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TECTONIC DEFORMATIONS IN THE QUATERNARY DEPOSITS OF THE LAKE VAN (EDREMİT BAY), EASTERN ANATOLIA, TURKEY

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Research Article

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ABSTRACT
The 23 October 2011 Van Earthquake (Mw: 7.2) was generated by the Van Fault Zone (VFZ) with reverse fault characteristics. The earthquake on the fault caused surface deformation with 10 cm displacement observed in engineering structures. On land the VFZ has general E-W strike and 28 km length. The western end of the fault is within Lake Van. This study aimed to determine the tectonic structures and evolution in the Quaternary of Edremit Bay using detailed mapping of the VFZ with land and underwater research methods, investigation of its continuation into Lake Van and common assessment of land and underwater data. Continental data showed the presence of E-W fold axes affecting Quaternary units in the hanging-wall and footwall of the VFZ. Offshore studies using shallow seismic profiling (GeoAcoustics) and multibeam bathymetric data acquisition determined that the underwater section of the VFZ had similar characteristics to those on land. Quaternary successions on the lake floor observed on seismic sections clearly showed folds in both blocks of the fault with axes parallel to the strike of the fault. The underwater ridge that is an extension of Çarpanak Cape coincides with the ridge structure on the hanging-wall block of the fault on land. Surface deformation related to the 23 October 2011 earthquake developed in a broad zone of the hanging wall of the VFZ. The research findings show the deformation along the VFZ in the Quaternary is in accordance with the deformations developing during the last earthquake.

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1. Introduction

Turkey is located in the Alpine-Himalayan earthquake belt. This area is a result of the continental collision between Arabia and Eurasia along the Bitlis-Zagros Thrust Zone, and presents active tectonic structures related to intracontinental approach in Eastern Anatolia and tectonic escape deformation in Central/Western Anatolia (Figure 1). Eastern Anatolia has been under a N-S directional compressional tectonic regime for nearly 12 million years (Middle-Upper Miocene) (Ketin, 1977; Şengör and Kidd, 1979; Şengör and Yılmaz, 1983; Dewey et al., 1986; Şaroğlu and Yılmaz, 1986; Yılmaz et al., 1987; Koçyiğit et al., 2001). The Van Earthquake (Mw: 7.2), occurred east of Lake Van on 23 October 2011 caused the death of more than 600 people and injured nearly 2000 people (AFAD) in addition to cause severe damage, is the most recent event showing the continuation of this compressional regime in the present day. Studies after the earthquake showed the source of the earthquake was the Van Fault Zone (VFZ) (Emre et al., 2011, 2012, 2013; Özalp et al., 2011; Özkaymak et al., 2011; Doğan and Karakaş, 2013; Koçyiğit, 2013). Although little information about activity of the fault at literature, the remaining area of the VFZ has been stated to be a nearly E-W trending, north-dipping active thrust/reverse fault cutting and deforming Late Pleistocene-Holocene age lake/stream units in previous studies (Özkaymak, 2003; Özkaymak et al., 2004). The earthquake did not produce a clear surface rupture on land, with deformation structures at the surface reflecting the thrust nature of the faulting mechanism and with this deformation affecting nearly 8 to 12 km on land (Emre et al., 2011, 2013; Özalp et al., 2011; Özkaymak et al., 2011; Doğan and Karakaş, 2013; Koçyiğit, 2013). The deformation structures observed on land ended northwest of Bardakçı village

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Figure 1- Active tectonic map of Turkey. Lines with filled triangles are active subduction zones, lines with empty triangles are active thrust belts on land, thick lines are strike-slip faults and notched thin lines are normal faults. Large dark arrows indicate direction of motion of lithospheric plates, values show GPS velocity relative to Eurasia (adapted from Okay et al., 2000; GPS velocity values taken from Reilinger et al., 2006).

on the shore of Lake Van and after the main shock the distribution of aftershocks in the region showed that the fault causing the earthquakes may continue toward the west on the floor of Lake Van (Figure 2).

According to earthquake catalogues, it is known that the study area and close surroundings experienced many destructive earthquakes in the historical period (<1900) (Ergin et al., 1967; Soysal et al., 1981; Tan et al., 2008; Ambraseys, 2009). The natural records relating to these earthquakes may be better preserved in unconsolidated or semi-consolidated sediments on the lake floor compared to on land. This study used high resolution shallow seismic marine geophysics and multibeam bathymetric mapping data for the eastern half of Lake Van to discuss and interpret the continuation of the VFZ, source of the 23 October 2011 Van Earthquake, on the lake floor and the deformation structures due to tectonics observed in Edremit Bay.

2. Neotectonic Setting

The world's largest sodic lake, Lake Van, is surrounded by the provinces of Van and Bitlis. In the north and west entirely volcanic in the south metamorphic and east are predominantly outcrops of sedimentary rocks are covered with fields that it is located in a region with many bays and capes. With area of 3,522 km² and volume of 607 km³, the lake circumference is 430 km (Kadıoğlu et al., 1997). At its widest point the distance from Van to Tatvan is 130 km, with a mean water level 1648 m above sea level, mean depth of 171 m and maximum depth of 460 m (Kempe et al., 1991; Kadıoğlu et al., 1997).

Neotectonic regime of Turkey began Middle-Upper Miocene about 12 million years ago as a result of continent-continent collision of the Arabian and Eurasian plates at Eastern Anatolia (Şengör and Kidd, 1979; Şengör, 1980; Şengör and Yılmaz, 1983; Dewey et al., 1986; Şaroğlu and Yılmaz, 1986; Yılmaz et al., 1987; Bozkurt, 2001; Koçyiğit et al., 2001). The right lateral strike-slip North Anatolian Fault (NAF), left lateral strike-slip East Anatolian Fault (EAF) and the active subduction zone formed by the subduction of African oceanic lithosphere under the Aegean Sea along the Hellenic-Cyprus Arc developing after the collision are the neotectonic structures playing major roles in shaping the Anatolian plate and surroundings (Figure 1) (Hempton, 1987; Koçyiğit et al., 2001). After continental collision in Eastern Anatolia the region entered a very active period tectonically

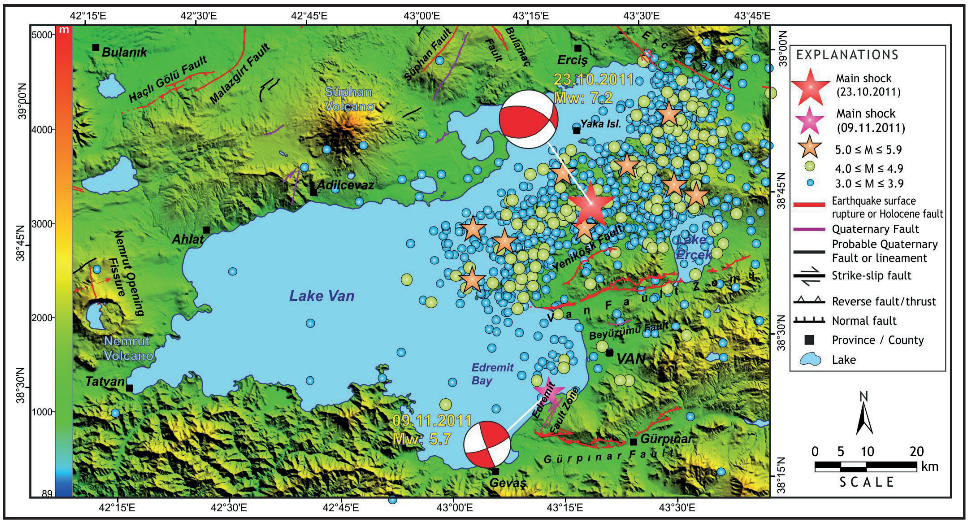

Figure 2- Map showing active faults in Lake Van and surroundings and distribution of main shock and aftershocks of the 23 October 2011 Van and 9 November 2011 Edremit earthquakes. Gürpınar Fault and Edremit Fault zone taken from Özalp et al. (2015); Beyüzümü Fault from Ateş et al. (2007); other active faults from Emre et al. (2013) and seismological data from Kandilli Observatory (KRDAE) records.

with simultaneous volcanic activity began. During the neotectonic period, the result of dominant N-S directed compression was a complicated tectonic structures comprising diagonal NE-SW left lateral and NW-SE right lateral strike slip faults, E-W fold axes, reverse faults and thrusts, N-S oriented normal faults or extensional fractures, were formed in the Eastern Anatolia high plateau (Şaroğlu, 1985; Şaroğlu and Yılmaz, 1986; Şaroğlu et al., 1987, 1992; Bozkurt, 2001; Koçyiğit et al., 2001; Emre et al., 2013). Parallel to the compression direction, the N-S oriented extensional fractures controlled volcanic output. After continent-continent collision, crustal shortening developed in this period and the regional elevation increased (Şaroğlu and Yılmaz, 1986; Yılmaz et al., 1987; Şengör et al., 2003, 2008; Dhont and Chorowicz, 2006; Zor, 2008; Tezel et al., 2013).

One of the most important geological structures formed by continent-continent collision is the Bitlis Zagros Thrust Belt (Şengör, 1979; Şengör and Yılmaz, 1981), extending to the Iranian border (Figure 1). The Lake Van Basin, immediately north of the Bitlis Zagros Thrust Belt, is located east of the Karlıova triple junction where the NAF and EAF intersect (Figure 1). The basin began to form in the Late Pliocene and it is proposed that the effect of volcanism gained its current form at the beginning of the Quaternary (Blumenthal et al., 1964; Wong and Finckh, 1978; Degens et al., 1984). Lake Van contains three important basins called Tatvan, North and Deveboynu, separated by ridges (Cukur et al. 2013, 2014). The deepest of these, the Tatvan Basin, has been determined to contain 600,000 years of lacustrine sediments (Litt et al., 2014; Cukur et al., 2013, 2014). The Deveboynu Basin is smaller than Tatvan with 1.5 km E-W extension and 6 km N-S extension and average water depth of 300 m (Cukur et al. 2013, 2014). The study area placed on a section, nearly 18 km shelf with E-W orientation and nearly 8 km of slope feeding the Deveboynu Basin from the east.

One of the important records of the tectonism playing an effective role in shaping Lake Van Basin is seismites. The term seismite defined for the first time by Seilacher (1969) is generally used for fine gravel, sandy and silty deposits and deformation structures that may form due to earthquakes. These structures develop due to liquefaction of unconsolidated sediments which are important in terms of reflecting the occurrence of ancient earthquakes. Seismites are commonly observed within Quaternary-aged lacustrine sediments outcropping east of Lake Van (Üner et al., 2010), indicating the region has a very active structure in terms of seismicity.

There are many active faults in the Eastern Anatolia regions that are sources of earthquakes. 13 September 1924 Pasinler (Ms: 6.8), 6 September 1975 Lice (Ms: 6.6), 24 November 1976 Çaldıran (Ms: 7.5), and 30 October 1983 Horasan-Narman (Ms 6.9) earthquakes are all large earthquakes which occurred in the instrumental period, apart from the 2011 Van earthquake. Before the 2011 Van earthquake the number of mapped active faults in the region was so few as to be insignificant (Ketin, 1977; Şaroğlu et al., 1987, 1992; Koçyiğit et al., 2001; Özkaymak, 2003; Özkaymak et al., 2004). However, the focal mechanism results from some moderate earthquakes occured east and southeast of Lake Van in the years between 1988-2003 indicated the presence of almost E-W thrust/reverse faults in this area producing earthquakes (Özkaymak et al., 2004; Üner et al., 2010). The 23 October 2011 Van earthquake (Mw: 7.2) indicated the region is still being formed by the effect of a N-S oriented compressional tectonic regime and is the most recent event proving the presence of the VFZ. After this earthquake many studies were carried out about the active tectonics of the region (Emre et al., 2011, 2012, 2013; Özalp et al., 2011; Özkaymak et al., 2011; Doğan and Karakaş, 2013; Koçyiğit, 2013; Görür et al., 2015). Of the current tectonic structure in the region and surroundings where the 23 October 2011 Van earthquake occurred, the Erciş, Çaldıran, Hasantimur Gölü, Süphan and Malazgirt faults are strike-slip. The Muş thrust forms the northern boundary of the Muş Basin, the western continuation of the Lake Van Basin. The Nemrut extensional fissure, where Nemrut volcanism outcrops, is the best example of extensional structures in Eastern Anatolia (Şaroğlu, 1985; Şaroğlu et al., 1987, 1992).

3. Onshore Features of 23 October 2011 Van Earthquake Surface Rupture

About 10 km north of the Van City, the VFZ extends in a nearly E-W direction on land between Lake Erçek and Lake Van (Figure 2). Fault was firstly named and mapped as an active fault by Emre et al. (2012), the total length of the fault on land is 28 km. The eastern tip of the fault is within Lake Erçek while the western tip is located within Lake Van. Morphologically, the north block of the fault is higher than the south block (Figure 3a). On land a 12 km section extending east from Lake Van is a single fault, while toward the east it bifurcate into two parallel sections 17 km long and 2 km wide (Figure 2 and 3b).

In the east the VFZ is geologically observed within an accretionary prism (Sümengen, 2008) comprised of ophiolitic, metamorphic, volcano-sedimentary, sedimentary and carbonate rocks developed in the age between the Late Permian and Early Miocene. The western segment cuts Early Eocene-Pliocene sedimentary and carbonate rocks (Sümengen, 2008), Quaternary age slope debris, alluvial fans and fluvial deposits and sequences comprised of terrace and delta deposits from Lake Van (Özalp et al., 2015). Morphologically though the fault is defined by broken slope terrain in the field, findings of old surface faulting showing Holocene activity is not clear. Additionally folding observed in Quaternary lacustrine-fluvial deposits, elevated lake terraces and ancient coastal markings are formations in the hanging-wall block documenting the activity of the fault.

The 23 October 2011 Van earthquake (Mw: 7.2) was originated from the E-W oriented VFZ between Lake Van and Lake Erçek nearly 10 km north of the city of Van and at 16 km depth (Figure 2; Emre et al., 2011, 2012, 2013). The earthquake caused nearly 12 km of surface rupture in the western section of the VFZ. The surface ruptures that developed were observed as uncontinuous hairline fractures, causing deformation of asphalt and stabilized roads and concrete water canals perpendicular to the fault (Emre et al., 2011, Özalp et al., 2011; Doğan and Karakaş, 2013). The fault plane solutions of the main shock of 23 October 2011 earthquake, aftershock earthquake distribution and field findings revealed that the source fault had nearly E-W oriented reverse fault/thrust characteristics (Figure 2).

Fault planes preserved within basement units N-NE of the Van Organized Industrial Zone were measured (Table 1) and kinematic analysis was performed. Analysis of fault planes used the method recommended by Marrett and Allmendinger (1990) in FaultKinWin 1.2 [computer program developed for analysis of fault plane data by Almendinger vd. (2001)] and results are presented as fault plane solutions (Figure 3c). Accordingly results obtained from measurements taken for kinematic analysis of the VFZ show that in this section of the zone the fault segment developed under the effect of NW-SE compressional forces and is a dip-slip reverse fault with a very small right lateral strike-slip component.

4. Offshore Studies

4.1. Data Acquisition and Processing

To analyze the continuation of the VFZ on the floor of Lake Van and all details of other tectonic

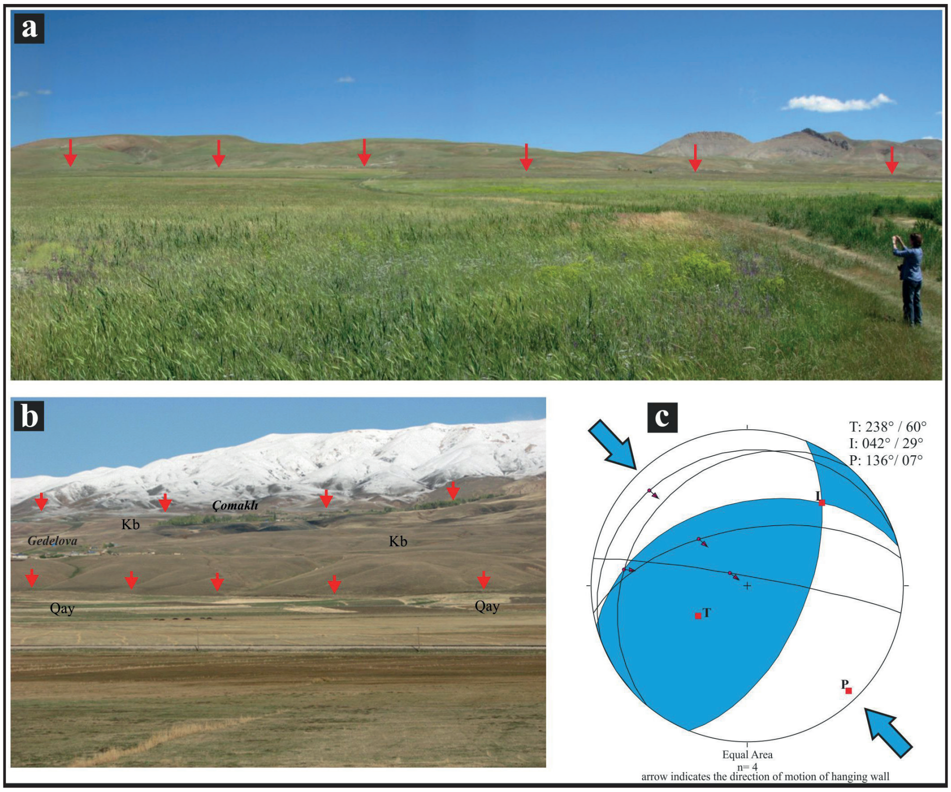

Figure 3- (a) General appearance of VFZ (view N-NW) observed between basement units and ancient alluvial fan sediments (Qey) east of Van Organized Industrial Zone. (b) General appearance of VFZ splitting (view N-NW) between the Bakışık melange (Kb) and alluvial fan sediments (Qay) west of Erçek Lake. (c) Equal-area lower-hemisphere of plane data belonging to the VFZ (P: compression axis; T: extension axis; I: central axis). Fault plane solutions used FaultKinWin (V. 1.2.2, Allmendinger, 2001).

Table 1- Data related to fault planes measured in the field for kinematic interpretations of the VFZ.

No	Longitude E	Latitude N	Strike	Dip Degree and Direction	Rake Angle and Direction	Strike-Dip Value (Right Hand Rule)
1	352835	4272770	N70°E	15°NW	60° West	250/15
2	352800	4273080	N40°E	25°NW	60° West	220/25
3	352517	4272953	N80°W	85°NE	80° West	280/85
4	352500	4272943	N80°E	60°NW	60° West	260/60

deformation structures in Edremit Bay, geophysical studies were completed in the area between Çarpanak Island and Edremit. The gathered data were compared with structures observed on land with the aim of ensuring a holistic view. During the study completed in 2012, high resolution shallow seismic data were gathered along the planned lines with the 14 m Fatih65 boat (Figure 4). The line directions were selected to be perpendicular to the extension of the VFZ on land where it entered the lake at the shore. Due to shallowing of the lake in the eastern section of Edremit Bay, seismic records could not be gathered due to the proximity of the shore. Additional to this study, a multibeam echo sounder was used to determine traces and effects of faults or deformation that may be visible on the floor of the lake and floor morphology was investigated with the gathered data.

During this data acquisition stage, the data were collected by a GeoAcuoustics system consisting of a Boomer energy source, a single channel hydrophone, a receiver with filters, a recorder, and a power supply. The pulse of energy was between 175–280J depending on the depth and the frequency of the pulse was 200Hz–7 kHz. According to vertical resolution theory at this frequency interval, is about 5-20 cm. The sampling interval was 40 microseconds. During data processing, the mean water velocity (1475-1490 m/s) measured by CTD which was used time to depth. Additionally as it was a single channel system, the basic data processing modules of filtering and gain processing were applied to data. For bathymetry a multibeam echo sounder (Elac SeaBeam 1050D) with 180 kHz transducer was used. During recording, navigation was ensured by using the Hypack program with the aid of GPS.

4.2. Bathymetry and Underwater Morphology

Depth data were collected along seismic lines determined at 2 km intervals and this data was assessed to investigate morphology variations. The map was created by evaluating data, not by the method of multibeam depth measurements of full coverage, that is created not only line data collected with multibeam echo sounder but also previously completed bathymetry maps (Wong and Degens, 1978; SHOD, 1985) were investigated to prepare a map ensuring a general approach to bathymetry in the study area (Figure 4).

To research the continuation on the lake floor of surface deformations observed on land on the fault causing the earthquake, the effects of freshwater and sediment inputs into the lake and wind and currents were evaluated together. The results of this investigation did not encounter clear deformation due to the fault at the resolution of the obtained map on the lake floor morphology similar to on land.

When the map is examined, at the most eastern of Edremit Bay, it is observed that the depths gradually increase westward from the shore. Depth is parallel to the shore first -25 m, then -50 m and continues to increase to -100 m and after reaching depth of -300 m towards the Deveboynu Basin (Figure 4).

4.3. Seismic Stratigraphy

This study was performed by using seismic reflection methods recorded structures observed on the floor of Edremit Bay forming the southeast section of Lake Van and presents significant data for interpretation. This data provides a significant contribution to observations of the effects of forces affecting the region in the neotectonic period on the floor of Lake Van and to research of the western extension of the VFZ on the lake floor.

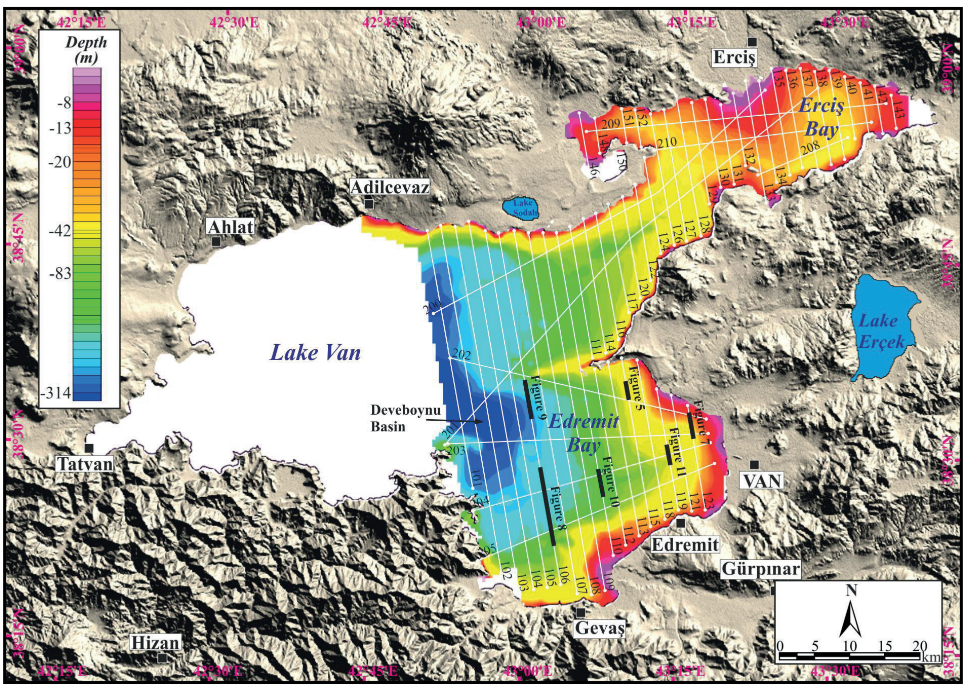

Figure 4- Location of bathymetry and seismic and hydrographic lines in Lake Van. Bathymetry was produced from data collected during this study using a multi-beam depth sounder at line intervals of ~2 km and previous studies.

On seismic lines two main stratigraphic types of reflection data were observed; (1) seismic units with clear or semiclear continuous reflection (Figure 5; seismic units shown with orange and red) and (2) seismic units that are unclear or not continuous (Figure 5; seismic units between the orange and red units). The seismic units in the first group were interpreted as geological lacustrine sedimentary sequences. The seismic units in the second group were assessed as mass flows due to tectonic or volcanic shaking of sediments that found on slightly more inclined surfaces or basement rock units overlain by basin sediments.

4.4. Faults and Other Tectonic Deformations

4.4.1. Van Fault Zone

Line 115 is the most clear profile that VFZ is observed on the lake floor (Figure 4). Along the line the deformation structure with reverse fault/thrust character with fallen southern block along the nearly E-W oriented fault is very clearly observed. When the seismic units presenting clear and continuous reflection affected by the fault are investigated, within the upper young sediments the dip slip amount on the fault has a very small value, while at lower levels in older sediments, the slip amount reaches higher values (Figure 5). This deformation structure in the fault zone is the most important data that showing the fault continuously produced earthquakes from past to present. Additionally along the zone the deformation structures in the current sediments on the footwall and hanging-wall blocks are other important structures showing current activity of the fault (Figure 5). The fold structure related to compressional deformation close to north of the upthrust block of the fault is noteworthy. According to the investigated seismic lines, the VFZ is interpreted to extend along the lake floor toward the west for nearly 9 km (Figure 6).

South of the VFZ the zone of faults striking between E-W and N70°W with observable length from 7-15 km with variable reverse fault/thrust character is noteworthy (Figure 6). Along Line 123 where this fault zone is clearly observed, the reverse fault/thrust faults are clearly seen to cut basement and overlying younger seismic units (Figure 7). Within the thrust belt when placement of seismic units clearly distinguished due to different reflection characteristics are evaluated, it appears that the northern blocks of all faults are elevated. According to seismic data and the tectonic structure of the region, all structures in the fault belt are interpreted as slices belonging to a system thrusting from north to south.

4.4.2. N-S Fault

The structure on seismic sections bounding the east of Deveboynu Basin in the west of Edremit Bay was remarkable. This tectonic structure with nearly NNE-SSW orientation is clearly observed on Line 106 (Figure 8). On the profile representing the area between Gevaş and Sodalı Lake, the structure appears to be a fault zone with length of 10 km (Figure 6) and width of 500 m (Figure 8). Three different seismic units are observed at the North section of the fault zone. The uppermost unit has a semi-prominent non-continuous reflection profile. Below this is a level of seismic units with very clear, continuous and parallel reflections. At the bottom there is a seismic unit with semi-prominent appearance and lacking continuation in all areas. Taking account of the location within the region’s tectonic regime, the geometry of the structure and the seismic units it cuts, it was interpreted as a left lateral strike-slip fault zone (Figure 6). Though not clear on seismic profiles, it is considered that this structure may continue for a certain length to the SW.

4.4.3. Çarpanak Ridge

The ridge known as Çarpanak Island at the west of Çitiören village northwest of Van city continues into Lake Van in the form of a cape. Seismic reflection and multibeam bathymetry studies observed that this ridge on land continues toward the west on the lake floor (Figure 6). On seismic sections, the sections including the western extension of the Çarpanak Ridge are observed to contain deformation structures. In the central section of Line 106, in the area south of the Çarpanak Ridge a reverse fault/thrust structure is noted (Figure 9). Interpretation of seismic units (yellow and orange lines) differentiated by reflection characteristics and used as marker horizons found the fault, with a strike-slip component, appears to affect current sediments on the lake floor.

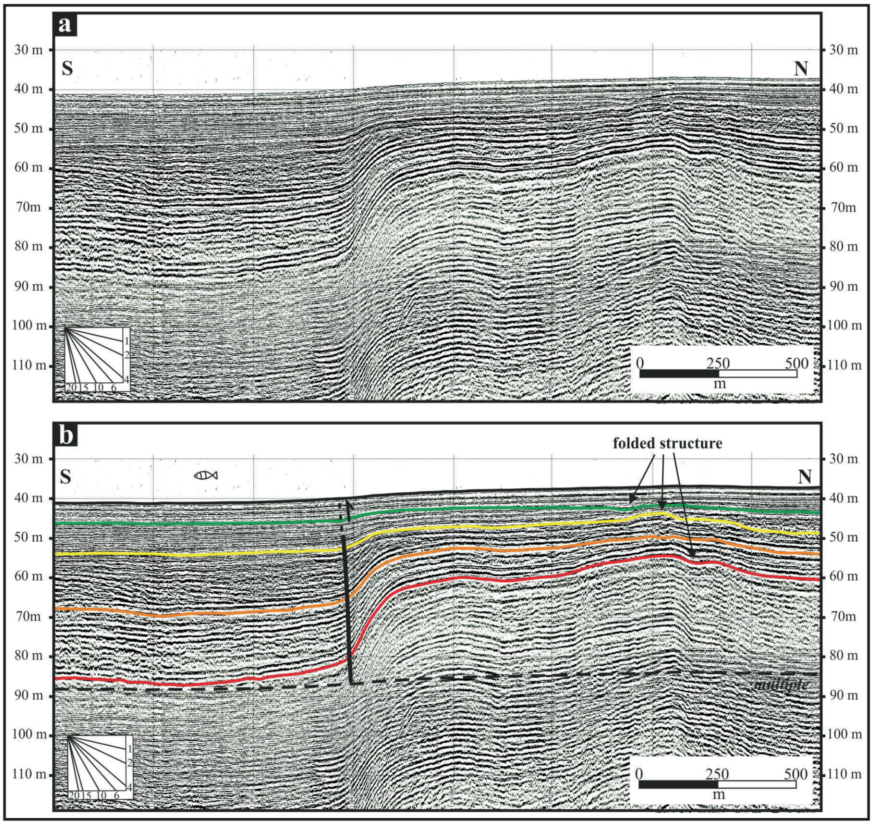

Figure 5- (a) Single channel high resolution shallow seismic system (GeoAcoustics) profile of the north section of Line 115 taken between Çarpanak Cape and Edremit (for profile location see figure 4). (b) Interpretation of the profile. The western extension of the VFZ in this section on the lake floor is shown with a thick black line. Moving to previous periods the slip amount in seismic units shown in different colors cumulatively increased and the development of a fold structure is observed in the hanging-wall.

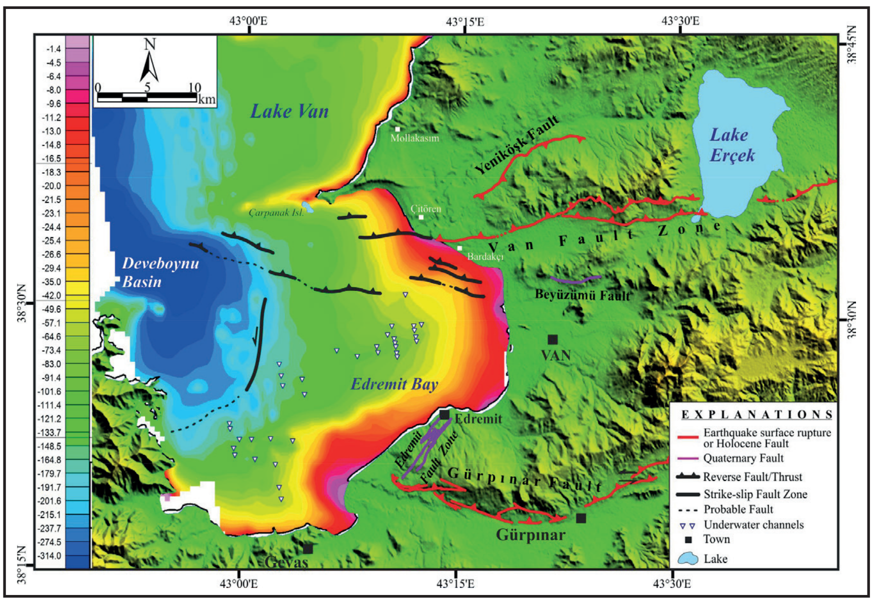

Figure 6- Map showing western continuation of the Van Fault Zone and other structures within Lake Van interpreted from seismic profiles and active faults observed on land. Depth map was produced using multibeam sounder on lines at intervals of 2 km and mapping from previous years. On land the Beyüzümü Fault was taken from Ateş et al. (2007); Van Fault Zone and Yeniköşk Fault from Emre et al. (2013); and Gürpınar Fault and Edremit Fault Zone from Özalp et al. (2015).

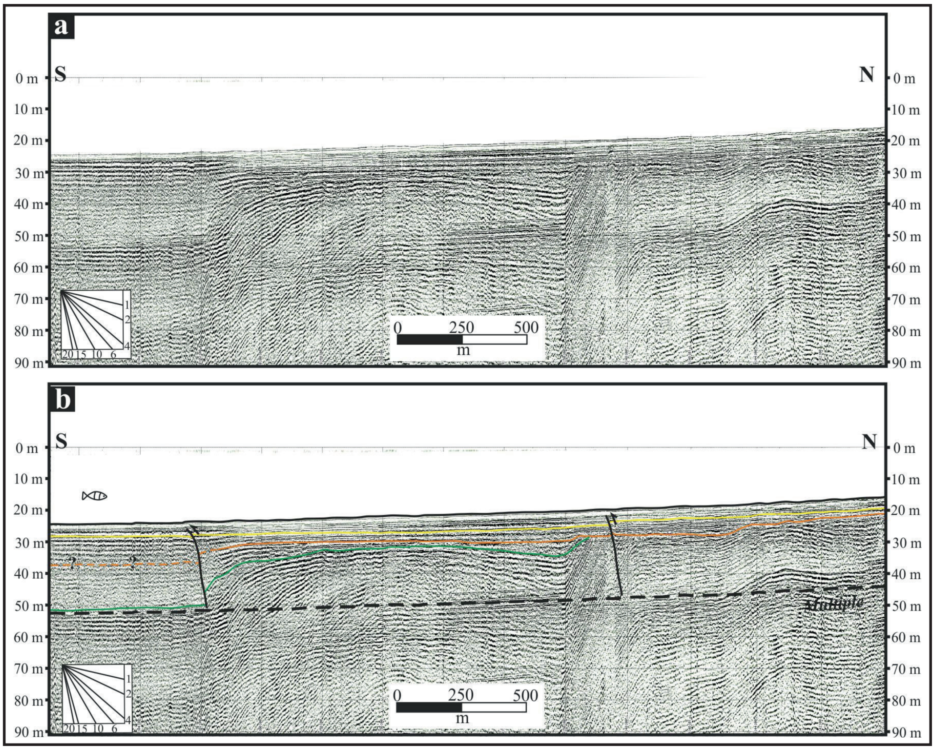

Figure 7- (a) Single channel high resolution shallow seismic system (GeoAcoustics) profile of the north section of Line 123 taken from Bardakçı village to Edremit (for profile location see figure 4). (b) Interpretation of the profile. In this section structures related to the fault zone observed on the lake floor south of the VFZ are shown with thick black lines and the seismic units affected by these structures are shown with colored lines.

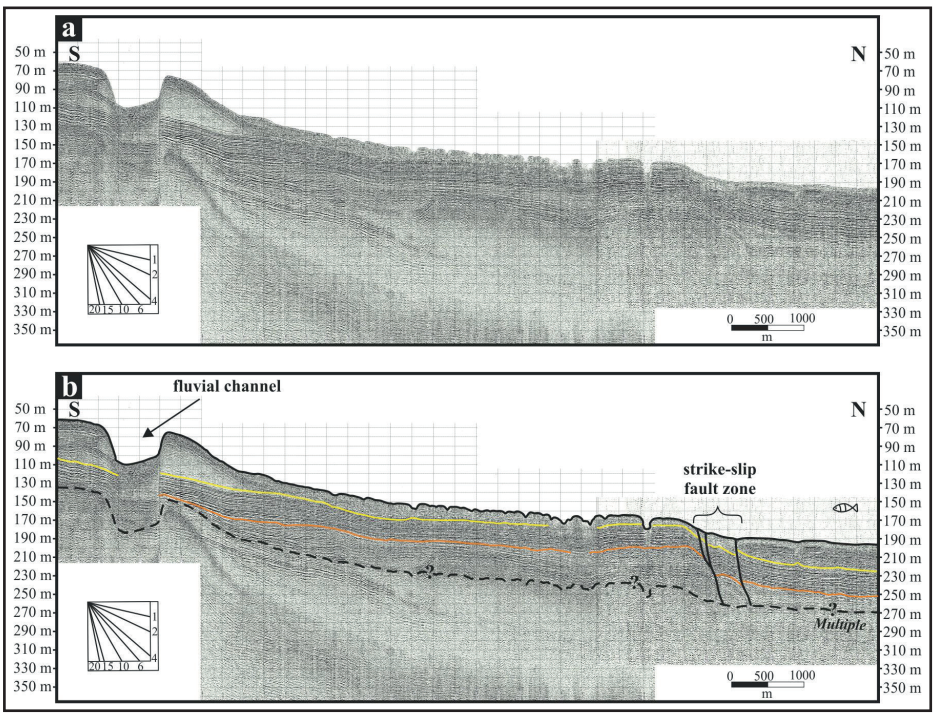

Figure 8- (a) Single channel high resolution shallow seismic system (GeoAcoustics) profile of the south section of Line 106 taken between Gevaş and Sodalı Lake (for profile location see figure 4). (b) Interpretation of the profile. In the south of this section a broad and deep fluvial channel is observed on the lake floor, in the north structures related to a strike-slip fault zone are mapped in thick black lines and the seismic units affected by these structures are shown with colored lines.

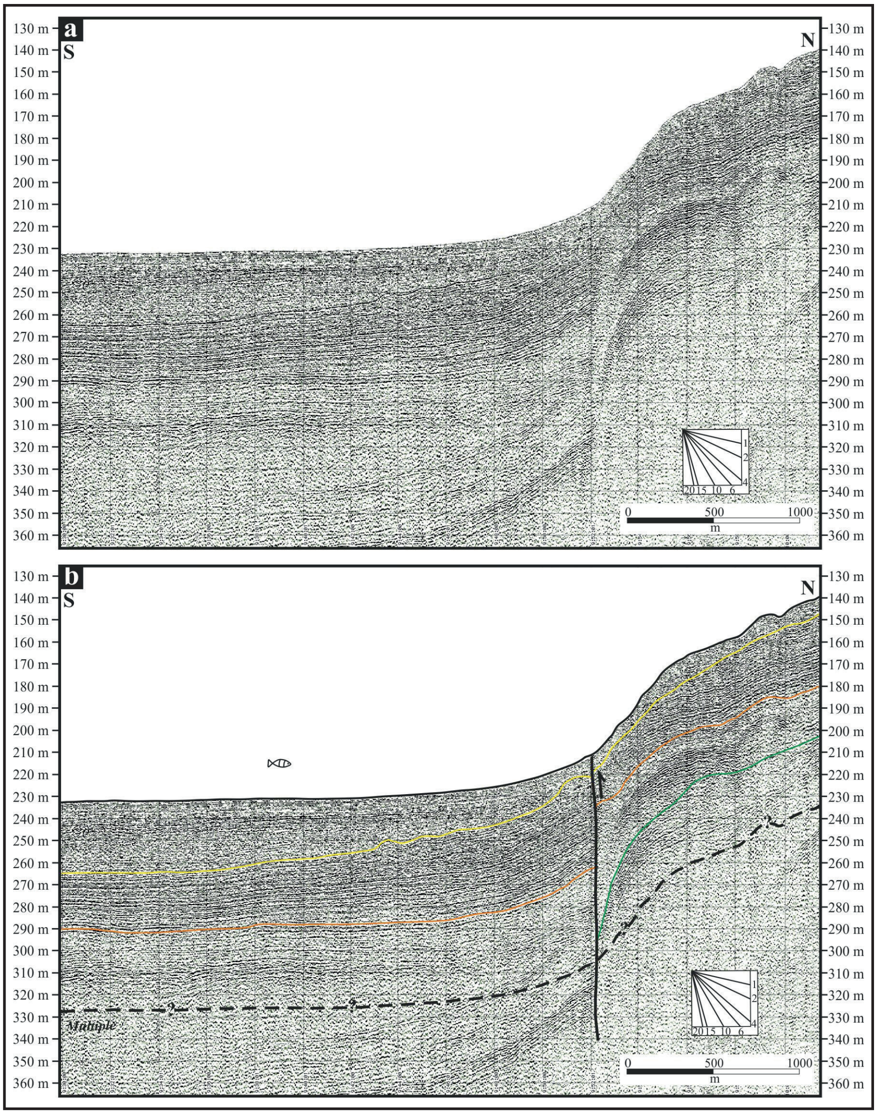

Figure 9- (a) Single channel high resolution shallow seismic system (GeoAcoustics) profile of the west section of Line 106 between Gevaş and Sodalı Lake (for profile location see figure 4). (b) Interpretation of the profile. A reverse fault/thrust immediately south of the Çarpanak Ridge is observed on the lake floor. Within units in the footwall and hanging-wall of the fault folded structures are found to develop linked to the direction of compression.

4.4.4. Paleo-Drainage Channels

On seismic sections there are fluvial channels commonly observed on the shelf. These channels are evaluated as structures that developed due to the shelf being above water until recent times as a result of climatic or tectonic effects. On seismic lines, there are channel structures observed in many different areas of the lake floor (Figure 6). The channels observed on the floor of Edremit Bay on Lines 106 and 110, generally have a U-shaped geometry with depths of nearly 40 m and widths up to 900 m (Figures 8 and 10). Another example of a channel observed on seismic lines are buried sediment-filled channels. The example on Line 119 of a buried fluvial channel defines paleogeographic changes in the lake water level linked to climate. These structures are important to indicate periods when the lake level fell and the shelf became land. On figure 11 the discordance between seismic units distinguished by different reflection characteristics is clearly observed. Above the older seismic units shown with purple and green lines, a V-shaped fluvial channel developed shown with a red line and representing an erosion surface during a period when the lake level fell. After this period, the fluvial channel observed on this section was drowned again and was filled and

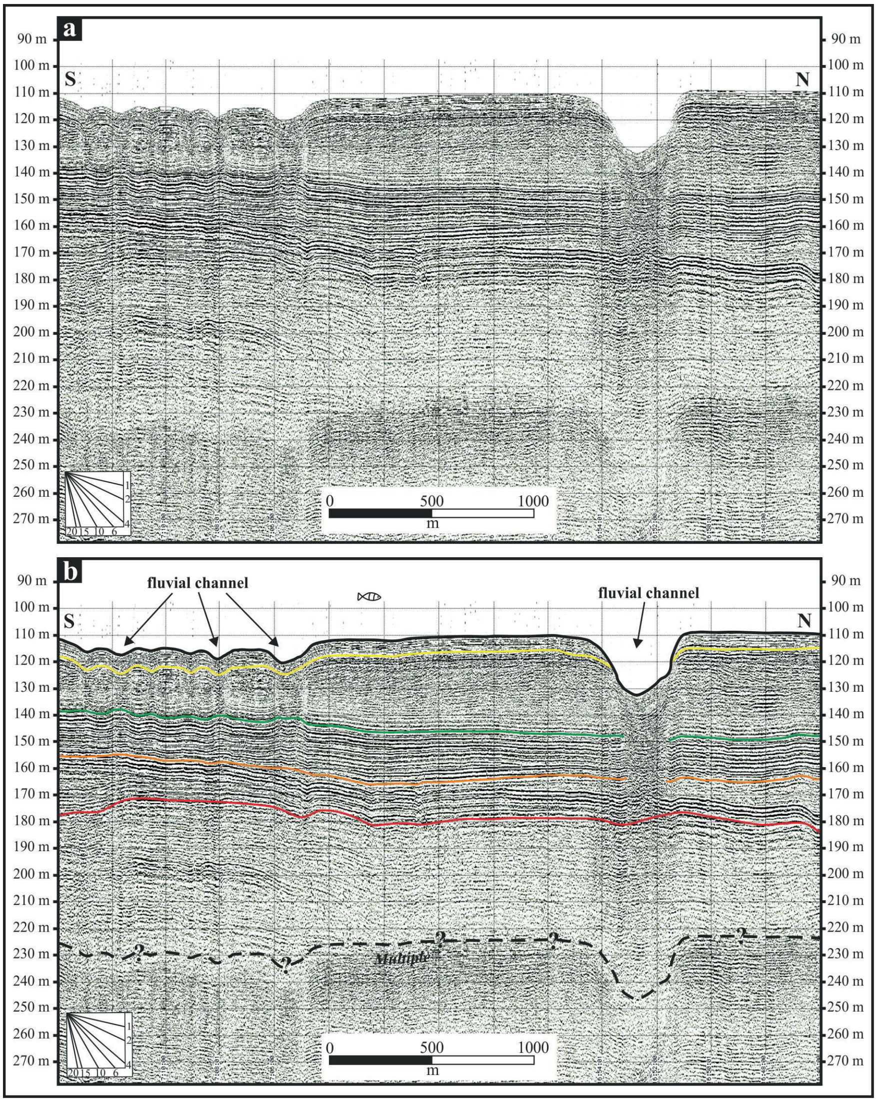

Figure 10- (a) Single channel high resolution shallow seismic system (GeoAcoustics) profile of the south section of Line 110 between Gevaş and Sodalı Lake (for profile location see figure 4). (b) Interpretation of the profile. In this section of slope portions of Edremit Bay, in the very south many fluvial channels are observed. Additionally in deeper areas to observe seismic reflection units more easily they are shown in different colors.

buried by younger sedimentary packets shown with blue and yellow lines.

5. Discussion and Conclusions

The Eastern Anatolian region, containing Lake Van, has been compressed in a N-S direction since the Late Miocene (Şaroğlu and Yılmaz, 1984; Dewey et al., 1986; Bozkurt, 2001; Şengör et al., 2003, 2008; Dhont and Chorowicz, 2006; Elitok and Dolmaz, 2008; Zor, 2008; Tezel et al., 2013). As a result, extensional fractures parallel to the N-S compression direction, E-W fold axes, reverse faults and thrusts and NW-SE oriented right lateral and NE-SW left lateral strike-slip faults have begun to form (Şaroğlu, 1985; Şaroğlu and Yılmaz, 1986; Bozkurt, 2001; Koçyiğit et al., 2001; Özkaymak et al., 2011; Koçyiğit, 2013). One of these structures and the source of the 23 October 2011 Van earthquake is the VFZ, without clear old surface faulting proving activity during the Holocene but with slope breaks in morphology allowing recognition of the fault. This situation may be explained in three ways; (1) the recurrence interval for earthquakes resulting with surface rupture on the fault is very long, (2) previous earthquakes developed similar surface deformations with the last earthquake as described above and (3) the active erosion processes in the region are more rapid than tectonic effects. The 23 October

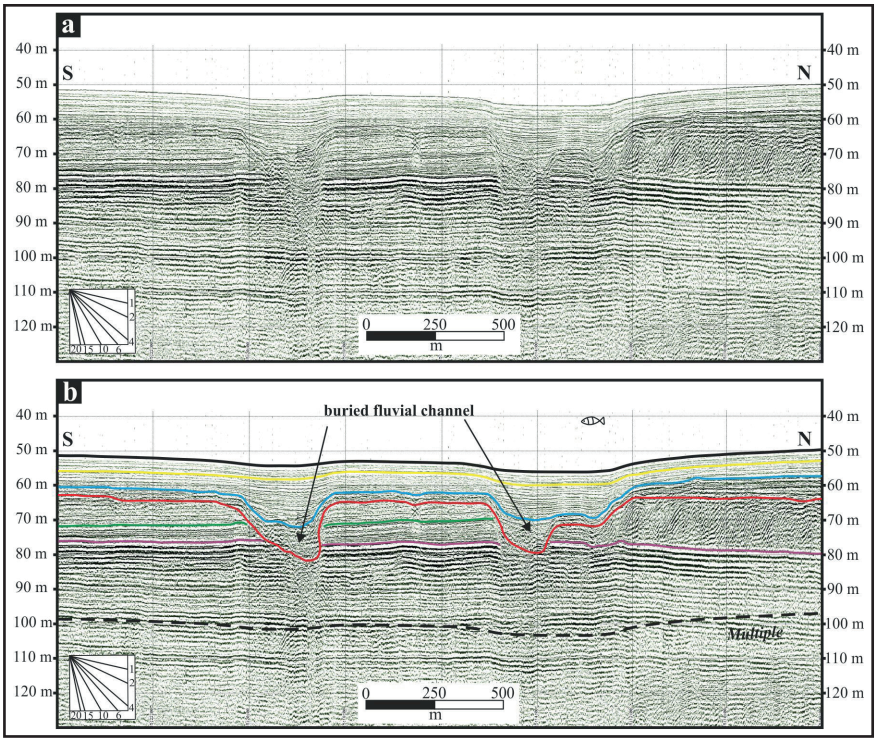

Figure 11- (a) Single channel high resolution shallow seismic system (GeoAcoustics) profile of the central section of Line 119 taken between Edremit and Çitören village (for profile location see figure 4). (b) Interpretation of the profile. In the eastern section of Edremit Bay buried fluvial channels are observed on the lake floor. To observe the structure seismic units are shown in different colors. The V-shaped valley formation in older units is filled with current sediment packets from a later period.

2011 Van earthquake is the most current example proving the presence of N-S compressional tectonic processes affecting Eastern Anatolia, and showing that the earthquake hazard in Eastern Anatolia is at least as high as in other regions of the country. After the earthquake, field studies along the VFZ and shallow seismic profiling studies in Edremit Bay in the lake have mapped structures (Figure 6).

Investigation of seismic data collected from the eastern half of Lake Van observed similar characteristics underwater as on land and mapped these structures on the lake floor. Accordingly, the source fault for the 23 October 2011 Van Earthquake was determined to continue nearly 9 km to the west based on deformation structures observed on the lake floor. However, due to the properties of the systems used no clear findings were obtained related to surface rupture. Additionally in accordance with the tectonic structure of the region, south of the VFZ a zone comprising reverse component faults with nearly E-W orientation and length reaching 15 km was determined. This fault zone mapped by this study (Figure 6) and the reverse fault bounding the north of Deveboynu Basin (Figure 12) interpreted during studies in the west of Lake Van by Cukur et al. (2014) are concordant with each other in terms of strike and mechanism. Another important tectonic structure in the same area is the nearly N-S fault bounding the east of the Deveboynu Basin. This structure, interpreted as a strike-slip fault according to seismic sections and regional tectonic setting, was mapped as an east-dipping normal fault zone by Cukur et al. (2014) (Figures 6 and 12). Apart from these tectonic structures folds in young sediments especially on land are widely observed on seismic lines on the lake floor (Figure 5). These structures mapped in the hanging-wall and footwall of the VFZ have E-W strikes in accordance with reverse fault/thrust structures developed by N-S compression.

In the western section of Lake Van, studies of the Ahlat Basin have identified the age of the oldest sediment in the lake basin as 600,000 years (Litt et al., 2014; Cukur et al. 2013, 2014). As a result the units over the basement observed within Edremit Bay must be deposited from the Holocene-Middle Pleistocene.

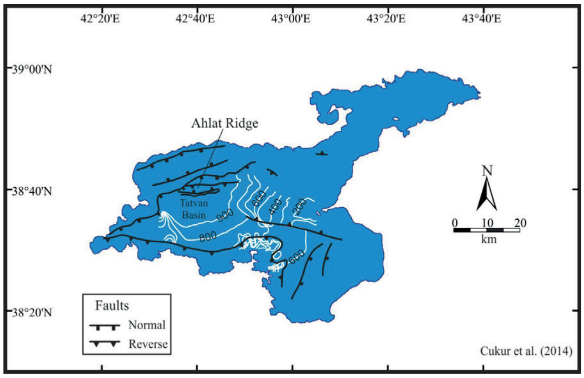

Figure 12- Depth of the upper section of acoustic basement of the southwest of Lake Van. Acoustic basement deepens toward the west. E-W striking reverse faults are observed locally. Acoustic basement was not resolved in the northwest and northeast sections of the lake. Contour interval is 50 m (adapted from Cukur et al., 2014).

Studies completed in the region after the 23 October 2011 Van earthquake observed shoreline changes that may cause in the physical geography of Lake Van (Emre et al., 2011; Özalp et al., 2011). The most important of these was a rise in the shoreline of nearly 40 cm observed near Çarpanak Island closest to the earthquake epicenter. Additionally near Mollakasım village, satellite images clearly observed elevated shorelines from previous periods (Emre et al., 2011). During studies, nearly ENE-WSW striking reverse faults and fold axes affecting Miocene-Late Quaternary sedimentary deposits were observed north and south of the Çarpanak Ridge on land and on the lake floor and active structures cutting Quaternary-Holocene age units were observed on seismic sections of the lake floor (Figure 6). Koçyiğit (2013) mentioned the presence of an active reverse fault with significant left lateral strike-slip component immediately south of the ridgewith ENE strike and 25 km length. This situation is explained by active structures observed on land and on the lake floor south of the Çarpanak Ridge being affected by similar tectonic activity to the latest earthquake during the recent geologic past (Late Quaternary-Holocene).

Important data to show seismic activity in the historical or prehistorical period of a region are seismites. Seismites are structures developing linked to liquefaction of unconsolidated sediments. According to Atkinson (1984), in order for liquefaction to occur, an earthquake must have magnitude (M) of at least 5. However, according to a study by Moretti (2000) investigating the correlation between earthquake source and liquefaction, more than 90% of liquefaction areas are within 40 km of the earthquake epicenter, while the remaining 10% are found at maximum 100 km distance related to large earthquakes. Our studies on land have encountered seismites in the Plio-Quaternary age Büyükçay Formation SE of Andaç village on the Van-Gevaş road (Figure 13) (UTM: 0341721 E, 4244340 N). These structures, while drawing attention to the current tectonic situation of the region, show that earthquakes of M 5.0 or above due to active faults or volcanism have frequently occurred.

Seismic reflection data offer significant clues related to the lake's recent history apart from structural interpretations. On lines in the section forming the study area of the lake, fluvial channels were very clearly observed on the lake floor. While Wong and Degens (1978) and Wong and Finckh (1978) assessed these structures as similar to karst structures, Cukur et al. (2013) interpreted them as braided channel systems forming as a result of erosion

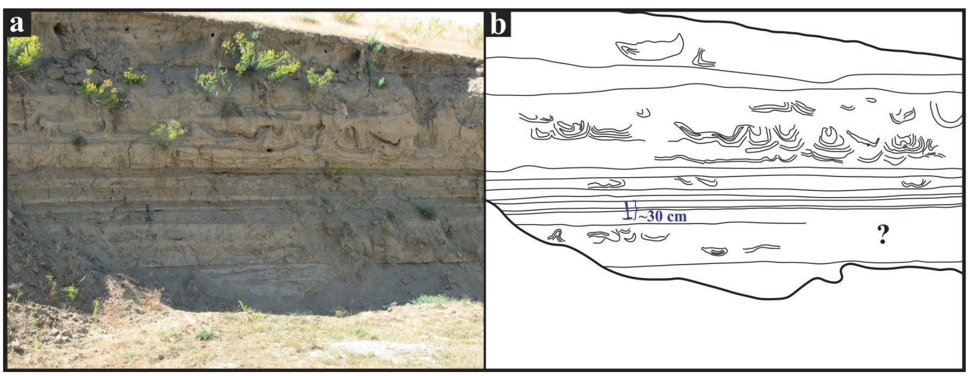

Figure 13- (a) General appearance of seismites (view SW) observed within sandstone, siltstone and conglomerate forming Plio-Quaternary lacustrine and fluvial sediments SE of Andaç village on the Van-Gevaş road in the study area. (b) Interpretative sketch of the photograph.

by sediment-loaded flows within horizontally layered fan sediments based on new seismic data. According to a morphology map created by Cukur et al. (2015) using multi-beam bathymetry data, they proposed these structures are normal channel structures of a drainage system. According to Wong et al. (1978) and Wong and Degens (1978), during the last low level of the lake from 7500 to 4500 years ago erosion was very active and from that time channels were probably preserved and flattened. We observed two different fluvial channels on the lake floor. The first of these developed in parallel to climatic changes in previous times when the water level in the lake fell and then when the lake level rose, was drowned and then filled with young sediments and buried. The other developed on land formed in the period when the lake level last fell, and when the lake level rose remained as fluvial channels without infilling by sediment packets. These structures provide important data in terms of proving the many climatic falls and later rises in lake level in previous times.

According to the results of this study obtained from land and offshore data from Lake Van basin, deformation structures are observed over a very wide area, the region is very active tectonically and active faults have the potential to produce large earthquakes. In terms of regional earthquake risk analysis, in addition to the VFZ, all active faults in the region are significant. As a result it is recommended that fault parameters such as the slip rate and recurrence interval of these active structures be determined by paleoseismology and GPS studies.

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