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Evolution of ancient Lake Ohrid: a tectonic perspective

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Abstract

Lake Ohrid Basin is a graben structure situated in the Dinarides at the border of the Former Yugoslavian Republic of Macedonia (FYROM) and Albania. It hosts one of the oldest lakes in Europe and is characterized by a basin and range-like geological setting together with the half-graben basins of Korca, Erseka and Debar. The basin is surrounded by Palaeozoic metamorphics in the northeast and north and Mesozoic ultramafic, carbonatic and magmatic rocks in the east, northwest, west and south. Palaeocene to Pliocene units are present in the southwest. With the basin development, Neogene sediments from Pliocene to recent deposited in the lows. Three major deformation phases lead to the basin formation: A) NW–SE shortening from Late Cretaceous to Miocene; B) uplift and diminishing compression during Messinian - Pliocene; C) vertical uplift and (N)E–(S)W extension from Pliocene to recent. Neotectonic activity of the study area ~~concentrates on~~ N–S trending normal faults that ~~flank~~ the Ohrid Basin on the ~~east and west~~. Seismic activity with moderate to strong events is documented during the last 2000 y; the seismic hazard level is among the highest of the Balkan Peninsula. Activity of the youngest faults is evidenced by earthquake data and field observations. Morphotectonic features like a wind-gap, fault scarps, a stepped series of active normal faults, deformed palaeosols, and fault-related hydrothermal activity are preserved around Lake Ohrid and allow delineating the tectonic history. It is shown that the Lake Ohrid Basin can be characterized as a seismogenic landscape. This paper presents a tectonic history of the Lake Ohrid Basin and describes tectonic features that are preserved in the recent landscape. The analysis of morphotectonic features is used to derive the deformation history. The stratigraphy of the area is summarized and concentrates on the main units.

1 Introduction

Lake Ohrid (693 m a.s.l.) in the southwest of the Former Yugoslavian Republic of Macedonia (FYROM in the following referred to as Macedonia) and the east of Albania (Fig. 1) ~~counts~~ as one of the oldest lakes of Europe. Biological studies on endemic fauna give hints on a Pliocene age (Stankovic, 1960). With a length of 30 km and a width of 15 km it covers an area of 360 km^2 ~~and~~ is larger than the neighbouring lakes of ~~Makro~~ and Mikri Prespa. The lake is surrounded by the Mokra Mountains to the west (1.514 m) and the Galicica Mountains to the east (2.265 m). The entire area can be characterized as a seismic landscape (Michetti and Hancock, 1997; Michetti et al., 2005). Historical earthquake data and instrumental seismicity prove that the Ohrid area is still tectonically active.

The lake is of scientific interest for a number of disciplines. Biologists carry out research on endemic species that evolved in the almost 300 m deep lake. Hydrologists and hydrogeologists investigate the inflow rate variations, the chemical content and the origin of the karst springs that mainly feed Lake Ohrid besides only small streamlets. Geoscientists focus their research on the evolution of the lake and the neighbouring intramontane basins. Palaeoclimatologists expect one of the furthest reaching sediment archives for the reconstruction of palaeoenvironmental conditions.

This paper concentrates on the tectonic evolution of the Lake Ohrid area and describes tectonic features that are present in the basin surroundings. The geological and geodynamical settings are summarized and the main units are discussed.

2 Geodynamic setting

The geodynamics of Macedonia are mainly controlled by the Northern Hellenic Trench and the North Anatolian Fault Zone (Fig. 1). The Lake Ohrid Basin ~~is~~ the largest of a number of basins in the Dinaride-Alpine mountain belt that stretches along the western shore of the Balkan Peninsula. This belt formed as a result of the ongoing Dinaric subduction, being characterised by a compressional stress regime nowadays. The Ohrid Basin, the Debar Basin to the north, the Korca and Erseka Basins to the south, and the lakes of Mikri and Makro Prespa to the southwest are situated in a basin and range-like geodynamical setting (Figs. 2 and 3). The entire area is controlled by present day E–W extension (Fig. 3). Lake Ohrid Basin marks the transition between the Palaeozoic orogen in the east (Pelagonian) and the Mesozoic rocks (Apulian) in the west (Robertson, 2004). Jozja and Neziraj (1998) and Tremblay et al. (2009) describe ~~those~~ units as Western Macedonian and Mirdita Ophiolite Zones. Today, the main structural sections of the Eastern Adriatic coast can be subdivided into a compressional coastal domain, followed by a narrow zone of transition west of Lake Ohrid and the extensional domain in which the Neogene basins formed (see Fig. 3). The roll back of the subducted slap (Fig. 3) leads over time to a westward migration of the entire system. This is also evidenced by the westward migration of the NS extensional domain of Eastern Macedonia, which is influenced by the North Anatolian Fault Zone (Fig. 1) with its extension into the Aegean and the initiation of its right-lateral slip in the Early Pliocene (Dumurdzanov et al., 2005, Burchfiel et al., 2008). The older N-trending basins in Eastern Macedonia were disrupted by E–W trending basins, so the faults become younger to the west (Dumurdzanov et al., 2005).

During Palaeozoic, a regional foliation developed in the Cambrian and Devonian units. Thrusts and folds were the dominating deformations during the Mesozoic orogeny, later dominated by normal and strike-slip faulting, mainly in N–S direction. Fault patterns of the surroundings of Lake Ohrid indicate a diverse stress history.

Ohrid Basin is a graben structure caused by the E–W directed extension, while the associated Korca and Erseka Basins are half-grabens, bordered by a NW–SE trending normal fault on their eastern side. The sedimentation in the Ohrid Basin began in Late Miocene with the formation of a pull-apart basin, controlled by right-lateral strike-slip movements. Subsidence and further extension account for the major dynamic component since Pliocene-Pleistocene. Several ~~100 m~~ of sediments accumulated since the Late Miocene (Dumurdzanov et al., 2004). According to Dumurdzanov et al. (2004) the

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oldest sediments in the lake are probably the Pliocene Piskupstina and Solnje Formations. Today, sedimentation is likely to be compensated by subsidence.

Lake Ohrid Basin is flanked by active N–S trending normal faults that have a clear expression as fault scarps in the present-day landscape. ~~These normal faulting~~ can also be derived from recent earthquake data (Fig. 2). Morphological features tend to trend mainly N–S in the west of the lake and N–S to NNE–SSW in the east. Further sets of NW–SE and E–W lineaments are also present. ~~Latter~~ are most likely related to the E–W extension of the basin (Wagner et al., 2008). Active faulting along an E–W trending fault has been described from Lake Prespa (Dumurdzanov et al., 2005). Between the lakes, the Galicica mountain range is separated from the Mali I Thate Mountains in the south by a normal fault that cuts the mountain ridge at ∼1500 m a.s.l. (Aliaj, 2000). Fault surfaces and lineations are preserved in the entire area. Burchfiel (2006) ~~reports recent~~ slip-rates of not more than 2 mm~~/a~~ with a very high uncertainty due to imprecise GPS data.

2.1 Seismicity and neotectonics

In 518 AD, an earthquake destroyed the cities of Ohrid and Skopje (110 km NNE of Ohrid) (Petrovski, 2004). The event was so strong that almost the entire city of Ohrid had to be rebuilt, Skopje suffered heavy damages. This ~~can count as~~ the strongest historical quake to have hit Macedonia. Another strong earthquake in the study area is reported by the ancient historian Procopius (ca. 500–565 AD) who mentioned Lychnidus in his Secret History or History Arcana (Atwater, 1927). Lychnidus ~~commonly counts~~ as the old name of Ohrid, but there are also ~~arguments to~~ place it close to Sveti Naum at the southern shore of the lake (Lempriere, 1838). The text of the Secret History Arcana is an emotional harangue against emperor Justinian and his wife and describes the catastrophe during Justinian times, most probably 526 AD. A local earthquake that destroyed the entire city and left the majority of the inhabitants dead, must have had a magnitude greater than 6, even taking into account poor building standards and historically (or politically and personally) intended exaggerations. Even

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if the fatalities were not caused by building collapse due to shaking but resulted of secondary seismic effects like rockfalls, landslides, dry-running wells etc., a medium-strong event (Michetti et al., 2007) must be assumed. Ambraseys (2009) lists a strong event in 527 AD, which would fit the historical data of the reign of Justinian. It is not clear whether this event is related to the earthquake of 518 AD which destroyed Ohrid and Skopje or if, due to historical uncertainties, only one event took place. Other significant events occurred in 548, 1673, 1871, 1889, 1896 and 1911 (Ambraseys and Jackson, 1990; Goldsworthy et al., 2002; Ambraseys, 2009).

Instrumental seismicity records in the Ohrid area reach back to the early 20th Century. The strongest event ever measured here took place on 18 February 1911. The magnitude 6.6 earthquake (EMS X) occurred in the Ohrid-Korca area in a depth of 15 km (Milutinovic et al., 1995; Muço, 1998). Burton et al. (2004) list only moderate events (except the 1911 earthquake) in shallow depths (<60 km) for the study area. Background seismicity is low compared to Greece, Western Albania and the Eastern Macedonia-Bulgaria region. Most recent events are the 23 November 2004, M~~W~~ 5.4 earthquake in the Korca region (40.39° N, 20.48° E; focal depth ~20 km, normal faulting) and the 6 September 2009, MW 5.6 event in Albania. This earthquake ~~happened~~ in a depth of 2 km (e.g. EMSC, 2010). The normal faulting mechanism (see Fig. 2) is a result of the E–W extension. Even though hundreds of houses were damaged and some dozens even destroyed, no fatalities were reported. A series of more than 35 aftershocks occurred in the following days. The shallow epicenters in combination with the poor building standards in the region are responsible for the ~~great number of~~ damages. Smaller recent events have shallow epicenters up to 25 km depth, deeper events are rare. Most of the earthquakes are associated to the fault zones that border the Ohrid Basin (Aliaj et al., 2004). ~~The fault~~ plane solutions of the recent earthquakes fit the geodynamic setting with mainly compression along the Albanian coast and normal faulting mechanisms, that contribute to the extensional domain, inland (Figs. 2 and 3).

Maximum peak ground accelerations expected for a return period of 500 y reach from 0.30 g in the east of Ohrid (Lake Prespa region) to 0.50 g in the west of the study area (Brahim, 2005). Together with the east of Macedonia, the Ohrid-Korca area has the highest seismic hazard of the country.

3 Geological overview

Lake Ohrid Basin, a graben structure, is located at the contact between the Mirdita Ophiolite Zone, one of the internal zones of the Albanides, and the Korabi Zone of the Western Macedonian Zone. In the lake region the units of the Korabi Zone are thrusted over the Jurassic ophiolites of the Mirdita Zone (Fig. 4). The contact of the two zones can be observed south of the Lini Peninsula (Fig. 5) at the western shore of the lake. The geodynamic setting with the Palaeozoic thrusting and todays extensional regime lead to the general impression of a NW–SE striking of the large geological units. While the Shebeniku Ophilolitic Massif of the Mirdita Zone forms parts of the SW graben shoulder, Triassic carbonates and clastics of the Korabi zone are widely exposed to the SE and NW of the lake (Fig. 4). At the NE margin of the basin the underlying Palaeozoic metamorphic rocks of the Korabi zone are exposed. This thrust-like geological setting is modified by the Tertiary to present extensional regime, which leads to the basin formation and the beginning of flysch and molasse sedimentation.

3.1 Korabi zone

The Korabi Zone (Fig. 4) in the lake area is characterized by Palaeozoic, mostly metamorphic and magmatic rocks, which are superposed by Mesozoic Triassic to Early Jurassic limestones in the horst shape of an anticline structure, developed between Ohrid and Prespa lakes (Fig. 4). The Devonian metamorphic rocks consist mainly of greywackes and phyllites with a complex metamorphic history. These metamorphics crop out at the NE lake shore around the city of Ohrid. South of the city of Ohrid they are preserved as a tectonic window due to extensive normal faulting (Fig. 4). In the northern part of the Galicica Mountain range (Fig. 5), marbleized limestones are

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preserved locally at the top of the mountains, e.g. NE of the village Kosel (Dumurdzanov and Ivanovski, 1977). Palaeozoic granitic intrusions are preserved north of Lake Prespa. The Triassic to Early Jurassic carbonates are mainly intensively folded limestones and partly dolomites (Fig. 4). Most parts of the eastern graben shoulder and NW shores of the lake are built up by this Mesozoic stratum. The Galicica Mountain range is widely characterised by karstified carbonates that extent to the south to the Mali i Thate Mountain chain (Fig. 5). The mainly massive and thick limestones are locally thin-bedded and intercalated with radiolarites and cherts, e.g. NE of Ljubanista (Fig. 5). Along prominent normal faults, like the one at the village of Dolno Konjsko (Fig. 5), south of the city of Ohrid, serpentinites are exposed as isolated blocks in shear lenses. Robertson (2004) discusses controversially their origin as diapirs. Furthermore, Mesozoic intrusions of rhyolithes and diabases are preserved in between the limestones and dolomites east of Kosel (Fig. 5).

3.2 Mirdita zone

The Shebenik Ophiolite Complex of the Mirdita Zone (Fig. 4) belongs to the eastern ophiolithe belt (Kocks et al., 2007). After the model of Robertson and Shallo (2000), the Shebenik Ophiolites formed within the Pindos-Mirdita Ocean after west tending subduction that started in Late Jurassic. Due to trench-margin collision at Late Jurassic-Early Cretaceous, the ophiolites were emplaced eastwards. The igneous ophiolites are of Early to Middle Jurassic age (Fig. 4) and show supra subduction zone (SSZ)-affinities in accordance to the model. They consist mainly of Lherzolites and Gabbros; interlayered pyroxenitic dykes and minor harzburgites and serpentinites (Hoeck et al., 2002; Kocks et al., 2007) have been described as well. The upper part of the sequence is dominated by basaltic breccias and turbidites with conglomerates of ophiolitic clastics which bear Fe-Ni ore deposits. The ore deposits were intensively mined in the past in the lake area. To the west the ultrabasic units of the Shebeniku Ophiolitic Massif are transgressive covered by thin shallow water carbonates of Late Cretaceous age (Fig. 4) with rudists (Jozja and Neziraj, 1998). This transgression is characterised by

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an angular unconformity. Figure 6a shows the contact of the clastic ophiolite debris and the shallow water limestones. At the western shore line this contact is often indicated by linear orientated tailings from mining operations. Anyhow, these contacts are not always sedimentary and uniform. Due to intensive normal faulting during the extensional stage the deposits are arranged staircase-like and the contacts are often disturbed (Fig. 6b).

3.3 Syn- and postorogenic development

During alpine orogeny from Eocene until Pliocene, flysch and molasse-like sediments were deposited, which are now exposed as deformed nappes (Jozja and Neziraj, 1998). They cover the ophiolitic Mirdita units to the west. Further remains are preserved covering discordant Korabi units in the south of the lake (Fig. 7b) and in the Struga Plain. They consist of Palaeocene conglomerates, silt- and sandstones of the flysch, overlain by Neogene molasse clastics, mainly conglomerates, sands and boulder gravels. Molasse outcrops at the lake are located near Pogradec (Pliocene) and west of Prrenjas (Fig. 5; Eocene to Tortonian), which consist of folded and thrusted granite-bearing conglomerates and sandstones. A further outcrop is near Ljubanista close to the southern shore of Lake Ohrid (Fig. 7b), where the river Cerava cuts into Pliocene conglomerates consisting of sands and gravels. These have been transported by the river Cerava from the Albanian side. The deposits are built up from eroded Cenozoic molasse deposits of the Korca Basin which have been redeposited in the Ohrid Basin. They are superposed discordantly by Pleistocene conglomerates which have been transported from the heights of Mali I Thate and Galicica Mountains. The transportation processes were diminished by ongoing subsidence, which divided the Ohrid from the Korca basin in Late Pliocene and Early Pleistocene.

SE of Trpejca, Pleistocene carbonate-cemented, coarse-grained angular colluvial sediments form a large and well-preserved debris cone (Fig. 7d). Other areas are characterized by the formation of huge palaeosols, which are for example preserved within the hanging wall of an active normal fault at the eastern graben shoulder NW of

Dolno Konjsko (Fig. 7c). The youngest deposits in the Ohrid Basin are the Quaternary plains of Struga in the north and Pogradec in the south. While the plain of Pogradec provides indications for a drying up of shallow lake areas filled with fine grained sediments, the northern plain is build up by gravel and sand strata from river deltas and alluvial fans. North of the city of Ohrid in the village of Kosel the so called Duvalo "volcano" can be observed. The fault-related hydrothermal field with carbon dioxide and hydrogen sulfide exhaling solfatara or fumaroles (geochemical data are not available; Fig. 7a) is situated some kilometres north of the town of Ohrid and stretches along a N20E striking lineament (Arsovsky and Hadžievsky, 1970) in highly altered Phyllites of Devonian age which are koalinisated. These rocks bear sulfur which was mined and used for spa and therapeutic purposes. Today the hydrothermal field is filled up with building rubble, waste, and cadavers and therefore the solfatara are buried successively. Further south along the lineament, thermal sulfur-bearing springs occur in the village of Velgosti. As fumaroles are in general related to former volcanic activity, the area was mapped intensively, but no evidence of volcanic rocks or pyroclastic depositions were found. The geothermal anomaly observed here is most likely related to tectonic activity.

4 Tectonic history

The above mentioned three phases of deformation left their imprint in the geological units around Lake Ohrid. The first phase of NW–SE shortening in the Late Cretaceous formed folds and thrust faults (Dumurdzanov et al., 2005), with NW–SE striking fold axes and faults (see Figs. 4 and 5). Younger Cenozoic (Late Miocene) deformation is characterised by normal and strike slip faulting which is caused by NW–SE shortening and uplift. This lead to the reactivation of inherited faults and subsequently pull apart-like opening of the Ohrid Basin (Dumurdzanov 2005; Ilic and Neubauer, 2005). After Burchfiel et al. (2006), the recent transition zone (today located in Central Albania) between extensional and the compressional regime is evidently marked by right-lateral strike-slip which can be identified from displacement vectors derived from GPS measurements and geological data. Concerning the westward migration of the deformation domains as explained in Chap. 2, this transition zone is probably responsible for initial dextral strike-slip movement which leads to a pull apart-like opening of the basin. In addition, E–W trending faults indicate dextral strike-slip movements such as the fault separating the Galicica from the Mali I Thate Mountains (see Chap. 2 and Fig. 7d). The counterpart of the fault can be found south of the Lini Peninsula at the western bank of the lake. Preliminary results of palaeostress and fault pattern analysis (unpublished data) support the dextral movement as well.

From Pliocene to present E–W extension prevails resulting in a general uplift with local subsidence, and the development of N–S striking normal faults (Aliaj, 2000). Figure 8 presents a panoramic view of the surroundings of the Lini Peninsula. En echelon N–S striking folds in ophiolites of the Shebeniku complex at the Lini half-graben can be seen. The Lini half-graben is composed of Neogene sediments (Jozja and Neziraj, 1998) whereas the front part of the Peninsular is made up of Middle to Late Triassic limestone. To the west, ophiolites and limestones ~~follow,~~ where the limestones form the hard cap rock of the sequence and are underlain by the ophiolites. Several sets of normal faults are preserved. The staircased geomorphology gives evidence for several fault generations. This can also be seen from the displacement of the Cretaceous limestone caps (Fig. 5), which protect the formation from erosion. This morphological structure is typical for the basin and also continues into the lake. The west coast has a steeper relief ~~which tributes to~~ the halfgraben theory of Aliaj (2000).

Seismic surveys in the lake (Lindhorst et al., 2010), preservation of fault scarps and tectonically cut alluvial fans show that the faults get younger towards the lake. Wagner et al. (2008) present hydroacoustic data that clearly show the extension of the N–S trending normal faulting ~~in~~ the lake sediments. This step-like expression of extensional deformation is typical for tectonic landscapes as promoted by Michetti et al. (2005). Usually, the youngest elements become activated by neotectonic activity; however, a reactivation of older faults may occur. Different fault systems have been investigated in the vicinity of the lake. From relative ages of these faults the N–S trending extensional structures are definitively the youngest. These preliminary results fit well to the model of the first three deformation phases (from 4 deformation phases in total) published by Ilic and Neubauer (2005) from the Dinarides area (Internal Dinarides to the north). The oldest deformation phase is dominated by E–W shortening and characterised by reverse and strike-slip faults in Eocene, followed by NE–SW contraction with N/NW-trending dextral and W/WSW-trending sinistral strike-slip faults in Oligocene to early Miocene. In Early to Middle Miocene, NE–SW extension lead to mainly NW-trending normal faults, and finally N–S shortening with dextral wrenching, resulting in NW-trending dextral and NE-trending sinistral strike-slip faults.

Along the slopes of the Galicica Mountains and below the wind gap shown in Fig. 7b several generations of postglacial scarps can be identified which form characteristic features in the landscape. According to Papanikolaou et al. (2005) they give evidence for a subsidence rate which is today not outpaced by erosion or sedimentation and indicates active subsidence. Further north at the Galicica Mountains close to Dolno Konjsko a post-glacial palaeosol crops out (Fig. 7c), which is offset against Triassic limestones. The NE–SW striking fault shows several meters of displacement. The palaeosols and the overlying sediments were dragged into the fault zone, forming a wedge. On top new sediments accumulated ~~discordantly~~. This outcrop illustrates the neotectonic activity of today (inactive or slower) normal faults that border Lake Ohrid to the east.

5 Conclusions

The different deformation phases that affected the study area lead to a highly complex fault pattern. Slickensides and other markers of tectonic movement are locally preserved at fault scarps and allow reconstructing the deformation history. Geomorphological features like the wind-gap, deformed palaeosols and the stepped landscape are present day expressions of the basin formation process since Late Cretaceous.

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The occurrence of the hydrothermal field near Kosel is most likely fault related since no other hints for volcanic activity in younger times have been found. Field observations and recent earthquake data lead us to conclude that the N–S striking faults which border Lake Ohrid are the active elements today and that extension is ongoing. The entire lake area can be classified as a tectonic landscape. Further investigations are needed to refine the chronological resolution and to precisely date the neotectonic activity.

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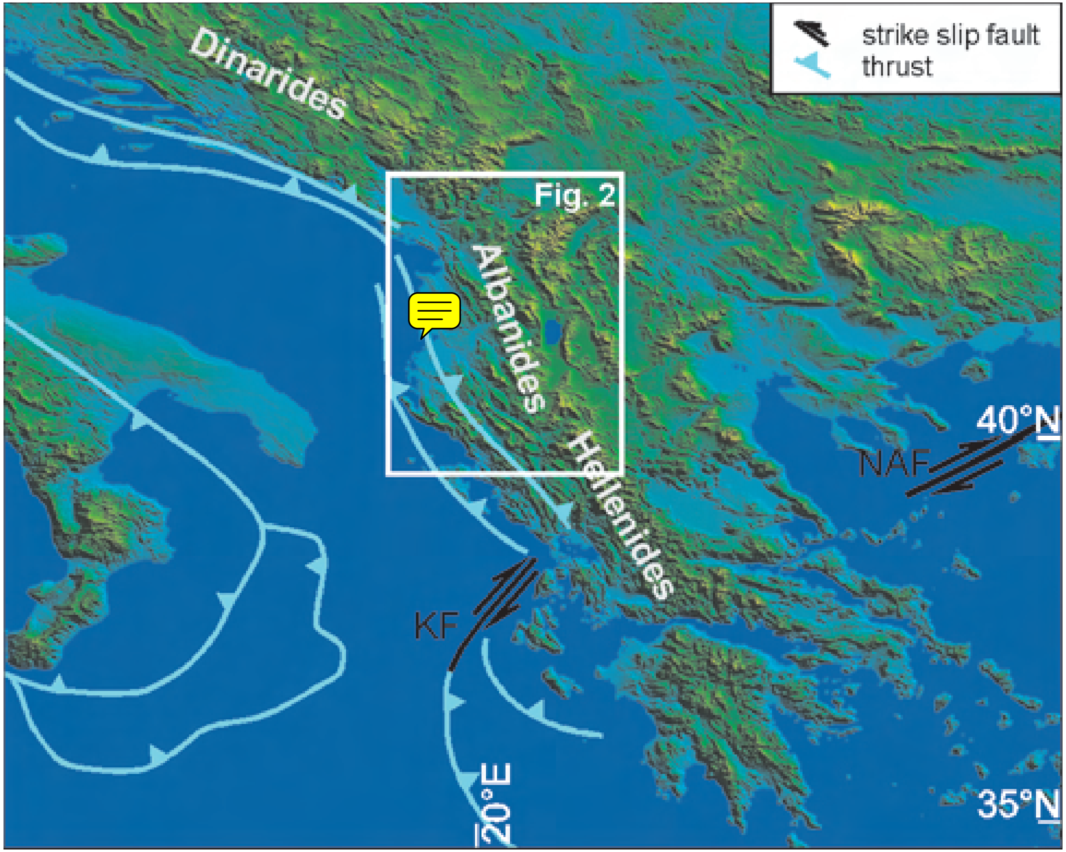

Fig. 1. Overview of the eastern Mediterranean geodynamic situation. Inset shows study area in Fig. 2. KF=Kefalonia Transform fault, NAF=North Anatolian Fault.

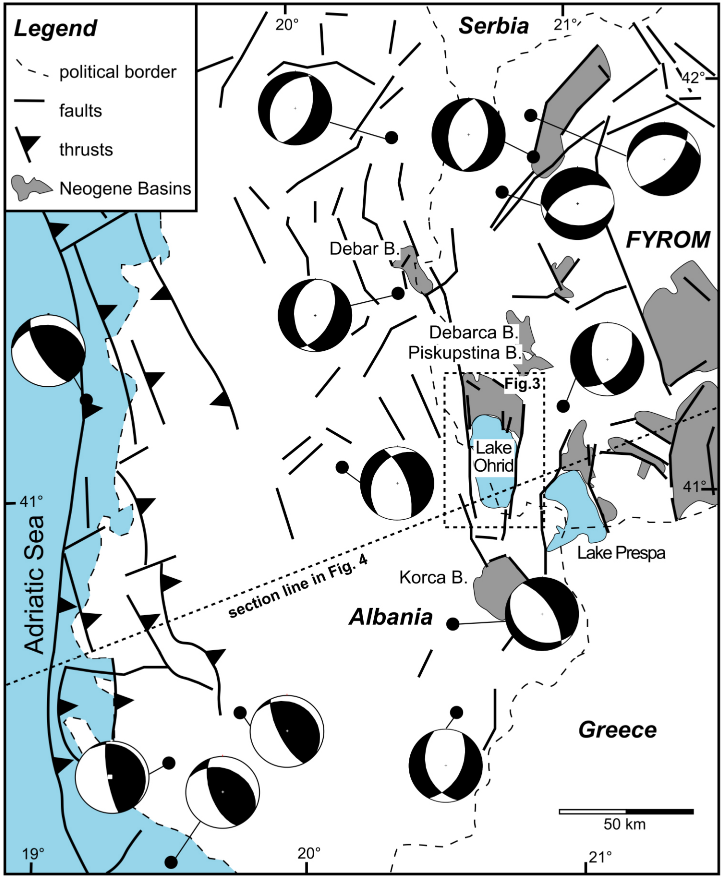

Fig. 2. Fault plane solutions of several earthquakes in the triangle Albania, FYROM and Greece (source: NEIC earthquake data base; CMT focal mechanisms). Note that the change from compressional to extensional domains is associated with Neogene basins (shaded areas) and normal faults (modified from Dumurdzanov et al., 2005). See section in Fig. 3 for structural trends.

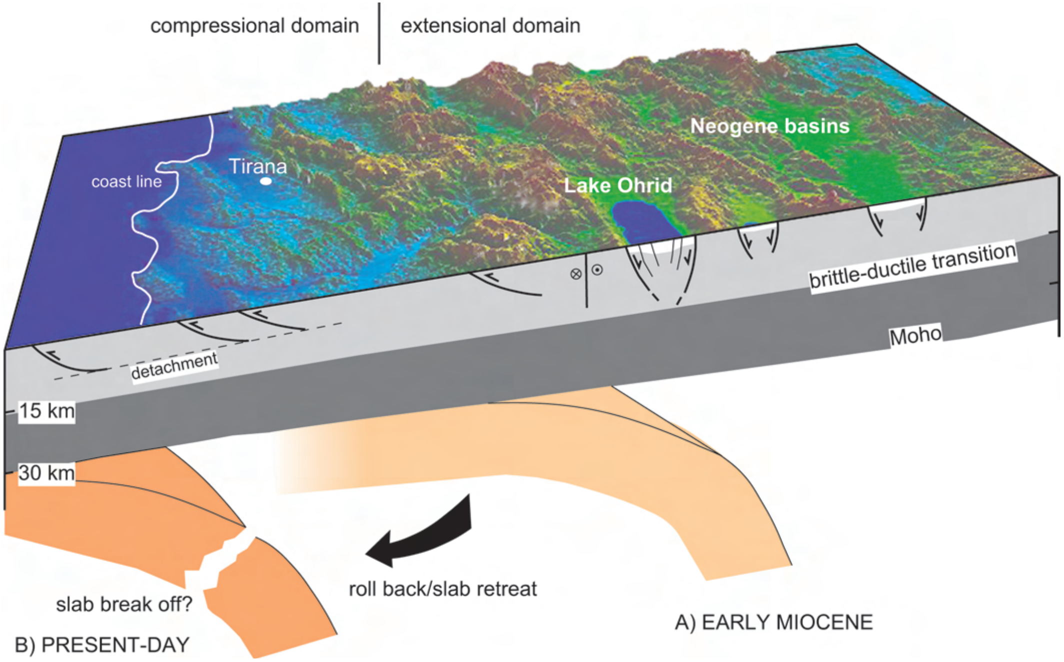

Fig. 3. Structural cross section from the Adrian coast to the Neogene basins in the Balkanides. ~~Within the extensional domain basins form, whereas the frontal part is characterised by thrusts.~~ Note subduction roll-back since Late Miocene. The Moho dips eastward from 30 km to about 40 km depth (Anderson and Jackson, 1987; Milivojevic, 1993; Grad and Tiira, 2007).

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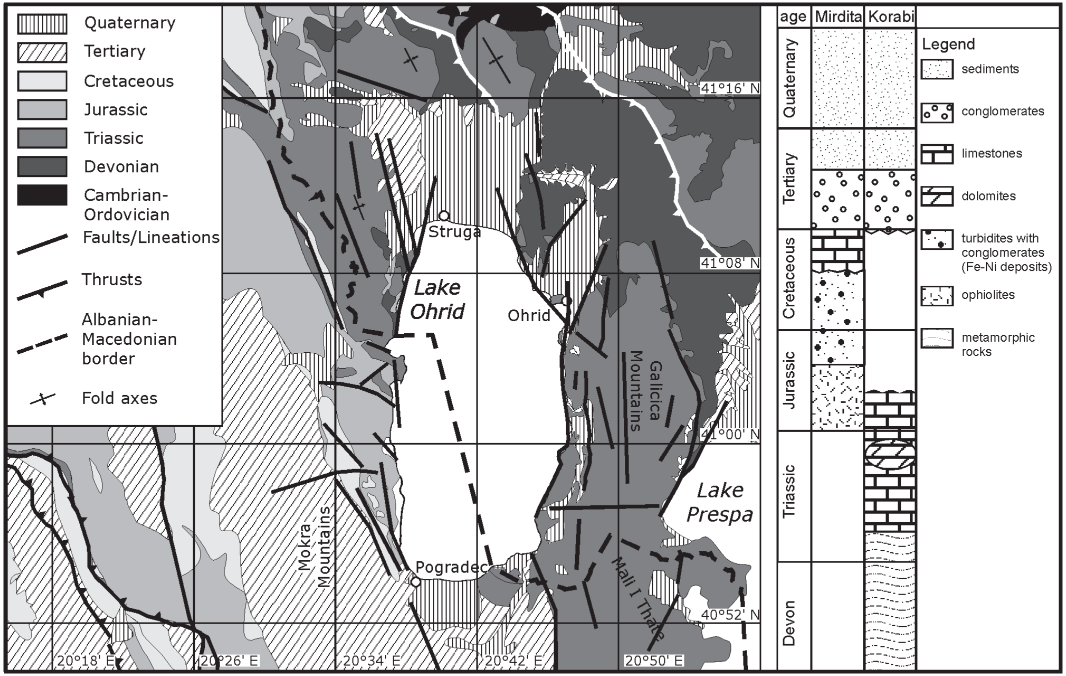

Fig. 4. Left: Geological map of the Lake Ohrid area. Main structural elements are shown. Right: Stratigraphy of Mirdita and Korabi units. Compiled after Dumurdzanov and Ivanovski, 1977; Premti and Dobi, 1994.

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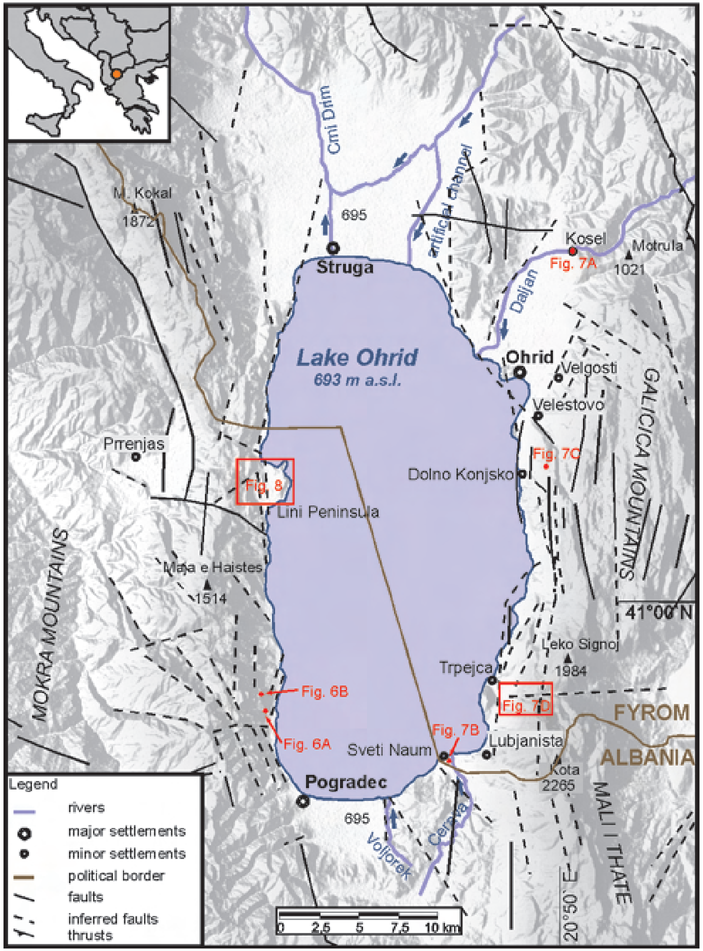

Fig. 5. Geomorphic overview map of Lake Ohrid with main structural features. Red marked areas point to the locations of Figs. 6–8.

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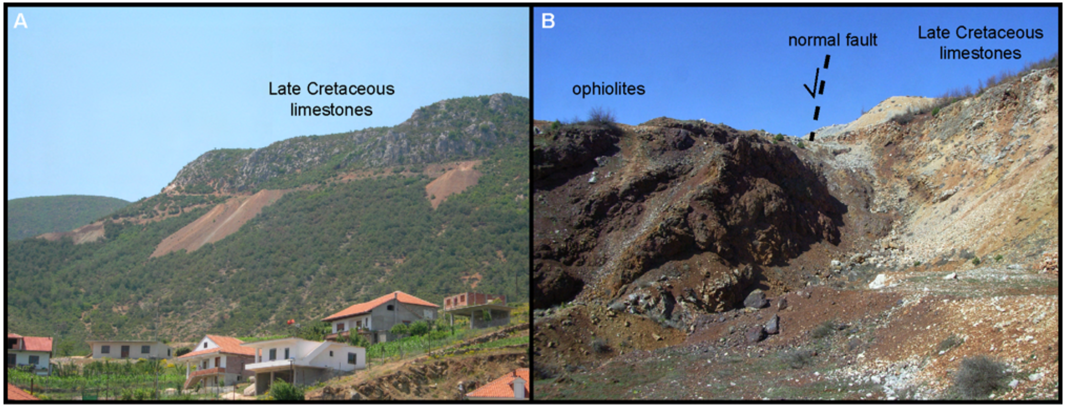

Fig. 6. **(A)** Contact between Mirdita ophiolites and Late Cretaceous limestones is marked by large tailings (west coast of Lake Ohrid, Albania). **(B)** Close-up of ~~the tectonic contact between~~ Mirdita ophiolites and limestones of Late Cretaceous age, ~~which constitutes here a normal fault~~ (Albania, 40° 57′ 48″ N, 20° 36′ 22″ E).

Fig. 7. **(A)** "Duvalo" hydrothermal field near Kosel, note completely altered and sulfur-impregnated phyllites. **(B)** Pliocene conglomerates (P) of the river Cerava near Sveti Naum monastery, which are overlain unconformably by Pleistocene conglomerates (Q). **(C)** Active normal fault with a dragged palaeosol (P) near Ohrid. **(D)** Galicica mountain front (view from west) with stepped fault scarps (S) and a "wind gap". In the foreground, carbonate-cemented colluvial breccias (B) can be seen.

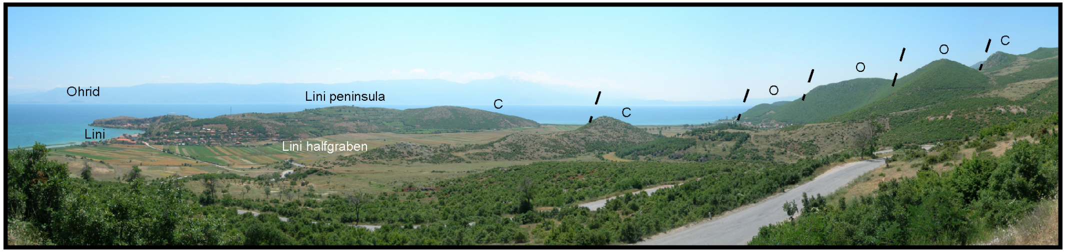

Fig. 8. Panoramic view of the Lini half-graben (Albania), note the stepped landscape due to normal faulting of the ophiolites (O) and Late Cretaceous limestones and Triassic carbonates (C).