Geologica Acta, Vol.15, Nº 2, June 2017, 107-120
DOI: 10.1344/GeologicaActa2017.15.2.3

geologica acta

New active faults on Eurasian-Arabian collision zone: Tectonic activity of Özyurt and Gülsünler faults (eastern Anatolian Plateau, Van-Turkey)

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ABSTRACT

The Eastern Anatolian Plateau emerges from the continental collision between Arabian and Eurasian plates where intense seismicity related to the ongoing convergence characterizes the southern part of the plateau. Active deformation in this zone is shared by mainly thrust and strike-slip faults. The Özyurt thrust fault and the Gülsünler sinistral strike-slip fault are newly determined fault zones, located to the north of Van city centre. Different types of faults such as thrust, normal and strike-slip faults are observed on the quarry wall excavated in Quaternary lacustrine deposits at the intersection zone of these two faults. Kinematic analysis of fault-slip data has revealed coeval activities of transtensional and compressional structures for the Lake Van Basin. Seismological and geomorphological characteristics of these faults demonstrate the capability of devastating earthquakes for the area.

KEYWORDS **Lake Van Basin. Eastern Anatolia Plateau. Compressional tectonics. Kinematic analysis. Quaternary faults.**

INTRODUCTION

Continental collision zones are sites of intense crustal deformation resulting in different geological processes such as crustal thickening, regional contraction, and volcanic activity. These zones present a complex tectonism commonly including thrusts and folds, and other structural elements such as strike-slip faults (Sylvester, 1988; Mann, 2007; Dooley and Schreurs, 2012). Studies of the later are much less common in those contexts. The Himalayan collision zones are well-known examples of this tectonism (Zhao *et al*., 2010).

Ongoing continental collision between the northward moving Arabian and quasi-stationary Eurasian plates gave rise to the formation of the Eastern Anatolian Plateau (EAP) since Middle Miocene (Şengör and Kidd, 1979; Şengör and Yılmaz, 1981; Dewey *et al*., 1986; Keskin *et al*., 1998) (Fig. 1A). The southern part of the EAP is a key region for understanding the tectonic activity and related deformation pattern of this collision zone where numerous researchers have focused since the 1980's. These studies indicate that major structures related to this tectonic activity are NE-striking sinistral, NW-striking dextral strike-slip faults and coeval E–W-trending reverse and N–S-trending normal

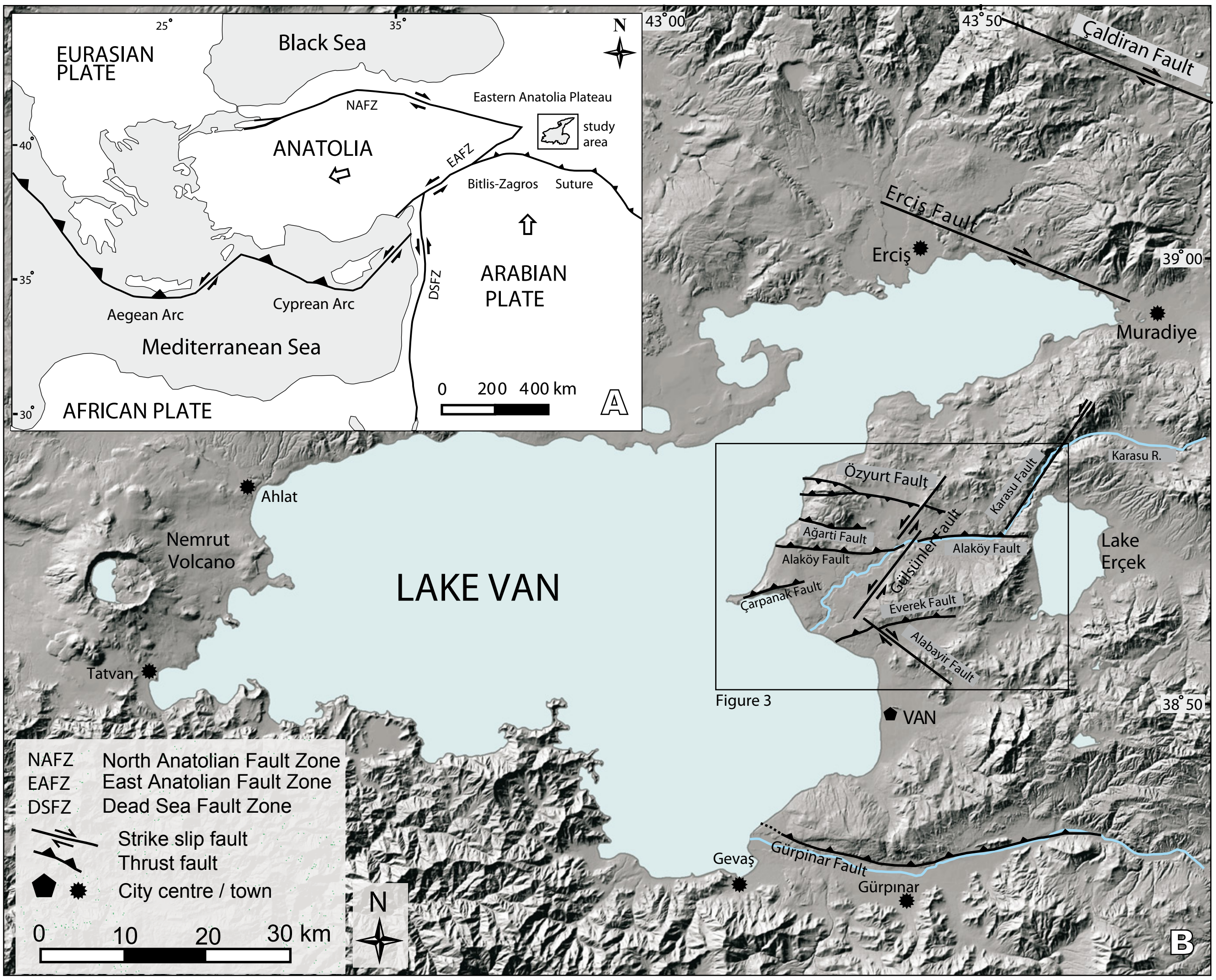

FIGURE 1. A) Major neotectonic features of Turkey and adjacent areas (white arrows indicate the motion of the plates), B) location map showing active faults on eastern part of Lake Van Basin.

faults. (Dewey *et al.*, 1986; Şaroğlu and Yılmaz, 1987; Yılmaz *et al.*, 1998; Koçyiğit *et al.*, 2001; Özkaymak *et al.*, 2011; Doğan and Karakaş, 2013; Koçyiğit, 2013; Okuldaş and Üner, 2013).

Numerous basins appear related to this compressional tectonism such as the Pasinler, Muş, and Lake Van basins (Şaroğlu and Güner, 1979). The Lake Van Basin is located at the southern part of the EAP. It formed in the Late Pliocene and was shaped by the volcanism that was active during the Quaternary (Degens *et al.*, 1984). The basin contains the largest sodic lake in the world (Lake Van) which was formed approximately 600kyr ago (Stockhecke *et al.*, 2014). East of this depression there are several active faults (*e.g.* Everek, Alaköy, Çaldıran, and Gürpınar faults) (Fig. 1B) that generate dense seismicity (Şaroğlu and Yılmaz, 1987; Koçyiğit *et al.*, 2001; Özkaymak *et al.*, 2011; Koçyiğit, 2013; Mackenzie *et al.*, 2016).

The Özyurt fault and Gülsünler fault are two active faults located east of the Lake Van Basin that are defined for the first time in this paper. They extend from north of the Van metropolis to the centre of the basin (Fig. 1B). The aims of this paper are to analyse these two faults and to discuss their interaction with morphological and palaeoseismological data.

REGIONAL GEOLOGY

The northward motion of the Arabian plate with respect to the Eurasian plate caused crustal shortening, thickening, and uplift of the EAP since Middle Miocene times (Şengör and Kidd, 1979; Yılmaz *et al.*, 2010). Deformation was dominated by approximately E–W-trending thrust faults (Şaroğlu and Yılmaz, 1987; Koçyiğit, 2013). In this period, the plateau was raised about 2km (Koçyiğit *et al.*, 2001) and the compressional basins, such as the Lake Van Basin were formed (Şaroğlu and Güner, 1979). Progressive contraction caused the westward escape of the Anatolian plate along the North and East Anatolian fault Systems during the Late Pliocene (Şengör *et al.*, 1985) (Fig. 1A). The strike-slip faulting dominated neotectonic deformation in the EAP (Koçyiğit *et al.*, 2001). NW-trending dextral faults (Çaldıran, Erciş, and Alabayır faults), NE-trending sinistral strike-slip fault (Karasu fault), and E–W trending thrust faults (Ağartı, Alaköy, Everek, Çarpanak, and Gürpınar faults) are the major structures of the region (Şaroğlu and Yılmaz, 1987; Koçyiğit *et al.*, 2001; Özkaymak *et al.*, 2011; Koçyiğit, 2013) (Fig. 1B). These very close thrust faults are interpreted as splays from the main detachment surface (Özkaymak *et al.*, 2011). N–S-trending normal faults are rarely observed in the area.

The volcanic centers Nemrut, Süphan, Tendürek, and Ağrı (Ararat) were developed on the plateau during the neotectonic period in Quaternary. Most of the plateau is covered by the products of this volcanism (Yılmaz *et al.*, 1987; Keskin *et al.*, 1998; Aydar *et al.*, 2003; Karaoğlu *et al.*, 2005; Özdemir *et al.*, 2006) while other areas are filled with lacustrine and fluvial deposits.

STRATIGRAPHY

In this study, Miocene and older units that are unconformable onto Mesozoic and older rock units are considered as basement while younger sedimentary sequences correspond to the basin fill related to the evolution of Lake Van Basin (Fig. 2).

Basement units

The oldest basement units are the Bitlis metamorphic rocks, at the southern part of the basin, outside of the study area. They mainly consist of Palaeozoic–Mesozoic gneisses, meta-basic rocks, and schists (Oberhänslı *et al.*, 2010; Yılmaz *et al.*, 2010). Jurassic limestones, Upper Cretaceous ophiolitic rocks (Yüksekova mélange) and Oligocene-Miocene turbidites are found to the east of the basin (Acarlar *et al.*, 1991; Şenel, 2008) (Fig. 3). Ophiolitic rocks including mafic-ultramafic tectonites and cumulates are related to the evolution of the Neotethian Ocean during the Cretaceous (Yılmaz and Yılmaz, 2013). Shallow to deep marine turbidites formed by sandstone-mudstone alternation with gravelly layers deposited during the closure period of this ocean from Oligocene to Miocene times (Acarlar *et al.*, 1991).

Basin sediments

Basement units are unconformably overlain by Pliocene fluvial deposits, Quaternary volcanics and lacustrine sediments younger than 600kyr (Stockhecke *et al.*, 2014). The basin infill ends with Late Quaternary travertine and recent unconsolidated fluvial sediments (Acarlar *et al.*, 1991; Şenel, 2008) (Fig. 2).

The Pliocene fluvial deposits include red conglomerates-sandstones and mudstones. These units are unconformably overlain by Quaternary lacustrine deposits which are thin- to medium-bedded semi-consolidated gravel-sand-mud alternations. Thin-bedded, clayey deep water lacustrine deposits and sand-gravel rich shallow water and lake shore deposits are frequently observed along the eastern side of the Lake Van. Pelecipoda (Dreissena sp.) rich, shore deposits are eroded by deltaic or fluvial sediments in many places due to water level oscillations. Alternation of lacustrine deposits with fluvial sediments suggests large scale fluctuations in the shoreline of the Lake Van.

Volcanic rocks are commonly observed at the northern and northwestern parts of the Lake Van Basin (Fig. 3). They include basalts and pyroclastics, derived from Nemrut and Süphan volcanoes. Pyroclastic layers alternate with lacustrine deposits due to the activities of these volcanoes.

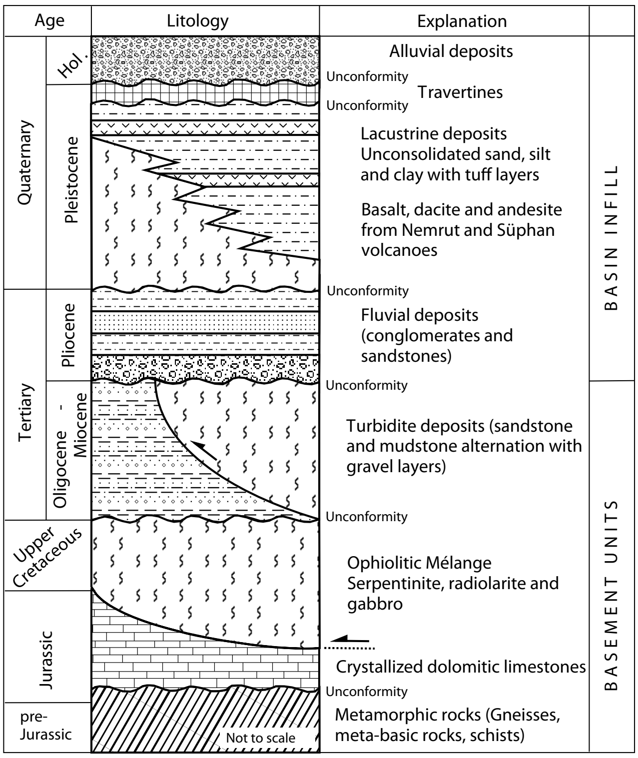

FIGURE 2. Tectono-stratigraphic chart of the study area (modified from Acarlar *et al.*, 1991; Şenel, 2008).

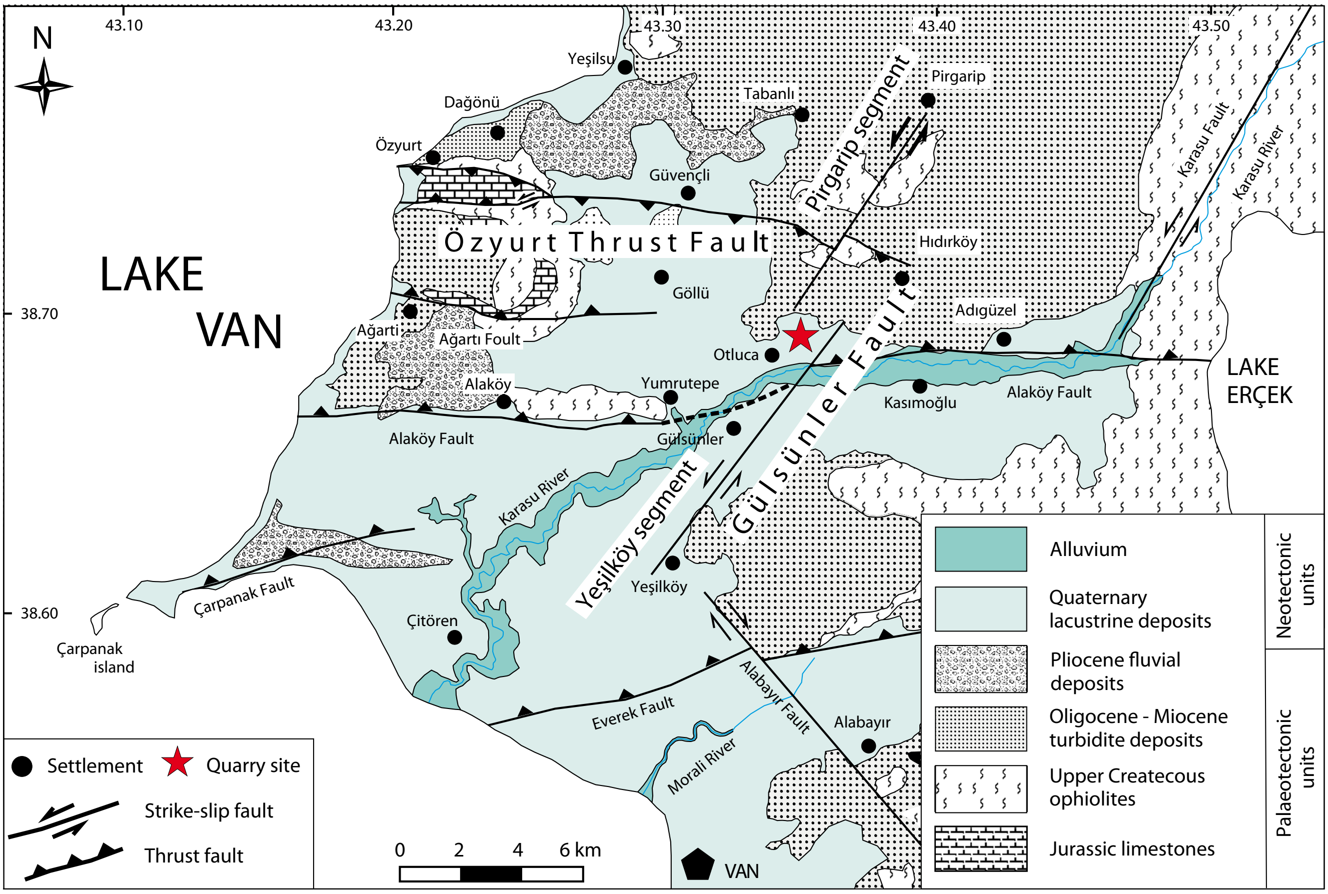

FIGURE 3. Geological map of the study area (modified from Acarlar *et al.*, 1991; Şenel, 2008).

Quaternary travertines and recent alluvial deposits are the youngest lithologies of the basin.

STRUCTURAL GEOLOGY

Methodology

Structural data, such as strike, dip, and slip-lineation measurements were collected from fault planes for determination of different deformation phases. Most of the data were obtained from gravel, sand, and silt-sized, semi-consolidated lacustrine deposits. Timing of faulting and deformation are distinguished by the age of the stratigraphic units and cross-cutting relationships.

Damian Delvaux's Tensor software (Win-Tensor 4.0.4) was used to analyze fault-slip data (Delvaux and Sperner, 2003). For the definition of the paleostress field, the nature of the vertical/sub-vertical stress axis and the value of ratio R were taken into calculations. Stress fields may vary from radial extension ($\sigma 1$ vertical, $0<R<0.25$), extension ($\sigma 1$ vertical) with pure extension ($0.25<R<0.75$) and transtension ($0.75<R<1$), to strike-slip stress fields ($\sigma 2$ vertical), with pure strike-slip ($0.25<R<0.75$), transtension ($0.75<R<1$) and transpression ($0<R<0.25$), or to compression ($\sigma 3$ vertical), with transpression ($0<R<0.25$), pure compression ($0.25<R<0.75$), and radial compression ($0.75<R<1$) (Delvaux *et al.*, 1997).

Özyurt thrust fault

Özyurt fault is a 19km long, E-W trending reverse fault that runs between Özyurt village to the west and Hıdırköy village to the east (Fig. 3). The southerly dipping eastern section of the fault, north of Hıdırköy, is the boundary between the Oligocene-Miocene turbidites and the Upper Cretaceous ophiolitic mélange units (Fig. 4A).

The western part of the Özyurt fault bifurcates into north and south branches to the west of Güvençli village. Southerly-dipping northern branch is 5km long which juxtaposes the Upper Cretaceous ophiolitic mélange units and Jurassic limestones (Fig. 4B-C). Northerly-dipping southern branch is 6km long which separates

FIGURE 4. Field photographs showing the Özyurt thrust fault; A) eastern part of the fault between Oligocene-Miocene turbidites and Upper Cretaceous ophiolitic mélange, B) northern branch of the western part of the fault, C) close-up view of the serpentinites from ophiolitic mélange and D) springs on southern branch of western part of the fault.

the same units (Fig. 3). Southern branch can clearly be followed by lithological borders and the alignment of water springs (Fig. 4D). The connection of the southern branch with eastern part of the Özyurt thrust fault is a NE–SW trending sinistral strike-slip fault near the Güvençli village (Fig. 5). The southern branch deforms the semi-consolidated, gravelly shore deposits of the Lake Van (Fig. 6A). Movement of the fault blocks caused re-orientation of pebbles along longitudinal axes in the fault zone (Fig. 6B). Prolongation of the branches cannot be observed to the west as the faults enter the Lake Van.

Fault-slip analysis of Özyurt thrust fault

Most of the fault zone at the western part of the Özyurt thrust fault juxtaposes Jurassic limestones and Upper Cretaceous ophiolitic mélange units. As these planes are situated on allochthonous ophiolites and older limestones, they may present some misleading results when their regional neotectonic activity is analysed. Only at one location the fault plane, cutting the Quaternary shore deposits of Lake Van, was evaluated (Fig. 6).

The result of the analysis indicates a N–S compressional stress regime (Fig. 6C). At this location the σ3 is vertical and according to value of ratio (R= 0.5), the type of deformation is pure compression (Delvaux *et al*., 1997).

Gülsünler fault

The 20km long Gülsünler fault is exposed between the Pirgarip and Yeşilköy villages. The N50ºE trending sinistral strike-slip fault has two segments namely the Pirgarip and Yeşilköy. The Yeşilköy segment constitutes the southern part of fault zone (Fig. 3). The Oligocene-Miocene turbidites and Quaternary lacustrine deposits are deformed by this segment that is about 14km long and well exposed in the east of Yeşilköy village. The southernmost part of this segment is steeply northwest dipping (74º) (Fig. 7A).

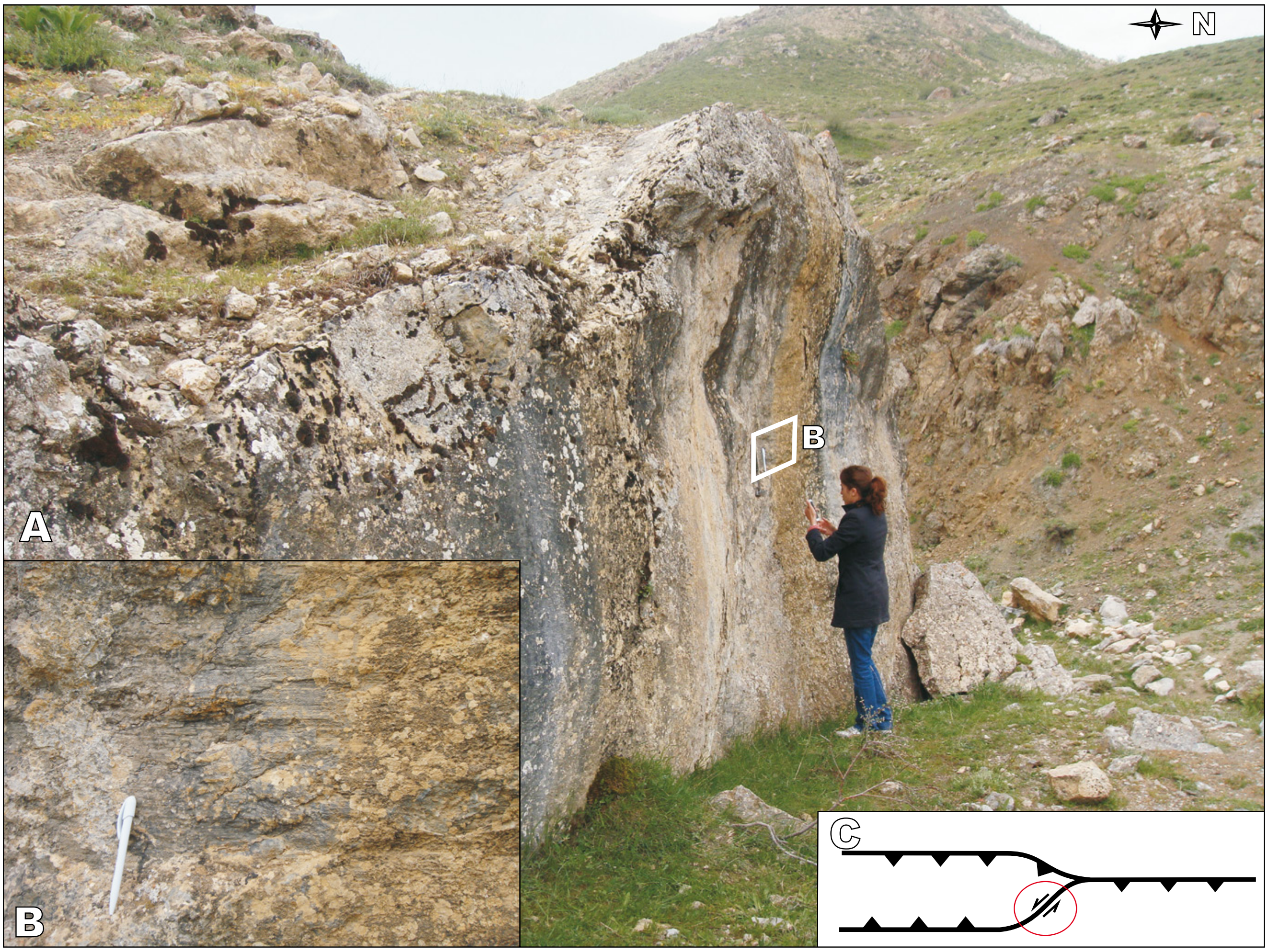

FIGURE 5. Field photograph of the eastern connection of the Özyurt thrust fault that has strike-slip character; A) vertical fault plane on Jurassic limestones, B) close-up view of fault plane and striations and C) plot of the fault plane (modified from Van der Pluijm and Marshak, 2004).

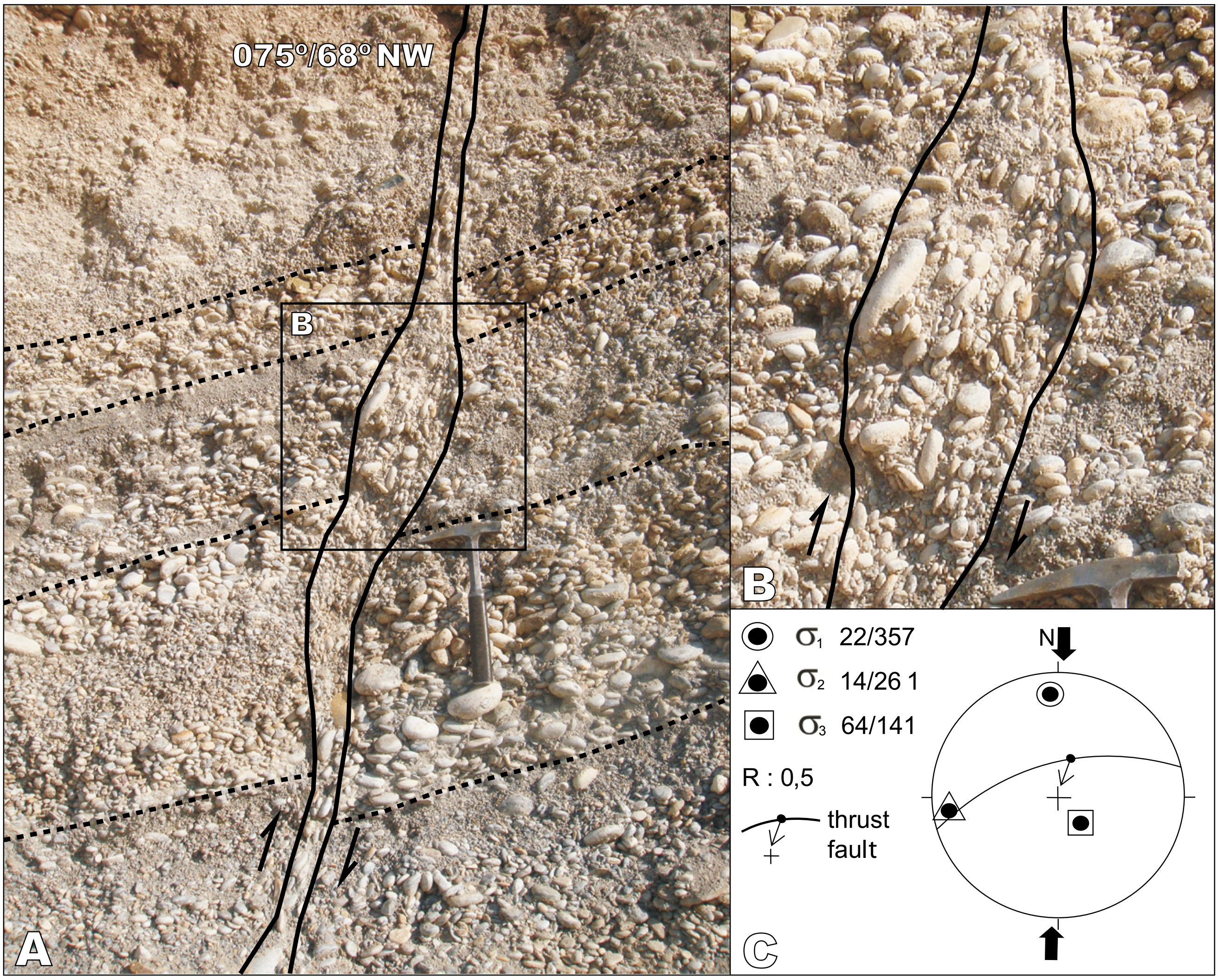

FIGURE 6. A) Field photograph showing the Özyurt fault in gravelly shore deposits of Lake Van, B) close-up view of fault zone (gravel orientations showing the direction of movement) and C) result of the palaeostress analysis on Schmidt lower hemisphere.

Alignment of the water springs and shifted drainage pattern are the morphological features of this zone (Fig. 7B-C). Bending zones of the Karasu river channel and the Alaköy thrust fault is located on the Yeşilköy segment (Fig. 3).

Sinistral motion along the segments is transferred by a step-over at the north of Otluca village. The Pirgarip segment cuts the Upper Cretaceous ophiolitic mélange units, Oligocene-Miocene turbidites, and Quaternary lacustrine deposits. The trace of this segment is evidenced by the shifting of the contact zone of ophiolites with turbiditic rocks in the field (Fig. 3).

Otluca quarry was excavated on the transfer zone of the two segments of Gülsünler fault (Fig. 3). The stratigraphic succession in the quarry is mainly composed of sandy and gravelly lacustrine and shore deposits of Lake Van. Horizontally bedded deposits consist of semi-consolidated, stratified sands and thin bedded clay alternations. One part of the quarry has 8 faults in the same wall (Fig. 8A). All fault planes have similar strikes (approximately N50ºW) but they have different fault character. A first group includes sinistral strike-slip faults with apparent normal component (# 2, 4, 6, 7, 8), a second group include normal faults (# 5, 9), and the third type is a reverse fault (# 3).

West wall of the quarry presents different faults with similar strikes. Thrust faults (# 10, 11, 12) and a normal fault (# 13) were determined in sandy and silty lacustrine deposits (Fig. 8B). Thin bedded, sandy delta-front deposits at the southern part of the quarry have high inclinations (68º) (Fig. 8C). These dip values higher than original depositional conditions (angle of rest) result from the deformation by faults on the lacustrine and shore deposits.

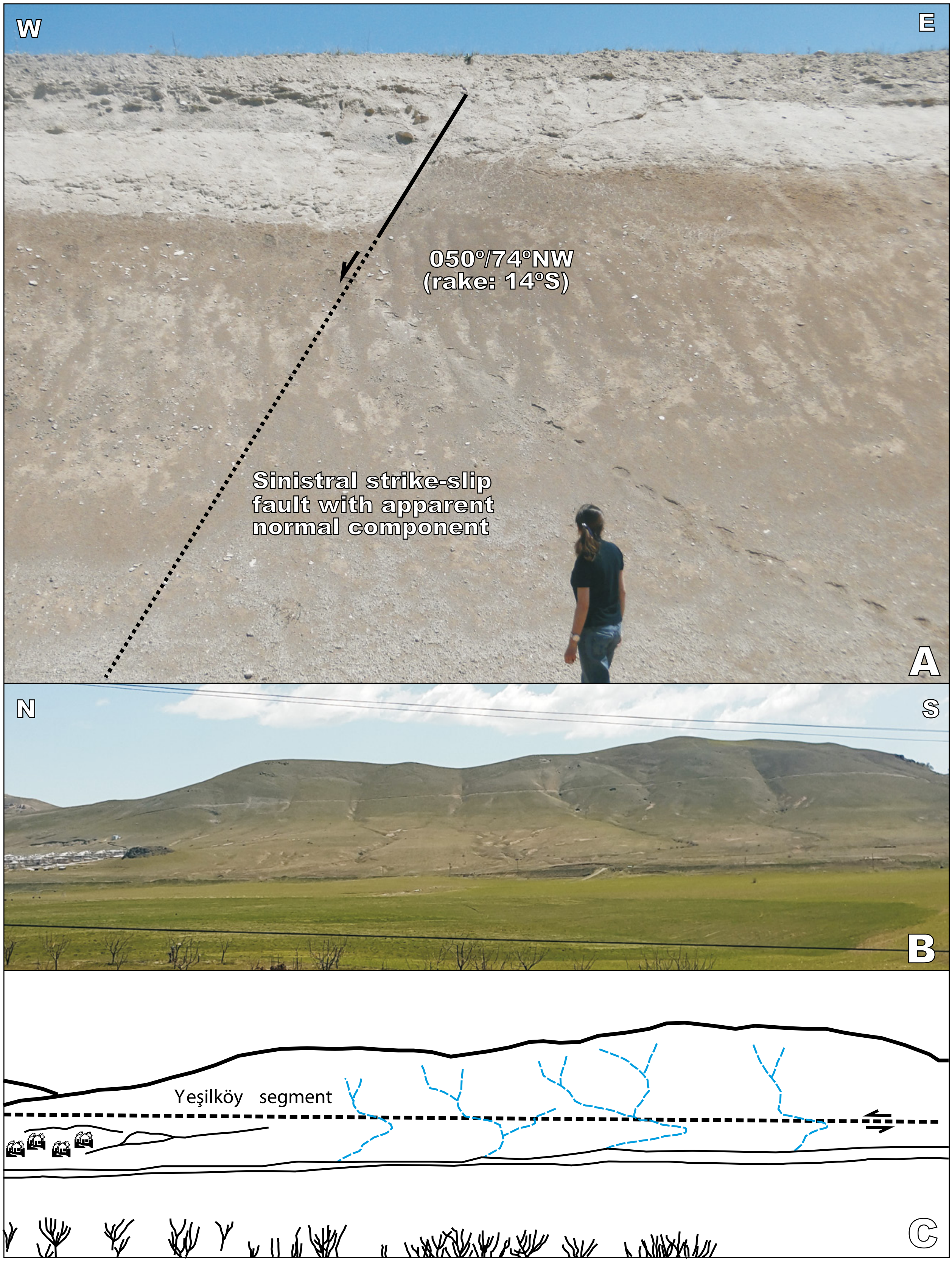

FIGURE 7. A) Field photograph showing the Quaternary fluvial and lacustrine deposits deformed by Yeşilköy segment of the Gülsünler fault. B) Photograph and C) line drawing of shifted drainage patterns on Yeşilköy segment (northeast of Yeşilköy village).

FIGURE 8. Photo showing the structural elements of Otluca quarry; A) faults on north wall of the quarry, B) a normal and three reverse faults on west wall of the quarry and C) tilted delta front deposits.

Fault-slip analysis of Gülsünler fault

Results of the analysis indicate three different deformation mechanisms. First data measured from Yeşilköy segment (# 1) (Fig. 9A). At this location the σ2 is nearly vertical and according to R values (R=0.5), the type of deformation is pure strike-slip (sinistral) stress regime (Delvaux *et al*., 1997) (Fig. 9B).

Second data set (# 2, 4, 5, 6, 7, 8, 9, 13) (Fig. 9A) picked from Otluca quarry is characterized by NE-SW tensional stress regime. At the same location, none of the principle stress axes are vertical. According to R values (R=0.78), the type of deformation is transtensional (Delvaux *et al*., 1997) (Fig. 9C). Third data set (# 3, 10, 11, 12) (Fig. 9A) from Otluca quarry refers to NE–SW compressional stress regime. At this location the σ3 is vertical and according to R values (R=0.5), the type of deformation is pure compression (Delvaux *et al*., 1997) (Fig. 9D).

Seismicity of Lake Van region

The Lake Van Basin is located on one of the most seismically active regions of Turkey. It experienced several destructive earthquakes in the historical and instrumental period (Pınar and Lahn, 1952; Ergin *et al*., 1967; Soysal *et*

location	nº	strike & dip	rake	sense	principle stress axis	value of ratio (R)
Yeşilköy segment	1	050/74N	14S	Sinistral	σ_1 = 20/203 σ_2 = 69/002 σ_3 = 07/111	0,5
Otluca quarry	2	125/89N	01W	Sinistral	σ_1 = 23/293 σ_2 = 67/117 σ_3 = 01/024	0,78
	4	150/85E	01W	Sinistral		
	5	135/59S	89S	Normal		
	6	124/89N	01W	Sinistral		
	7	130/86N	01W	Sinistral		
	8	146/87E	01W	Sinistral		
	9	140/43W	89W	Normal		
	13	160/26W	89W	Normal		
	3	137/71W	89S	Reverse	σ_1 = 30/227 σ_2 = 01/317 σ_3 = 60/048	0,5
	10	140/48W	89S	Reverse		
	11	130/62S	89S	Reverse		
	12	142/59W	89S	Reverse		

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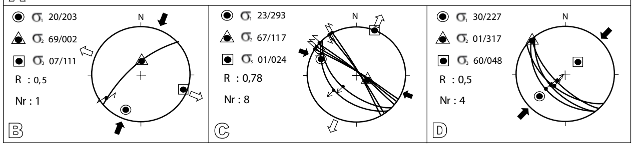

FIGURE 9. A) Fault-plane measurements on Yeşilköy segment and the north and west walls of the Otluca quarry. Results of the palaeostress analysis of striated fault planes with indications on Schmidt lower hemisphere; B) pure strike-slip stress regime, C) NE-SW tensional stress regime and D) NE-SW compressional stress regime.

al., 1981; Ambraseys, 1988; Ambraseys and Finkel, 1995; Tan *et al*., 2008; Selçuk *et al*., 2010; Utkucu *et al*., 2013). The most destructive earthquakes occurred in Lake Van region were Çaldıran Earthquake (Mw 7.3) and Van-Taban Earthquake (Mw 7.2). Çaldıran Earthquake (November 24th, 1976) was caused by the NW trending, dextral strike-slip fault, with large amount of casualties (3840 people) and damage in Çaldıran town and closer area (Eyidoğan *et al*., 1991).

Van-Tabanlı Earthquake (October 23rd, 2011) is the largest seismic event originated from a thrust fault in Turkey (Koçyiğit, 2013). The epicentre of the earthquake was located about 25km northeast of Van city centre. It caused 604 death and damage. Thousands of aftershocks occurred within a closer area.

Recent activities of new detected Özyurt and Gülsünler faults are determined by the seismological records of the National Earthquake Monitoring Center of Kandilli Observatory and Earthquake Research Institute-KOERI (KOERI, 2016). Epicentres of earthquakes ranging from 3 to 6 magnitudes (in 2011-2015 period) that match with the faults evidence the seismic activity of these faults in recent times (Figs. 10; 11).

The epicentres of diverse-sized 53 earthquakes are located on the Özyurt thrust fault (KOERI, 2016) (Fig. 10).

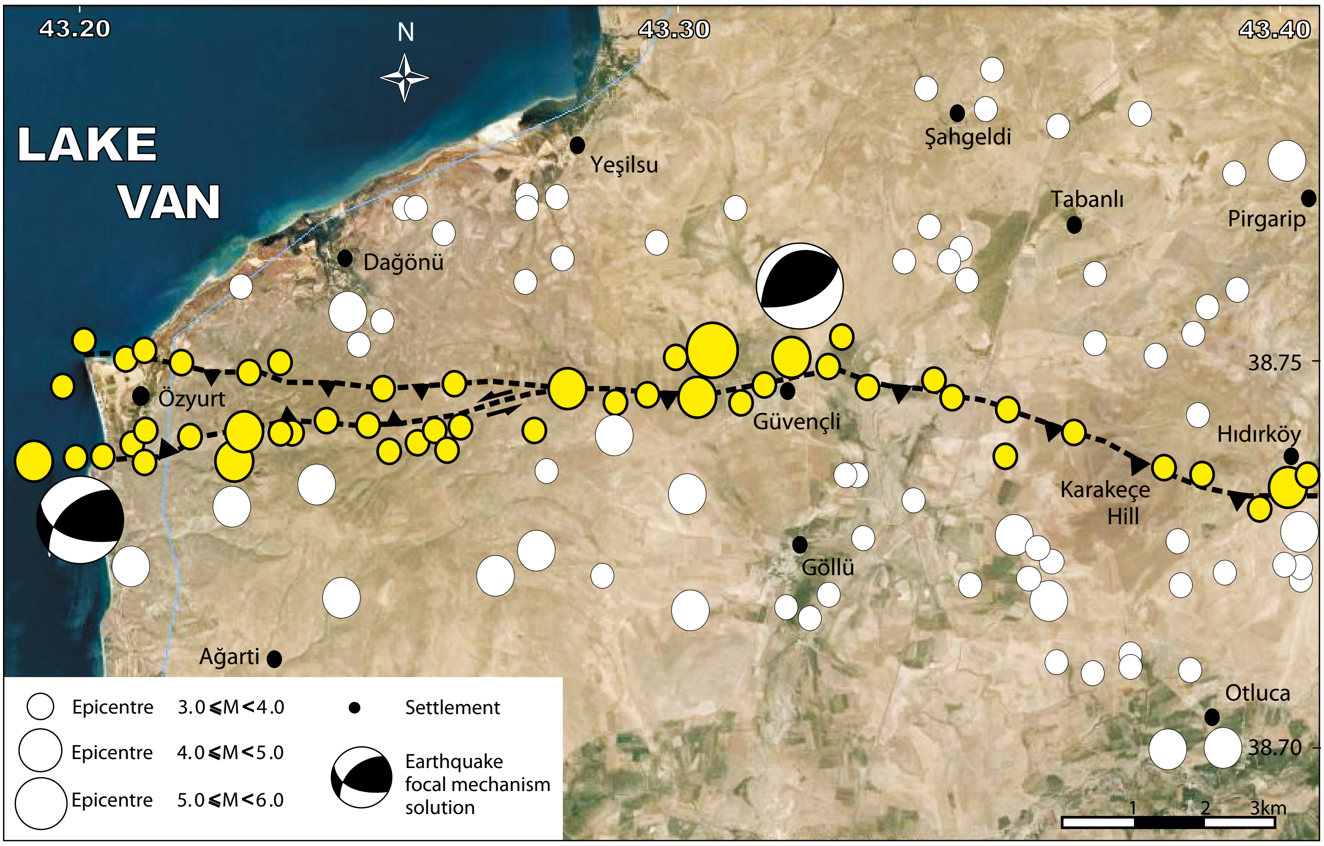

FIGURE 10. Earthquake records (M≥3.0) in instrumental period near the Özyurt fault (yellow circles showing earthquakes on the fault while white ones showing others) (KOERI, 2016).

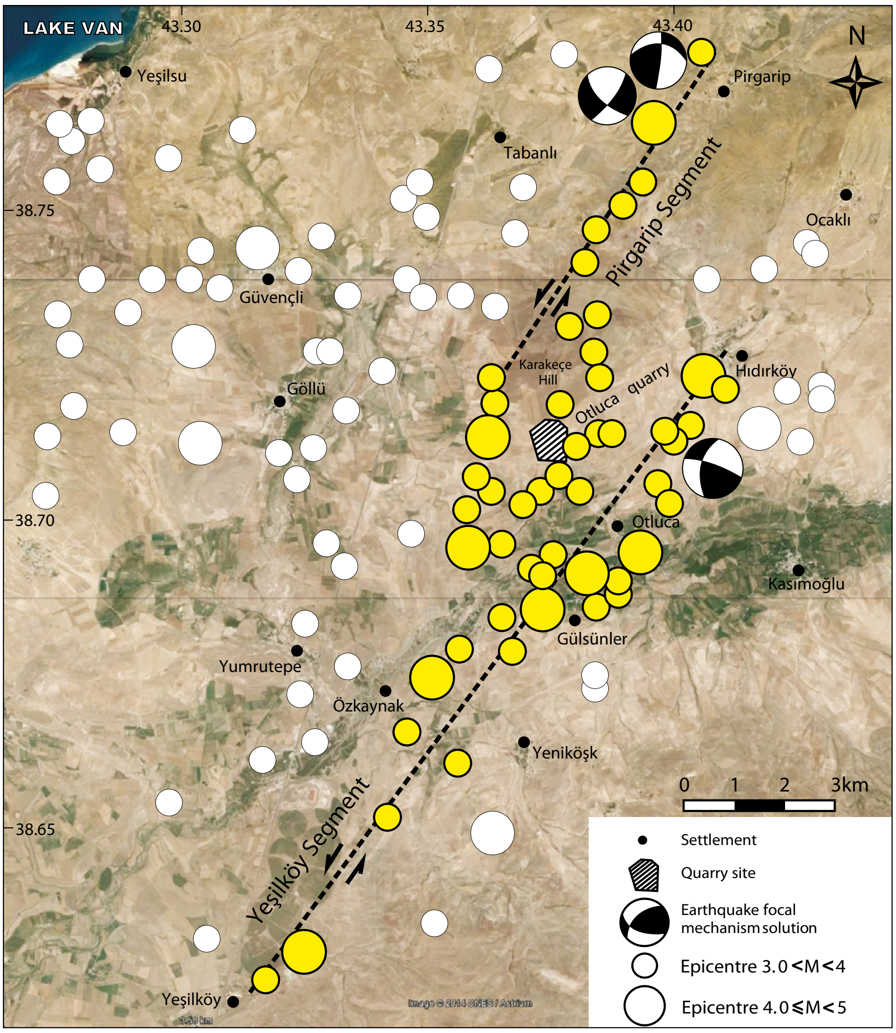

FIGURE 11. Earthquake records (M≥3.0) in instrumental period near the Gülsünler fault (yellow circles showing earthquakes on the fault while white ones showing others) (KOERI, 2016).

The distribution of these epicentres is compatible with the branched structure of the Özyurt thrust fault in the west. Earthquake focal mechanism solutions on Özyurt thrust fault taken from previous studies (AFAD, 2011; Irmak *et al.*, 2012) show the approximately E–W trending reverse fault activity (Fig. 10). The epicentres of 39 earthquakes coincide on the Gülsünler fault (KOERI, 2016) (Fig. 11). The distribution of these epicentres is coherent with the step-over morphology of Gülsünler fault. Earthquake focal mechanism solutions on Gülsünler fault taken from previous studies (AFAD, 2011; Irmak *et al.*, 2012) show the approximately NE–SW trending sinistral strike-slip fault activity (Fig. 11).

DISCUSSION AND CONCLUSIONS

The southern part of the Eastern Anatolian Plateau is less studied area than the other regions of Turkey. After October 23rd, 2011 Van-Tabanlı Earthquake, the studies about seismicity of the region increased (Özkaymak *et al.*, 2011; Altıner *et al.*, 2013; Di Sarno *et al.*, 2013; Doğan and Karakaş, 2013; Fielding *et al.*, 2013; Koçyiğit, 2013; Utkucu *et al.*, 2013; Çukur *et al.*, 2016).

Newly mapped Özyurt and Gülsünler faults provide important clues for understanding the neotectonic regime in the east of Lake Van and the northern part of Arabian and Eurasian collision zone. Geological properties and recent activities of these faults are determined on the basis of field studies and seismic records. The traces of faults observed in Quaternary semi-consolidated lacustrine and shore deposits of Lake Van are the main indication of this activity.

The eastern segment of the Özyurt thrust fault, north of Hıdırköy, includes southerly dipping fault planes unlike to the Ilıkaynak thrust fault (Koçyiğit, 2013). And, we found no field or seismic evidence of a direct connection between the two thrust faults.

Gülsünler fault is another structure introduced for the first time in this paper. NE- trending, sinistral strike-slip fault is determined with the help of lineaments, displacement of lithologies, and shifting of stream channels. The fault is divided in two segments, Pirgarip and Yeşilköy. Linkage of these segments is provided by the step-over zone. Otluca quarry is located on this step-over zone and excavated in Quaternary lacustrine deposits of Lake Van. Kinematic analysis of fault planes measured from the quarry exposes two different deformation stress regimes. One of them is NE–SW trending compressional regime, responsible for the occurrence of thrust faults while other one is NNE–SSW trending tensional regime. This combination could be explained as structures coevally developed in a restraining step-over (see examples of models in Dooley and Schreurs, 2012).

E–W trending Karasu river channel and Alaköy thrust fault are two significant morphologic structures of the region. They present remarkable sinistral shifting at the west of Gülsünler village. After this zone, the Alaköy thrust fault continues its original (E–W) direction. The shifting zone of these structures is located on the Yeşilköy segment of the Gülsünler fault. Similar shifting is also observed on the Özyurt thrust fault. The deformations on Özyurt and Alaköy faults and Karasu river channel made by the Gülsünler fault indicate that Gülsünler is younger and/or show higher activity than the other faults.

The last important tectonic activity is Van-Tabanlı Earthquake (October 23rd, 2011) originated from the Everek thrust fault. The Everek fault and recent activity along the Özyurt and Gülsünler faults indicate that strike-slip and reverse faulting deform the region as a result of N–S oriented contraction driven by the convergence between Arabian and Eurasian plates.

Both faults should be added on the Active fault Map of Turkey. The locations and positions of these active faults will play an important role for the determination of new residential and industrial areas near Van city centre and its surroundings.

ACKNOWLEDGMENTS

This study is part of a MSc. Thesis carried out by Sibel Dicle at Institute of Science in Yüzüncü Yıl University. Authors are grateful to Erman Özsayın, Azad Sağlam Selçuk, Ali Yılmaz, and anonymous reviewer for their help and suggestions.

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Manuscript received May 2016;
revision accepted January 2017;
published Online May 2017.