, J., Chough, S.K., Chun, S.S. & Han, Z., 2009a. Limestone pseudoconglomerates in the Late Cambrian Gushan and Chaomidian Formations (Shandong Province, China): soft-sediment deformation induced by storm-wave loading. *Sedimentology* 56, 1174–1195.

Chen, J., Van Loon, A.J., Han, Z. & Chough, S.K., 2009b. Funnel-shaped, breccia-filled clastic dykes in the Late Cambrian Chaomidian Formation (Shandong Province, China). *Sedimentary Geology* 221, 1–6.

Chen, J., Chough, S.K., Han, Z. & Lee, J.-H., 2011. An extensive erosion surface of a strongly deformed limestone bed in the Gushan and Chaomidian Formations (late Middle Cambrian to Furongian), Shandong Province, China: sequence–stratigraphic implications. *Sedimentary Geology* 233, 129–149.

Dasgupta, P., 1998. Recumbent flame structures in the Lower Gondwana rocks of the Jharia Basin, India – a plausible origin. *Sedimentary Geology* 119, 253–261.

Degens, E.T., Wong, H.K., Kempe, S. & Kurtman, F., 1984. A geological study of Lake Van, eastern Turkey. *Geologische Rundschau* 73–2, 701–734.

Degens, E.T., Wong, H.K., Kurtman, F. & Finckh, P., 1978. Geological development of Lake Van: a summary. [In:] E.T. Degens & F. Kurtman (Eds): *The geology of Lake Van*. The Mineral Research and Exploration Institute of Turkey (MTA) Publication 169, 134–146.

Fukuoka, M., 1971. Memories of earthquake and foundations. *Bridges and Foundations* 5, 1–10.

Galli, P. & Meloni, F., 1993. Nuovo catalogo dei processi di liquefazione avvenuti in occasione dei terremoti storici in Italia. *Il Quaternario* 6, 271–292 (in Italian).

He, B., Qiao, X., Jiao, C., Xu, Z., Cai, Z., Guo, X., Zhang, Y. & Zhang, M., 2014. Paleo-earthquake events in the late Early Palaeozoic of the central Tarim Basin: evidence from deep drilling cores. *Geologos* 20, 105–123.

Hempton, M.R., Dunne, L.A. & Dewey, J.F., 1983. Sedimentation in an active strike-slip basin, southeastern Turkey. *Journal of Geology* 91, 401–412.

Kempe, S., Khoo, F. & Gürleyik, Y., 1978. Hydrography of Lake Van and its drainage area. [In:] E.T. Degens & F. Kurtman (Eds): *The geology of Lake Van*. The Mineral Research and Exploration Institute of Turkey (MTA) Publication 169, 30–44.

Koçyiğit, A., 2013. New field and seismic data about the intraplate strike-slip deformation in Van region, East Anatolian plateau, E. Turkey. *Journal of Asian Earth Sciences* 62, 586–605.

Koçyiğit, A., Yılmaz, A., Adamia, S. & Kuloshvili, S., 2001. Neotectonic of East Anatolian Plateau (Turkey) and Lesser Caucasus: implication for transition from thrusting to strike-slip faulting. *Geodinamica Acta* 14, 177–195.

Kuzucuoğlu, C., Christol, A., Mouralis, D., Doğu, A.F., Akköprü, E., Fort, M., Brunstein, D., Zorer, H., Fontugne, M., Karabıyıkoğlu, M., Scaillet, S., Reyss, J.L. & Guillou, H., 2010. Formation of the Upper Pleistocene terraces of Lake Van. *Journal of Quaternary Science* 25, 1124–1137.

Litt, T., Krastel, S., Sturm, M., Kipfer, R., Örçen, S. & Çağatay, M.N., 2009. *Van Gölü Sondaj Projesi 'PALEOVAN', Uluslararası Bilimsel Kıta Sondaj Programı (ICDP): Yaklaşan Derin Sondaj Seferi ve Bilimsel Hedefler.* [Lake Van drilling project], 62. Türkiye Jeoloji Kurultayı Bildiri Özleri (Ankara), 718–719 (in Turkish).

Lowe, D.R., 1975. Water escape structures in coarse-grained sediments. *Sedimentology* 22, 157–204.

Molina, J.M., Alfaro, P., Moretti, M. & Soria, J.M., 1998. Soft-sediment deformation structures induced by cyclic stress of storm waves in tempestites (Miocene, Guadalquivir basin, Spain). *Terra Nova* 10, 145–150.

Moretti, M. & Sabato, L., 2007. Recognition of trigger mechanisms for soft-sediment deformation in the Pleistocene lacustrine deposits of the Sant 'Arcangelo Basin (southern Italy): seismic shock vs. overloading. *Sedimentary Geology* 196, 31–45.

Moretti, M. & Van Loon, A.J., 2014. Restrictions to the application of 'diagnostic' criteria for recognizing ancient seismites. *Journal of Palaeogeography* 3, 13–24.

Moretti, M., Alfaro, P., Caselles, O. & Canas, J.A., 1999. Modelling seismites with a digital shaking table. *Tectonophysics* 304, 369–383.

Moretti, M., Pieri, P., Tropeano, M. & Walsh, N., 1995. Tyrrhenian seismites in Bari area (Murge–Apulian foreland). *Atti dei Convegni Licenci* 122, *Terremoti in Italia, Roma* 1–2/12, 211–216.

Obermeier, S.F., 1996. Use of liquefaction-induced features for paleoseismic analysis – an overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. *Engineering Geology* 44, 1–76.

Obermeier, S.F., 1998. Liquefaction evidence for strong earthquakes of Holocene and latest Pleistocene ages in the states of Indiana and Illinois, USA. *Engineering Geology* 50, 227–254.

Obermeier, S.F., Jacobson, R.B., Smott, J.P., Weems, R.E., Gohn, G.S., Monroe, J.E. & Powards, D.S., 1989. Earthquake-induced liquefaction features in the coastal setting of south Carolina and the fluvial setting of the New Madrid seismic zone. *United States Geological Survey Professional Paper* 1504, 44 pp.

Özkaymak, Ç., Sözbilir, H., Bozkurt, E., Dirik, K., Topal, T., Alan, H. & Çağlan, D. 2012. 23 Ekim 2011 Tabanlı-Van Depreminin Sismik Jeomorfolojisi ve Doğu Anadolu'daki Aktif Tektonik Yapılarla İlişkisi [Seismic geomorphology of the October 23, 2011 Tabanlı-Van earthquake and its relation to active tectonics of East Anatolia]. *Jeoloji Mühendisliği Dergisi* 35, 175–199 (in Turkish).

Perucca, L.P., Godoy, E. & Pantano, A., 2014. Late Pleistocene-Holocene earthquake-induced slumps and soft-sediment deformation structures in the Acequion River valley, Central Precordillera, Argentina. *Geologos* 20, 147–156.

Plaziat, J.C. & Ahmamou, M., 1998. Les differents mécanismes a l'origine de la diversité des seismites, leur identification dans le Pliocene du Saiss de Fes et de Meknes (Maroc) et leur signification tectonique. *Geodinamica Acta* 11, 183–203.

Ricci Lucchi, F., 1995. Sedimentological indicators of paleoseismicity. [In:] L. Serva & D.B. Slemmons (Eds): *Perspectives in paleoseismology*. Association of Engineering Geologists Special Publication 6, 7–17.

Ringrose, P.S., 1989. Paleoseismic (?) liquefaction event in late Quaternary lake sediment at Glen Roy, Scotland. *Terra Nova* 1, 57–62.

Rodríguez-Lopez, J.P., Merléndez, N., Soria, A.R., Liesa, C.L. & Van Loon, A.J., 2007. Lateral variability of ancient seismites related to differences in sedimentary facies (the syn-rift Escucha Formation, mid-Cretaceous, Spain). *Sedimentary Geology* 201, 461–484.

Rodriguez-Pascua, M.A., Calvo, J.P., De Vicente, G. & Gómez-Gras, D., 2000. Soft sediment deformation structures interpreted as seismites in lacustrine sediments of the Prebetic Zone, SE Spain, and their potential use as indicators of earthquake magnitudes during the Late Miocene. *Sedimentary Geology* 135, 117–135.

Rossetti, D.F., 1999. Soft-sediment deformational structures in late Albian to Cenomanian deposits, Sao Luis Basin, northern Brazil: evidences for paleoseismicity. *Sedimentology* 46, 1065–1081.

Sarkar, S., Choudhuri, A., Banerjee, S., Van Loon, A.J. & Bose, P.K., 2014. Seismic and non-seismic soft-sediment deformation structures in the Proterozoic Bhander Limestone, central India. *Geologos* 20, 89–103.

Scott, B. & Price, S., 1988. Earthquake-induced structures in young sediments. *Tectonophysics* 147, 165–170.

Seed, H.B. & Idriss, I.M., 1982. *Ground motions and soil liquefaction during earthquakes.* Earthquake Engineering Research Institute (Berkeley), 134 pp.

Seilacher, A., 1969. Fault-graded beds interpreted as seismites. *Sedimentology* 13, 155–159.

Seilacher, A., 1984. Sedimentary structures tentatively attributed to seismic events. *Marine Geology* 55, 1–12.

Sims, J.D., 1975. Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. *Tectonophysics* 29, 141–152.

Spence, G.H. & Tucker, M.E., 1997. Genesis of limestone megabreccias and their significance in carbonate sequence stratigraphic models: a review. *Sedimentary Geology* 112, 163–193.

Şaroğlu, F. & Yılmaz, Y., 1986. Doğu Anadolu'da neotektonik dönemdeki jeolojik evrim ve havza modelleri [Geological evolution and basin models of the neotectonic period at Eastern Anatolia]. *Maden Tetkik ve Arama Dergisi* 107, 73–94 (in Turkish).

Şengör, A.M.C. & Yılmaz, Y., 1981. Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics* 75, 181–241.

Taşgın, C.K. & Türkmen, İ., 2009. Analysis of soft-sediment deformation structures in Neogene fluvio-lacustrine deposits of Çaybağı formation, eastern Turkey. *Sedimentary Geology* 218, 16–30.

Üner, S., Yeşilova, Ç., Yakupoğlu, T. & Üner, T., 2010. Pekişmemiş sedimanlarda depremlerle oluşan deformasyon yapıları (sismitler): Van Gölü Havzası, Doğu Anadolu [Earthquake-induced soft-sediment deformation structures (seismites): Van Gölü Basin, eastern Anatolia]. *Bulletin for Earth Sciences* 31, 53–66.

Valente, A., Ślącka, A. & Cavuoto, G., 2014. Soft-sediment deformation in Miocene deep-sea clastic deposits (Cilento, southern Italy). *Geologos* 20, 67–78.

Van Loon, A.J., 2002. Soft-sediment deformations in the Kleszczów Graben (central Poland). *Sedimentary Geology* 147, 57–70.

Van Loon, A.J., 2009. Soft-sediment deformation structures in siliciclastic sediments: an overview. *Geologos* 15, 3–55.

Van Loon, A.J., 2014a. The life cycle of seismite research. *Geologos* 20, 61–66.

Van Loon, A.J., 2014b. The Mesoproterozoic 'seismite' at Laiyuan (Hebei Province, E China) re-interpreted. *Geologos* 20, 139–146.

Van Loon, A.J. & Maulik, P., 2011. Abraded sand volcanoes as a tool for recognizing paleo-earthquakes, with examples from the Cisuralian Talchir Formation near Angul (Orissa, eastern India). *Sedimentary Geology* 238, 145–155.

Van Loon, A.J. & Mazumder, R., 2011. Can once lithified rocks later undergo soft-sediment deformation? *Sedimentary Geology* 238, 101–105.

Van Loon, A.J., Han, Z. & Han, Y., 2013. Origin of vertically oriented clasts in brecciated shallow-marine limestones of the Chaomidian Formation (Furongian, Shandong Province, China). *Sedimentology* 60, 1059–1070.

Van Loon, A.J. & Pisarska-Jamrozy, M., 2014. Sedimentological evidence of Pleistocene earthquakes in NW Poland induced by glacio-isostatic rebound. *Sedimentary Geology* 300, 1–10.

Visher, G.S. & Cunningham, R.D., 1981. Convolute laminations – a theoretical analysis: example of Pennsylvanian sandstone. *Sedimentary Geology* 28, 175–189.

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