VOLCANO-SEISMICITY OF LAKE VAN (EASTERN TURKEY): A COMPARATIVE ANALYSIS OF SEISMIC REFLECTION AND THREE-COMPONENT VELOCITY SEISMOGRAM DATA AND NEW INSIGHTS INTO VOLCANIC LAKE SEISMICITY

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Key words: Lake Van volcanic basin, seismic waveform patterns, volcano-seismicity, seismic reflection, volcano-/tectono-magmatic activity, seismotectonic behavior, hybrid events, harmonic tremors.

ABSTRACT *This study presents a methodological and conceptual approach to effectively consider the Lake Van volcanic basin and its seismicity relationships by using seismic reflection and three-component velocity seismogram data. We used a couple of data set with high resolution geochirp and multi-channel seismic reflection data collected all over the Lake Van basin. Lake-wide seismicity analysis are reconsidered by spectral analysing of KOERI earthquake data, seismic waveforms at VANB broadband station. Thus, we improved the efficiency of our data set to understand and explain the volcano-related seismicity and advanced our inputs for greater output. We noted a new paradigm for earthquake anomalies of Lake Van volcanic basin by meaning seismic monitoring of volcanic systems, which are signals with certain fixed and distinct meanings. These signals are waveform patterns that are typical expressions of seismotectonic behavior of various magma chamber processes underneath the lake. The waveform patterns are key signs and a reliable measure of the volcano-seismic activity in the lake. The hybrid events at the E and W-shores, the long-period events at the NE-corner and S-part of Lake Van and harmonic tremors are recorded. The neotectonic boundary settings of peculiar volcanic intrusions in the lake, the observed normal faults with considerable vertical offsets and associated fracture network system controlling the S-part and SW-corner of the lake can structurally explain the observed hybrid, long-period and tremor type waveforms of volcanic events. In this study, volcano-seismic monitoring of Lake Van basin supported by seismic reflection data highlighted very important network system of complex fractal relationships through the continental deformation by high level volcano-/tectono-magmatic activities beneath and around the lake. Its tectonothermal seismogenesis provided new insights into volcanic lake seismicity in the E-Turkey.*

INTRODUCTION

The Lake Van basin was formed about 100.000 years ago when the lavas of the Nemrut volcano blocked the outward drainage of water in the Muş Basin (Barka and Şaroğlu, 1995). The basin is the largest and deepest lacustrine environment (3600 km^2, 457 m max. water depth) in Turkey and the fourth largest one of the world, located in intensely deformed the EAAC, which is the product of young continent–continent collision zone of Arabian and Eurasian plates (Şengör et al., 1985; Dewey et al., 1986). In the EAAC and the surrounding area of Lake Van has major and anomalous neotectonic structures; NE and NW trending active conjugate strike slip faults, pull-apart and oblique-slip basins, E-W trending high-angle thrust faults, folds, compressional ramp basins, NE-SW aligned continental collision-related volcanoes and N-S trending tensional cracks functioned as magma conduits were created as a result of crustal shortening and thickening caused by the post-collisional convergence (Şengör et al., 1985).

METHODOLOGICAL APPROACH AND GEOPHYSICAL DATA

This paper, in fact, presents a methodological and conceptual approach to effectively consider volcanoes and seismicity relationships by using seismic reflection and seismological data. We have used a couple of data set with high resolution geochirp data (13 Khz) and mini airgun multi-channel seismic reflection data (200-2000 Hz) all over the Lake Van basin (Fig. 1). Lake-wide seismicity analysis are reconsidered by spectral analysing of KOERI earthquake data and seismic waveforms (at VANB broadband station, data from Horasan and Boztepe-Güney, 2006). We improved the efficiency of our data set to understand and explain volcano-related seismicity and advanced our inputs for greater output. Thus, we noted a new paradigm for earthquake anomalies of Lake Van volcanic basin by meaning seismic monitoring of volcanic systems, which are signals with certain fixed and distinct meanings.

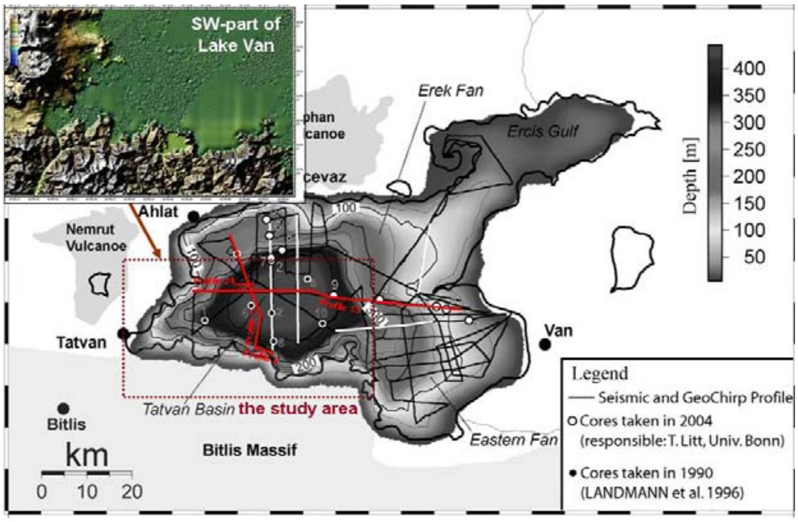

Figure-1. Multi-channel seismic and geochirp track lines with bathymetry all over the basin. The selected four seismic lines (red) numbered as profiles; 24, 13, 5, 6.

The major purposes of this paper are as the follows; analyzing the seismogram (waveform) records of crustal earthquakes in and around the Lake Van basin by comparing the waveform events and their locations with available multi-channel seismic reflection data. Understanding and explaining the volcano-magmatic, tectonic and physical processes resulting in the observed seismic events extracted from seismograms, searching for possible seismic sources (e.g., volcanic-seismicity) and lastly, considering a reliable volcano-tectonic model to explain anomalously dense and continuous seismic events in and around the Lake Van basin.

DISCUSSION AND RESULTS

The Lake Van basin is linearly surrounded by the Nemrut in the W, Süphan in the N and Tendürek in the NE active volcanic systems and strongly effected by a complex combination of magma chamber processes and related pressure changes (e.g., the stress state). This linear volcanic chain is also structurally disturbed, strongly tectonized by neotectonic episode of the EAAC and thus effectively perturbated by complex fracture system to enhance or maintain their present-day volcanic activation. Subsurface dynamical processes along this prominent volcanic zone can produce considerable magma chamber pressure gradients or high pressure differentials underneath lake basin. As well recognized in the seismic data (Figs. 2-3), at the S-portion of Tatvan basin along the S-transtensive fault, tower-like intrusive structural properties are originated from the subsurface chamber processes (Fig. 2). They obviously demonstrate the opening fracture or crack systems structurally represented by the SW-corner (Tatvan delta) (Fig. 2) and W-boundary normal fault system of Tatvan basin (Figs. 2-3). This suggested that isolated volcanoes can be rooted on geometrical discontinuities associated with strike-slip or oblique-slip faulting.

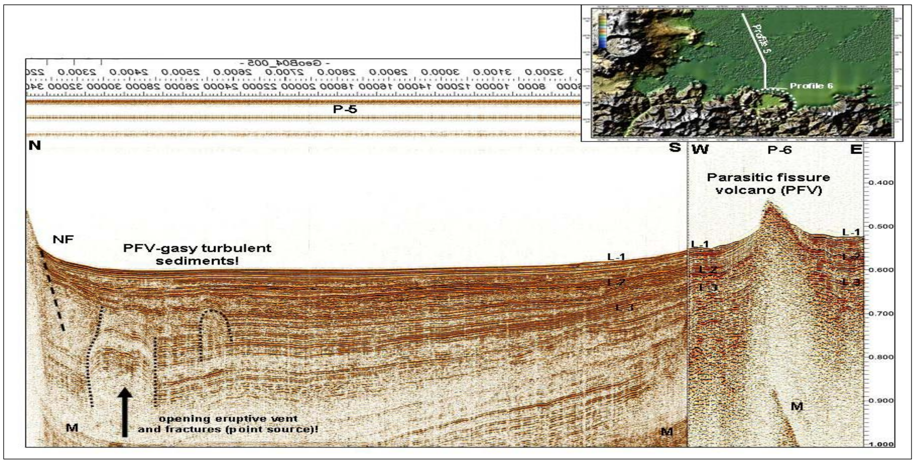

Figure-2. Profiles 5-6 combined by picking up layers (L-1,2,3) around the parasitic fissure volcano (PFV). Toward the N-boundary of the Tatvan Basin (TB), a normal fault (NF) controls TB (tilted block) and perturbated deep sediments by upward volcanic processes. Note that white circle shows the collapsed parasitic cone on the land.

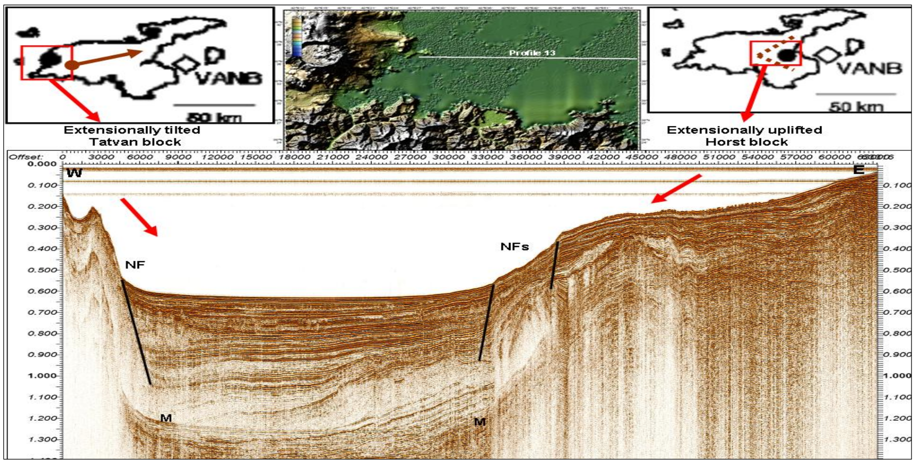

Figure 3. W and E-boundary of the Lake Van basin is normal fault-controlled. Tatvan Basin is tilted block. In W-boundary some sedimentary perturbations are noticed. E-boundary is an uplifted horst block (offshore Çarpanak spur zone). This profile illustrates an extensional-controlled basin (vertical offsets). Index maps (white) at top show the earthquake locations, along which this profile collected (red arrows sign).

It is clear that these volcanoes are related to open tension fractures serving as conducts for the magma and subjected to underneath volumetric expansion and pressure differentials to form the threshold of static stress triggering at about 10 kPa (Stein, 1999) and in some cases even an effect of the earth tides (about 1 kPa) proposed by Tanaka et al., (2004). Such stress changes, since, may alter fluid flow within the shallow crust. The Lake Van volcanic basin is seismically very active and the physical processes creating observed seismicity are various as a result of interaction of complex tectonic processes. The SW-corner of the Lake Van basin (S-portion of Tatvan basin) is effectively dominated by volcano-magmatic occurrences and related dynamic processes underneath and structurally controlled (e.g., tilted Tatvan block) by extensional fracture-fissure systems bounding this corner (Figs. 2-3). Based on seismic (or volcanic ?) architecture of figures (2-3), we postulate that moving magma dynamics, volcanic gases and fluids associated with a network of fracture-fissure systems, volcano-hydrothermal processes, pressure differentials can strongly trigger earthquakes, forming a concept of volcanic-seismology and seismic monitoring. Earthquake activity beneath a volcanic basin always increases before an eruption, because magma and volcanic gas must first force their way up through shallow underground fractures and passage ways. When magma and volcanic gases or fluids move, they will either cause rocks to break or cracks to vibrate. When rocks break high-frequency earthquakes are triggered. However, when cracks vibrate either low-frequency earthquakes or a continuous shaking called volcanic tremor is triggered. As magma begins to flow, melting and splitting base rock can be detected as volcanic earthquakes (e.g., 2-5 km beneath the surface at Sakurajima). As magma nears the surface and its pressure decreases, gases escape. The main components of volcanic gases (sulphur dioxide) and increasing amounts herald the arrival of increasing amounts of magma near the surface. Debris and mud flows are remobilized hydrated ash deposits from pyroclastic flows and ash fall deposits, moving downslope even at very shallow angles at high speed. Horasan and Boztepe-Güney, (2006) obtained the records of crustal earthquakes in and around the Lake Van by using the spectral analysis method and plotted the annual numbers of earthquakes with Md ≥ 4 versus years (1970–2004, KOERI) for the vertical cross sections along Profile A (across the Lake Van) and B (Çaldıran Fault segment). Examples for three-component velocity seismograms of long period and hybrid events (a and b) and tremors recorded at VANB broadband station and their normalized amplitude velocity spectra by Horasan and Boztepe-Güney, (2006). The hybrid events at the E and W-shores (Fig. 4), the long-period events at the NE-corner and S-part of Lake Van and harmonic tremors are recorded. It is reported that the waveforms of hybrid and long-period events are a reliable measure of volcano-seismic activity (Chouet, 1996; Gordeev and Senyukov, 2003) and seismic monitoring of volcanic systems. In and around the Lake Van region, these kind of events critically imaged by seismic reflection data have obviously dominated in the form of signals on the seismograms (Fig. 4). Seismogram data in Fig. (4) characterizing volcano-seismic events can express the symptomatic-hybrid deformation, continuous rhythmic or episodic earthquake (synchronous volcano-tectonic activity) and fast-slow processes. These waveform patterns are typical expressions of seismotectonic behaviour of various magma chamber processes (MCP) underneath lake basin. These waveform types of earthquakes that occur and where they start and end are also key signs of the volcanic seismicity having four major forms: short-period and long-period (Fig. 4), harmonic tremor and hybrid-mixed frequency events (long-short term periods) (Fig. 4). **1)** Short-period events are like normal fault-generated earthquakes (Figs. 2-3), caused by the fracturing of brittle rock as magma forces its way upward. Short-period events signify the growth of a magma body near the surface, known as 'a-type' waves. These seismic events are often also referred to as volcano-tectonic events or earthquakes (note the first 5, 8 and 15 s waveform patterns in Fig. 4). **2)** Long-period events as in the NE-corner of lake Van, Erçiş gulf and the further S, Bitlis thrust (depth: 7,5-8 km, Md: 3.5-3.6, record length: 60 s, frequency range: 1-2,5 Hz) are believed to indicate increased gas pressure in a volcano's plumbing system. These events can be also associated with an opening and resonating crack when the magma rises upward or existence of pressure transients within fluid-gas mixture (i.e., resonance effect within the magma itself) or fluid-solid contact (Chouet, 1996; Neuberg, 2000). These events can't have S-wave arrival and very emergent signal onset. The spectrum of long-period event has the frequency content restricted in a narrow band (1-2,5 Hz). Horasan and Boztepe-Güney, (2006) classified about 23% of 70 seismic events with Md ≥ 2 used as long period events. Their oscillations are the equivalent of acoustic vibrations in the context of magma chambers within the volcanic dome, known as 'b-type' waves.

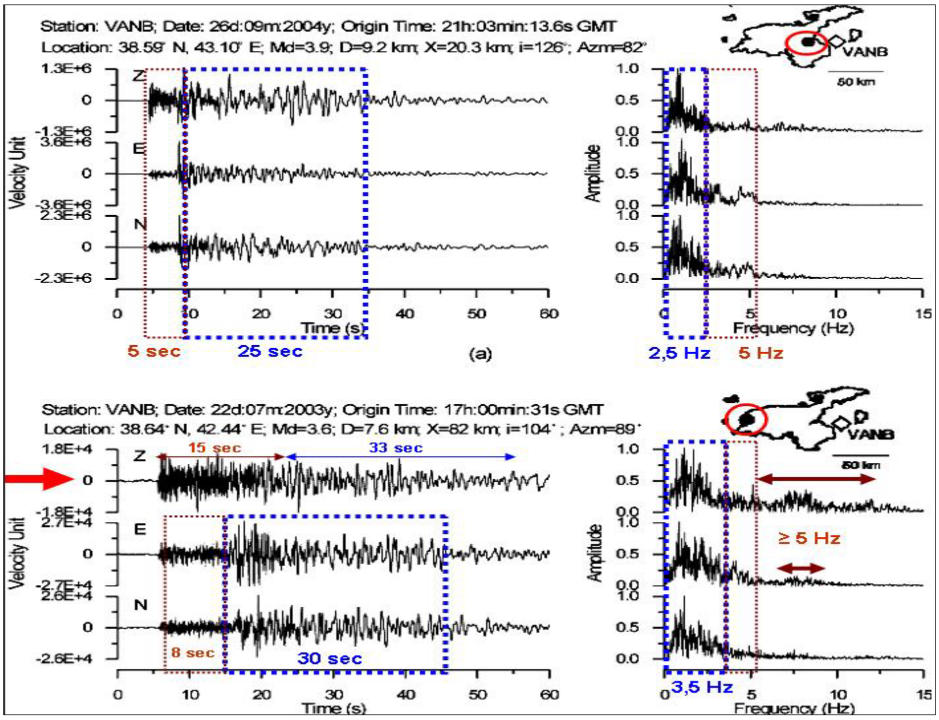

Figure 4. An example for three-component velocity seismogram of hybrid events (a and b) recorded at VANB broadband station and their normalized amplitude velocity spectra (Horasan and Boztepe-Güney, 2006). The locations of earthquakes are drawn by red circles (E-W). Hybrid events recorded at W and E-boundaries of the basin express extensionally tectonized central basin (Tatvan block) (compare the waveforms to Figs. 2-3). Note that Z-component (red arrow) at the W-boundary indicates the longer duration (15 s high, last part 33 s low frequency), higher velocity spectra and higher frequency content (3,5 Hz events seen greater than 5 Hz).

3) Hybrid events (Fig. 4) at the W-E boundaries of lake (depths; 7.6-9.2 km, Md; 3.6-3.9, record length; 60 s) can reflect the instability of high viscous lava domes (Miller et al., 1998) (Fig. 2). Hybrid events have higher frequency content at the beginning and P- and S-phases can be clearly defined (Fig. 4). The spectrum of a hybrid event has a peak between 1 and 2 Hz (Zobin, 2003). It is classified about 77% of 70 seismic events with Md ≥ 2 used as hybrid events. The frequency spectrum of hybrid events and durations evidencing seismic activity (Fig. 4) are good indicators of increasing eruption and seismicity, especially if long-period events become dominant and episodes of harmonic tremor appear. **4)** A small part of harmonic tremor-like signals recorded at VANB broadband station that occurred in the time periods on 14 November 2000 which are a few days before the Van earthquake of 15 November 2000, Mw; 5.7 which occurred at the S-shore of Lake Van (record length: 35 s, frequency range: 2,5-7,5 Hz). These waveforms are often the result of magma pushing against the overlying rock below the surface. A harmonic tremor signal is a continuous release of seismic energy typically associated with the underground movement of magma. It contrasts distinctly with the sudden release and rapid decrease of seismic energy associated with the more common type of earthquake caused by slippage along a fault. It is critically postulated that the source of seismic energy creating linearly polarised tremors in the horizontal plane is in the N-S direction of lake and this can be related to the stress loading created by thrust regime at the S-shore of Lake Van (Horasan and Boztepe-Güney, 2006). Teoman et al., (2006) also indicated that earthquakes are deviating to the shallower depths (5-15 km) in and around the Lake Van. The depth value (≤ 10 km) is an equivalent of crustal (oblique) flake detachment (Dewey et al., 1986), although the stress loading patterns locally observed by Teoman et al., (2006). We postulated that the shallowing volcano-/tectono-magmatic seismicity, spectral styles of waveform patterns and stress densification (localized condensation at Deveboynu peninsula) are due to dynamics of the upper crustal oblique flake in relation with volcano-magmatic intrusions in the lake. The neotectonic boundary settings of peculiar volcanic intrusions (Fig. 2) in the Lake Van basin, the observed normal faults with considerable vertical offsets (Figs. 2-3) and associated fracture network system controlling the S-SW-corner of the lake can certainly explain the observed hybrid, long-period and tremor type waveform styles of volcanic events. Major controlling factors might have been the shallow-seated, ductile shear zones as extracted from various waveform patterns, seismic reflection and deep tomographic data (Pn-Sn anisotropy). Because, doming hot asthenospheric material or post-collisional decompressional magmatism (e.g., alkaline basalts), (Şengör et al., 2003) reached the considerable levels beneath the lake, deformed the lake floor and strongly affected the distributional pattern of lake seismicity. The W and E-boundary sections of lake are extensionally faulted, confirming the idea that central Tatvan basin is tilted block, rapidly subsiding and trending to rotate. We postulated that the subsurface seismic expressions of central vent and parasitic fissure volcanoes through thick sedimentary sections (Fig. 2) are produced by upward moving materials of mid/lower crust-originated, partial magmatic fusion processes all along and around the crustal flake boundaries of the Lake Van-Muş basin system. Seismic and structural information of this crustal mechanism are efficiently expressed by a comparative analysis of seismic reflection and three-component velocity seismogram data. In this study, volcano-seismic monitoring of Lake Van basin supported by seismic reflection data highlighted very important network system of complex fractal relationships through the continental deformation by high level volcano-/tectono-magmatic activities beneath the lake and provided new insights into volcanic lake seismicity in the E-Turkey.

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