



Amount and location of tectonic uplift in the Urmia region of northwest Iran from the Permian to the Neogene

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Abstract

The Urmia Lake Basin is located between the West and East Azerbaijan provinces in the northwest of Iran. Lake Urmia is the twentieth largest lake and second largest hypersaline lake in the world. Stratigraphic columns have been constructed, using published information, to compare the sedimentary units deposited from the Permian to the Neogene on the east and west sides of the lake, and to use these to quantify subsidence and uplift. East of the lake, the sedimentary section is more complete and has been the subject of detailed stratigraphic studies, including the compilation of measured sections for some units. West of the lake, the section is incomplete and less work has been done; three columns illustrate variations in the preserved stratigraphy for the time interval. In all cases, the columns are capped by the Oligocene–Miocene Qom Formation, which was deposited during a post-orogenic marine transgression and unconformably overlies units ranging from Precambrian to Cretaceous. Permian to Cretaceous stratigraphy is used to measure subsidence in the Lake Urmia basin up to the end of the Cretaceous, and then, the subsequent orogenic uplift, which was followed by further subsidence recorded by the deposition of the Qom Formation in the Oligocene–Miocene.

Keywords Tectonostratigraphy · Stratigraphic column · Quantitative subsidence · Qom formation · Urmia Lake · West azerbaijan

1 Introduction

Lake Urmia is a shallow lake located in northwest Iran (Fig. 1) and one of the largest permanent lakes in the Middle East. Iran's biggest internal lake is located between the provinces of Western and Eastern Azerbaijan. The water of Lake Urmia is hypersaline with a salinity of more than 180 g/L, which has risen to 300 g/L during recent years [11].

Paleotectonics and plate-tectonic models are the best recorder for understanding the tectonics of sedimentary basins and tectonostratigraphy deals with distinguishing sedimentary sequences and tectonic setting [7]. Horizontal motions of plates, thermal changes through time, stretching and shortening of the crust, isostatic adjustments, mantle dynamics, surficial processes, and even

extraterrestrial events influence sedimentary basins [17]. Quantitative subsidence analysis has been widely used in sedimentary basins developed on passive margins as well as in foreland, fore-arc and back-arc, and intracratonic basins [27].

This study outlines the stratigraphic and structural evolution of the Lake Urmia region based on geological maps published by the Geological Survey of Iran. The Lake Urmia area in NW Iran is not only situated in an active tectonic region in junction with Anatolia, escaping to the west, and the Iranian microcontinent, escaping to southeast along the major strike-slip faults, but it is also located at the extension termination of the Main Recent Fault [22]. Active tectonics of NW Iran and SE Turkey involve a counterclockwise rotating array of NWSE trending, right-lateral strike-slip faults [8].

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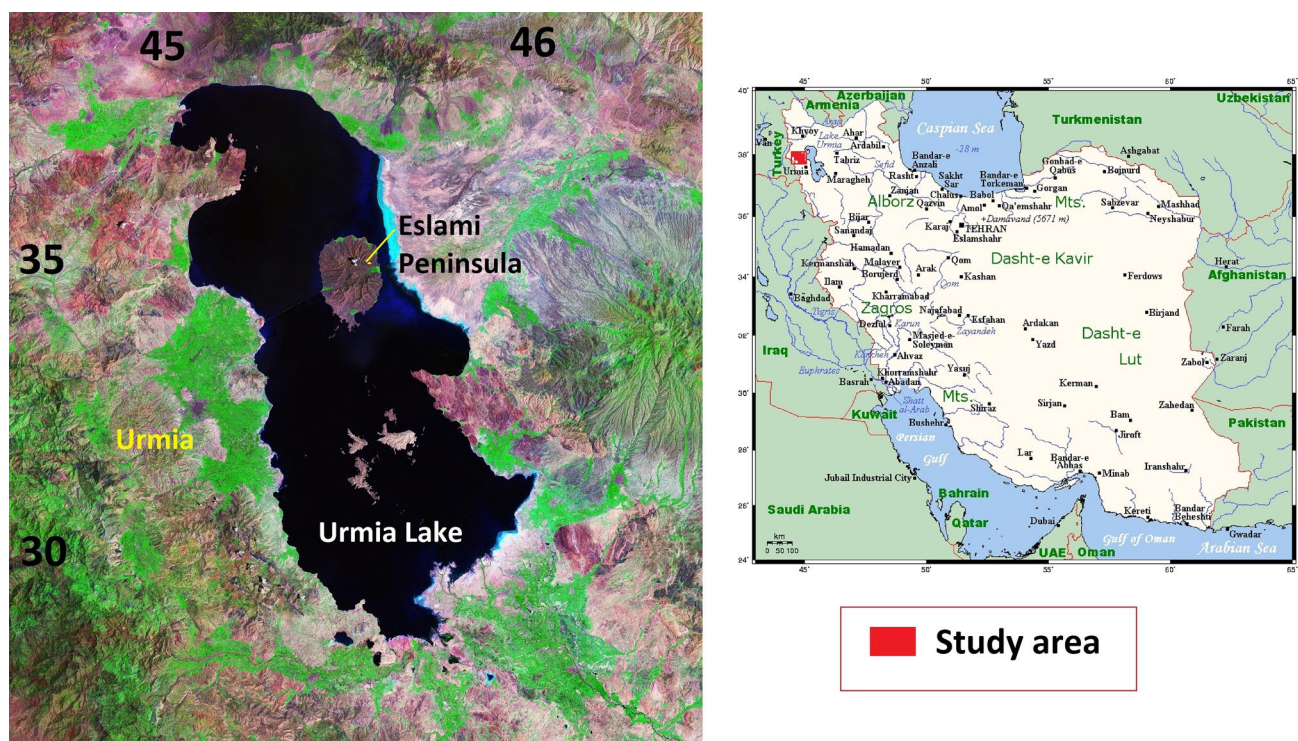


Fig. 1 Geographic location of the Lake Urmia, northwestern Iran

Two main periods of uplift can be recognized in the Permian to Miocene stratigraphy of the Lake Urmia region. The earliest coincides with the Cimmerian Orogeny in the Late Triassic [28]. The orogeny is attributed to the closure of the Paleo-Tethys Ocean in northern Iran [30]. The second is the Alpine Orogeny attributed to the closing of the Neo-Tethys Ocean along the Zagros Suture Zone at the end of the Cretaceous.

1.1 Cimmerian and alpine orogeny

The early Cimmerian orogeny (200–150 million years ago) is one of the most important tectonic events in the geological history of the Earth. The event was associated with compressional tectonics in northern Iran and tensional tectonics in the south. The late Cimmerian orogeny occurred as a significant tectonic event in Iran in Late Jurassic–Early Cretaceous times [24]. The Alpine orogeny is an orogenic phase continuing from the Late Mesozoic into the Cenozoic and has formed the mountain ranges of the Alpidic belt. The Alpine orogeny was caused by Africa, India and the small Cimmerian plate colliding with Eurasia in the north. Convergent movements between the tectonic plates had already begun in the early Cretaceous, but the major phases of mountain building began in the

Paleocene and Eocene. The orogenic processes continue today in some of the Alpidic mountain ranges [23].

2 Tectonostratigraphy

Following the Pan-African orogeny (about 550 million years ago), shallow marine sediments were deposited during the Late Ediacaran, and deposition extended across large areas of Iran during the Paleozoic (e.g., Alborz, Eastern Iran, Zagros; [14]). After a general regression and a distinct hiatus Permian marine transgression resulted in deposition Silurian rocks in most parts of Iran; the Permian sediments are represented by the Dorud sandstones, and Ruteh and Nesen limestone in the Alborz region [14].

The Lower Triassic sedimentary rocks in Iran are mainly of a shallow marine or continental shelf origin for example the Elik dolomites in Alborz, and the Sorkh shale and Shotori dolomites in Central Iran [14]. Both continuous and discontinuous transitions have been described between Paleocene and Eocene strata as is also the case with Eocene and Oligocene strata (e.g., Central Iran). The Oligocene and Miocene epochs were characterized by rapid subsidence, deposition, and facies changes in both marine and continental sedimentary

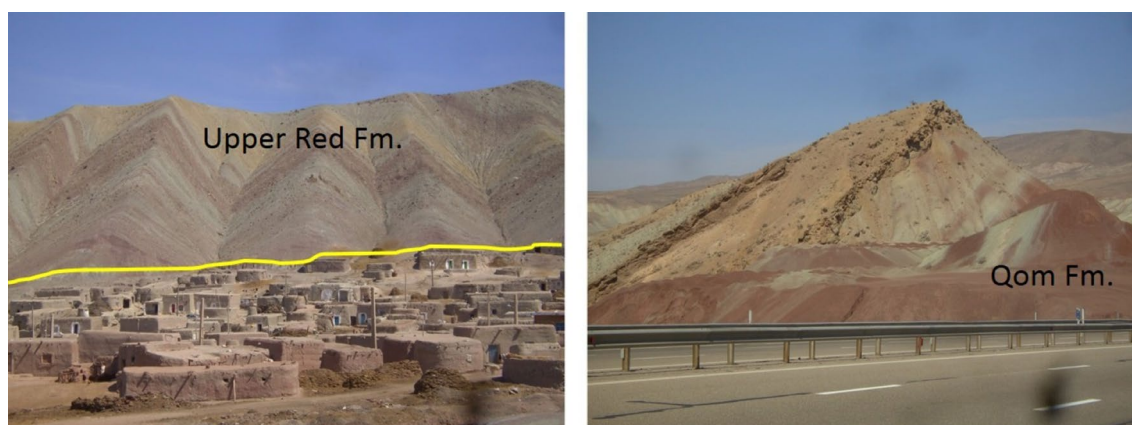


Fig. 2 Field photos of the Upper Red and Qom Formations at the study area, looking east

basins [14]. Oligocene sediments in most parts of Iran are of shallow marine character, turning into deeper marine facies in the Upper Oligocene through the Lower Miocene (e.g., Qom; Fig. 2). The middle-upper miocene sedimentary rocks are mostly continental. Quaternary sediment is a prominent feature of the plains of Iran [14].

The geology of the study area (Fig. 3) includes rocks ranging in age from Precambrian to Quaternary, including recent lake sediments [3, 4]. Kelts and Shahrabi [19] showed that Paleozoic metamorphic rocks occur on the western side of the lake, whereas the rocky cliffs on the eastern shores are composed of Mesozoic flysch. The northwestern shores, and many of the islands, are formed of Lower Miocene, represented by coral limestone of the Qom Formation.

2.1 East of Lake Urmia

The column east of the lake (Fig. 4) is principally based on four sources of information. The line of the section is shown by Shahrabi et al. [26]. The Dorud Formation is a basal sandstone and conglomerate unit and the overlying Ruteh Formation is mainly composed of limestone and dolomite. The total measured thickness for the Permian is 2510 m. In the Maragheh area, to the south of Ajabshir, it is considerably less. In this area, Alavi and Shahrabi [2] estimate thicknesses of 800 m decreasing southwards to 400 m. About 30 km farther to the east, in the Miyane area, Amidi et al. [6] show Jurassic rocks lying directly on the Lower Paleozoic so locally the Permian is completely absent. Alavi and Shahrabi [2] report that the boundary between the Permian and the Triassic is a laterite bed, which they include in the Permian. Gadirzadeh et al. [12] draw the Permian–Triassic boundary above this level in the Azarshahr area and assign the intervening rocks to the Permian Nesen Formation; on adjacent maps these rocks

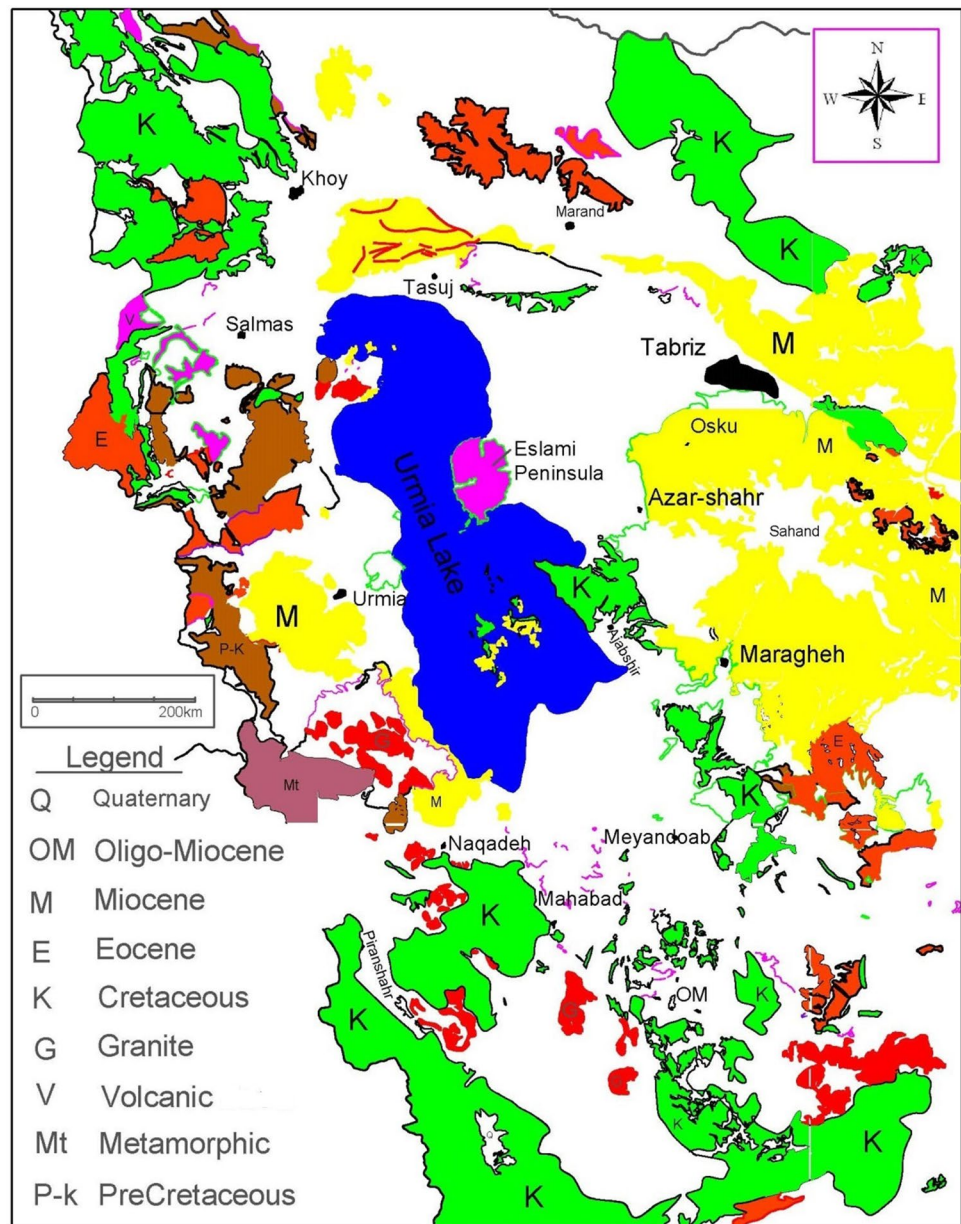
are included in the Triassic Elika Formation [2, 20] and this policy is followed on Fig. 4.

The column east of the lake (Fig. 4) is principally based on four sources of information: The first of these is a section measured through the Permian Dorud and Ruteh formations, west of Ajabshir, by Shahrabi [25]. The other sources for compiling the column east of the lake are the descriptive notes on the 1:100,000 geological map of the Maragheh area [2]; a section measured through the Jurassic by Shahrabi [25] and, the flysch is shown on Fig. 4 with an estimated thickness of 3000 m.

These describe the Triassic as being represented by the Elika formation consisting of limestone and dolomite. They estimate the thickness of the formation at 250 m. In the Osku map area to the north, the thickness of the Elika formation is estimated to be about 225 to 260 m [20]. The Elika Formation is Lower and Middle Triassic and, in the Maragheh area and most locations in the Osku area, it is directly overlain by Jurassic rock which means that the Upper Triassic is missing. However, in one location in the Osku area, Khodabandeh et al. [20] report 150 m of red sandstone, shale and limestone of the Upper Triassic Nayband Formation in faulted contact with other units. There is some doubt about the age assignment of these rocks because, in the neighboring map area of Azarshahr, their continuation is assigned to the Cambrian Lalun Formation, which contains similar rock types [12].

The other reference for the column east of Lake Urmia is a section measured through the Jurassic by Shahrabi [25]. The section was measured on Kuh-e-Guyposhti and the line of section is shown by Alavi and Shahrabi [2]. The Shemshak Formation lies disconformably on the Elika formation. It belongs to the Lower Jurassic and consists of 564 m of shale and sandstone. The base of the Jurassic contains a laterite horizon that indicates an interval of emergence and subaerial weathering before the Jurassic

Fig. 3 Geological map of the Lake Urmia region (modified from: [12, 15, 26])



transgression. The thicknesses of the Dalichay and Lar formations were measured at 253.5 and 282.5 m, respectively. The formations were deposited in a marine basin and consist of marl, sandstone, limestone and dolomite.

The flysch is shown on Fig. 4 with an estimated thickness of 3000 m. This thickness is post folding and not a stratigraphic thickness. It is based on the cross section through the Urmia 1:250,000 map area [25], where there is an outcrop pattern in the southeastern part of Lake Urmia. Also, the estimated thicknesses were determined by measuring the outcrop widths where these formations have been preserved in a syncline in the southwest corner of the Tasuj 1:100,000 map area [21].

In the Maragheh map area the Jurassic units are covered by up to 140 m of Cretaceous basal conglomerate, which contains pebbles derived from the Lar Formation [2]. The conglomerate is overlain by 50–300 m of *Orbitolina* limestone assigned to the Tizkuh Formation by Shahrabi et al. [26] and this unit grades up into a strongly folded flysch succession consisting of shale, sandstone and intercalated mafic volcanic rocks [2, 25].

2.2 West of Lake Urmia

The Permian west of the lake has a similar carbonate lithology to that east of the lake and is similarly divided into the Dorud and Ruteh formations. Shahrabi [25] gives an overall

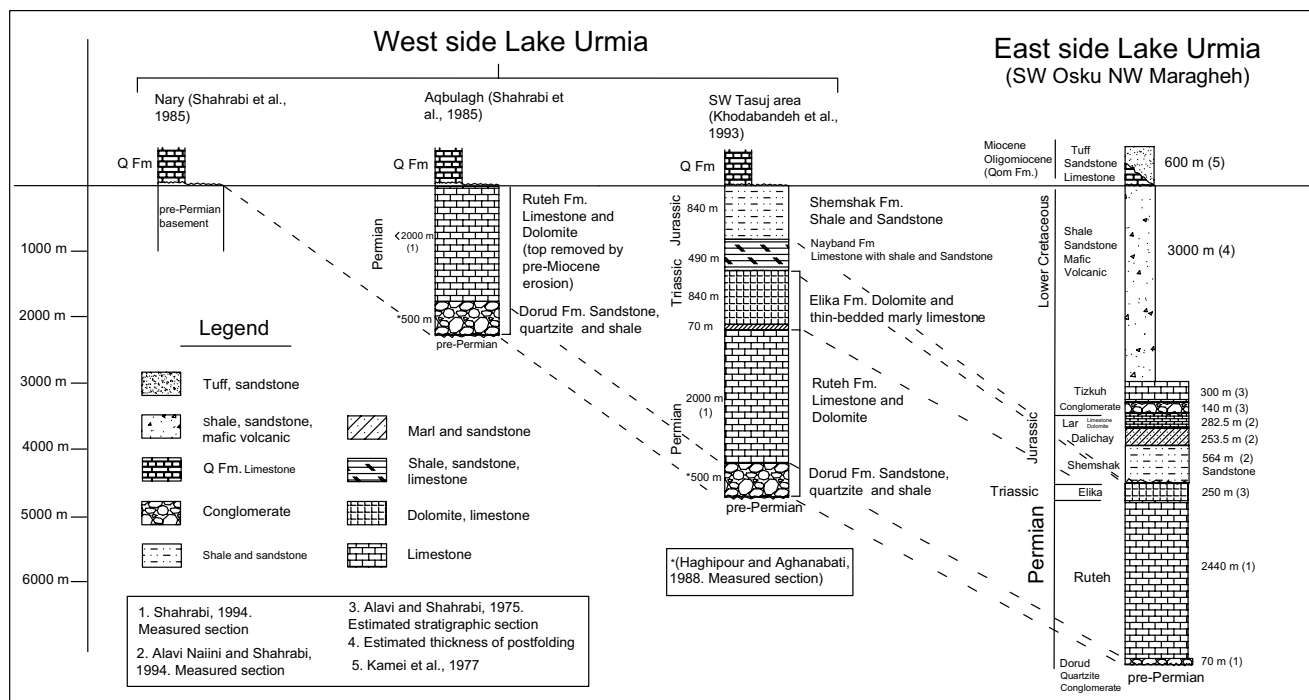


Fig. 4 Stratigraphic columns of strata on the west and east sides of the Lake Urmia. The columns are principally based on measured section information (the sum of thicknesses in west side: 840 + 49

0 + 840 + 70 + 2000 + 500 = 4740 m; the sum of thicknesses in east side: 3000 + 300 + 140 + 282.5 + 253.5 + 564 + 250 + 2440 + 70 = 7300 m; 7300 – 4740 = 2560 m differences)

thickness of 2500 m, based on estimates for the Mahabad [10], Khoy [13] and Serow [15] areas.

Mesozoic strata west of the lake are only preserved in a few synclinal areas of limited meter extent. The Triassic is composed of the Lower to Middle Triassic Elika and Upper Triassic Nayband formations, which together have an estimated 1415-m thickness of dolomite, and limestone with shale and sandstone. The Jurassic consists of the Shemshak Formation with an estimated 850 m of shale and sandstone. Younger Jurassic formations are not present and are presumed to have been eroded. The presence of the Upper Triassic suggests that the Jurassic may overlie it conformably and there may have been continuous sedimentation with no period of erosion, as east of the lake. The competent nature of the rock types and examination of satellite photos suggests no structural repetition by folds or faults. Accordingly, a true stratigraphic thickness can be calculated for the Triassic between 1000 and 1715 m, and for the Jurassic between 600 and 1030 m. Although the Triassic and Jurassic are only locally preserved on the west side of the lake, they consist of marine shelf facies which indicate that they were originally part of a more extensive sheet of sediments. It is therefore assumed that their absence in most places west of the lake is due to erosion and not to non-deposition.

Cretaceous rocks are absent in the area immediately west of the lake. However, they are mapped farther to the west on the Khoy and Serow areas [13, 15]. There, units possibly corresponding to the basal conglomerate, the *Orbitulina* limestone of the Tizkuh Formation and the flysch succession suggest a medium to deep water stratigraphy that can be correlated across the entire Lake Urmia region. If this is so, Cretaceous rocks are absent from the area immediately west of the lake because of erosion rather than non-deposition. The Miocene directly lies on older Cretaceous rocks on the west side of the lake, Fig. 5.

A sequence of Permian to Cretaceous rocks at least as thick as that seen on the east side of the lake and thicker was deposited on the west side of the lake as well. This sequence buried the pre-Permian basement to a depth of about 8000 m (sequences of east side). In order for the sequence to be completely eroded, as it is in many places, the pre-Permian basement had to be elevated by this amount relative to the east side of the lake, where the Cretaceous is still present.

Comparison of the Permian sections east and west of the lake is hampered by the absence of a published measured section from west of the lake to compare with that available from near Ajabshir [25]. However, the estimate of Shahrabi [25] for thickness west of the lake suggests that they are very similar. Where there is a notable difference

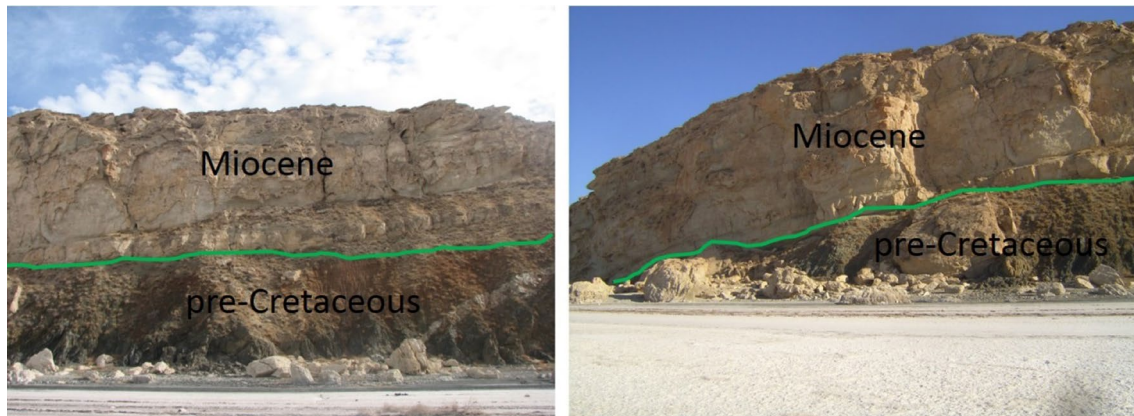


Fig. 5 Miocene overlies older rocks at the northwest of the lake (viewed looking to the west)

is in the estimate of only 400 to 800 m of Permian below the Triassic in the Maragheh area [2] and the complete absence of both Permian and Triassic.

In a part of the southwest corner of the Miyane map area, Jurassic is shown overlying pre-Permian rocks unconformably [6]. Furthermore, the Upper Triassic represented by the Nayband Formation, is present west of the lake but east of the lake it was either not deposited or was eroded before the disconformable deposition of the Jurassic [2]. In the Lake Urmia region, much farther from the collision zone, the Shemshak Formation lies disconformably on the Triassic and the only angular unconformity occurs where it overlaps onto pre-Permian rocks in the Miyane area.

2.3 Post-cretaceous overlap sequences

The basal units of the Paleocene and Eocene west of Lake Urmia consist predominantly of red conglomerate unconformably overlying Cretaceous and older rocks, including ophiolitic mélangé [15]. They are themselves overlain by units containing Eocene fossils [1]. In the Salmas area, the conglomerate is interbedded with shale, sandstone and limestone and is about 300-m thick [20], but to the south in the Serow area it reaches a thickness of 1000 m. East of lake, red conglomerate does occur locally [26], but is mostly absent beneath the volcanic rocks of the Karaj Formation (Eocene). Volcaniclastic conglomerate in the Azarshahr area in the northeast part of the lake is assigned to the Eocene by Gadirzadeh et al. [12], but there are no constraints on its age so it may not be correlative with the other conglomerate occurrences.

Andesitic lava flows and green tuff of the Karaj formation unconformably overlap Paleozoic, Jurassic and Cretaceous units southeast of Lake Urmia in the Maragheh area. The green tuff contains marine fossils [18]. There are also Paleocene mafic volcanic rocks in the Salmas area, north of the lake.

There is 1000 m of sandstone and Nummulitic limestone west of the lake belongs to Eocene [15, 16]. This unit contains marine fossils, ripple marks, worm traces and plant remains, which indicate a shallow marine environment in the Paleocene-Eocene [1]. Ripple marks with worm traces and plant remains, sandy marl and shale, and conglomerate are also seen in the Serow areas northwest of Urmia.

The Miocene contains basal conglomerate, sandstone and marl that unconformably lie on Eocene. The Oligocene–Miocene Qom Formation around Lake Urmia is about 2500 m thick and comprises two limestone-marl and molasse units.

The Qom Formation northwest and southeast of Lake Urmia belongs to the Upper Oligocene and Lower Miocene and lies unconformably on older units (Eocene). It contains limestone, clay and marl, and is well-bedded and fossiliferous. On the east side of the lake, the formation contains microlithic limestone, marl, clay and well-laminated limestone. It crops out on the islands in the lake and also east of the Azarshahr area, and lies unconformably on the Upper Cretaceous formations [12]. The Qom Formation is subdivided into these units in the Urmia region:

1. Limestone-marl: this unit contains limestone, marly limestone and marl with bedded and massive forms. The unit outcrops on the islands in the Lake Urmia. The fossils in these rocks are both marine and non-marine, and indicate interbedded facies of each.
2. Molasse: contains sandstone, shale, marl and conglomerate. Its thickness is 2000 m around Urmia city.

3 Discussion

Investigation of the Burguer gravity field of NW Iran shows that the gravity increases from east to the west from -150 to -100 m Gal indicating a decreasing crustal thickness [9]. During the Permian, a period of deposition began on the Iranian continental shelf and continued into the upper Cretaceous. To the east, part of the Iranian continent may have remained above sea level, but to the west the submerged edge of the continental shelf lay adjacent to the deep ocean basin of Tethys, which was underlain by oceanic crust. The deep sea sedimentary rocks of the coloured melange were deposited in this ocean basin and are exposed in the eastern part of the Urmia map sheet. The depression that now contains Lake Urmia was formed entirely on the Iranian continental shelf and the same sedimentary units of Permian to Cretaceous age can be identified both east and west of the lake.

Possible explanations for the reduced thickness or complete absence of the Permian are that it was never deposited, or that it was deposited, but then eroded during a regression in the Late Triassic. Either explanation indicates that the part of the continental shelf east of Lake Urmia was subject to emergent conditions in the Permian and/or Triassic in contrast with the area to the west, and therefore that the continental shelf at this time most likely sloped toward the west.

A westward slope of the continental shelf and consequent deepening of the sedimentary basin is supported by Mesozoic stratigraphy. The Lower and Middle Triassic units are thicker west of the lake than they are east of the lake which suggests a progression from shallower to deeper water from east to west and greater sediment accumulation in the deeper parts of the basin.

The absence of the Upper Triassic indicates a regression and emergent conditions. Alavi and Shahrabi [2] proposed that a Late Triassic to Early Jurassic erosional phase may have caused the complete removal of the Triassic in part of the Maragheh area.

The same pattern continued into the Jurassic with the Shemshak Formation showing a greater thickness west of Lake Urmia than east of it, again suggesting a deepening of the basin toward the west. Comparison of later Mesozoic units is not possible because, west of the lake, the later Jurassic units are not represented, almost certainly because of erosion, and no stratigraphic thicknesses have been published for Cretaceous units.

The Permian to Jurassic formations in the Lake Urmia region resemble and have been correlated with formations of the same age in the Alborz Mountains of northern Iran [3]. The interruption in the Mesozoic stratigraphic record east of Lake Urmia coincides with the timing of the

Cimmerian Orogeny in northern Iran and is most likely attributable to this event. In the Alborz Mountains, the orogeny is marked by an angular unconformity beneath the Shemshak Formation, which overlies a pre-Jurassic thrust stack [30]. The effects of the orogeny seem therefore to have been limited to regional uplift causing the Late Triassic regression and the emergence of the shallower parts of the basin above sea level.

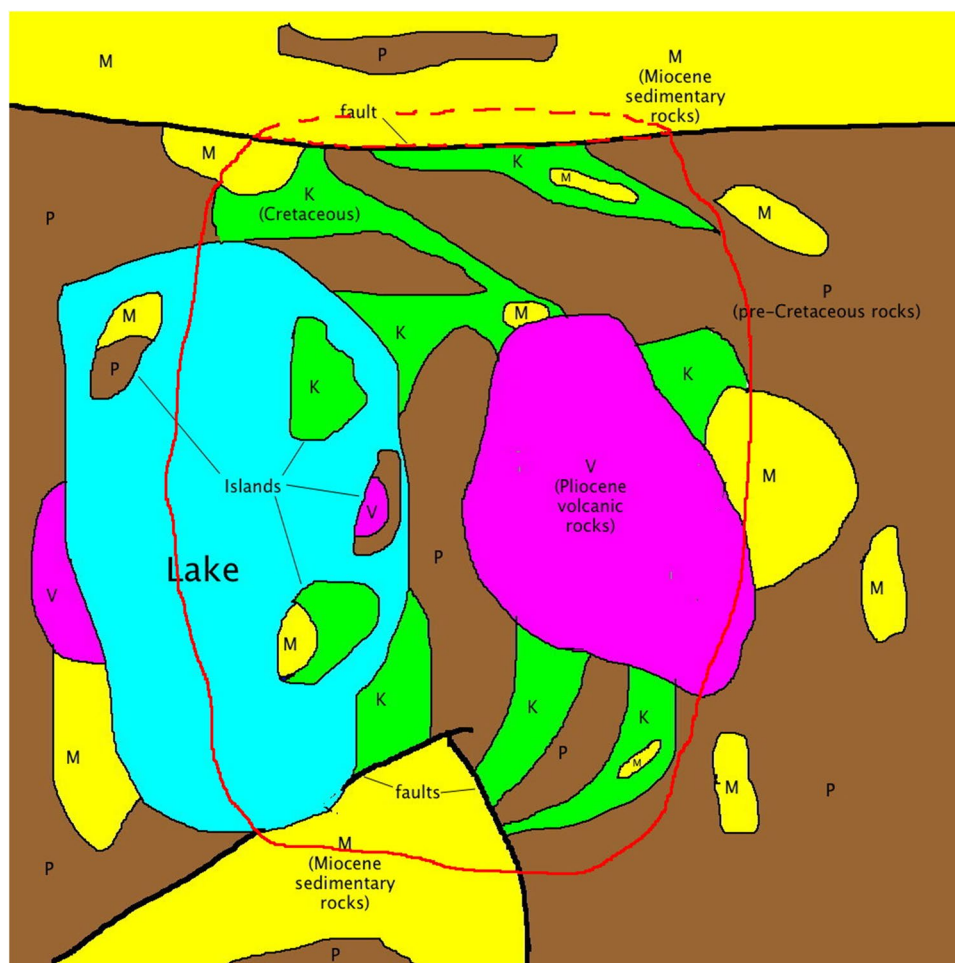
The contact between the Cretaceous and pre-Cretaceous is overlain unconformably by the Miocene. So, Miocene unconformably overlies pre-Cretaceous rocks (Fig. 5). When the Miocene sea flooded across and deposited its sediment, these pre-Cretaceous rocks must have been exposed at the surface in the area. Furthermore, the Cretaceous was exposed at the surface when the Miocene flooded across. For the pre-Cretaceous to be exposed in these areas in the Miocene, the Cretaceous would have had to be eroded away. Therefore, any place that is Cretaceous today was also Cretaceous when the Miocene sea flooded across, and so is inside the Cretaceous basin. Pre-Cretaceous rocks are exposed today, but they are not overlain by Miocene. It may be that Miocene lay directly on the pre-Cretaceous and that all the Cretaceous was eroded before the Miocene (Fig. 5). However, it is also possible that the Miocene was deposited on Cretaceous, and then, both the Miocene and the Cretaceous were eroded after the Miocene, exposing the pre-Cretaceous today. Miocene is faulted against Cretaceous or pre-Cretaceous rocks (Fig. 6).

Permian-Cretaceous sediment is the first surface that was horizontal (Fig. 7). During collision, the Cretaceous sediments were folded or faulted so that in the Lake Urmia area, and they sank in a basin and to the west and east they were elevated to form mountains. In the Oligocene and Miocene there was widespread deposition of shallow marine sediments of the Qom Formation. The base of these sediments was also horizontal because there was a shallow sea spread across a wide area.

4 Conclusions

The pre-Permian basement under this basin was likewise at a shallower depth in the east than in the west. This is the opposite of what we see today. The pre-Permian basement today is buried under almost 8000 m of Permian to Cretaceous sediment on the east side of the lake, where the Cretaceous outcrops at the surface, but west of the lake the pre-Permian is exposed at the surface. This was also how it was when the Oligocene–Miocene Qom Formation was deposited because this formation lies unconformably on Cretaceous on the islands at the east side of the lake and on Precambrian rocks in places on the west side.

Fig. 6 The boundary of the Cretaceous rocks are shown on this map is like the line. Present day geology of the region (not to scale)

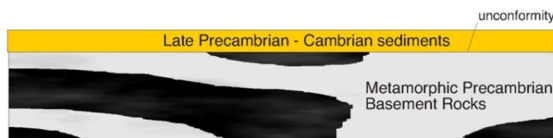


The change in the basin must have occurred between the deposition of the lower Jurassic rocks, which thicken to the west and so indicate a deepening basin toward the west, and the deposition of the Qom Formation, which lies on Cretaceous in the east and Precambrian in the west. Because the Middle Jurassic to upper Cretaceous is missing from the west side of the lake, we can not compare thicknesses to work out the depth of the shelf at these times. However, the notes on the Maragheh map do not mention any major unconformity from the Shemshak Formation up through to the Upper Cretaceous so it is likely that a major tectonic event did not occur until the top of the Cretaceous, and therefore that the shelf had the same form until then. This major tectonic event would be the continental collision between Arabia and Asia, which is generally viewed as being late Cretaceous to Eocene on lots of other evidence [5]. The late Oligocene to Miocene collision of Arabia and Eurasia was preceded by ~175 My of subduction of Neotethyan oceanic crust [29].

There are two possible reasons why the Middle Jurassic to Cretaceous is absent west of the lake: (1) They were never deposited, or (2) They were deposited and then eroded when uplift occurred as the shelf was deformed in continental collision at the end of the Cretaceous. The rocks that we do see indicate that the shelf deepened to the west and that this did not change until the end of the Cretaceous so we conclude that 2 is much more likely than 1. If this is true, a sequence of Permian to Cretaceous rocks at least as thick as that seen on the east side of the lake and probably thicker was deposited on the west side of the lake as well. This sequence buried the pre-Permian basement to a depth of about 8000 m. If the thicknesses of formations were equal in both east and west sides, the number of differences (2560 m) illustrates thickness of depositions that eroded and missed at the west side. In order for the sequence to be completely eroded, as it is in many places, the pre-Permian basement had to be elevated by this amount, while the east side of the lake, in

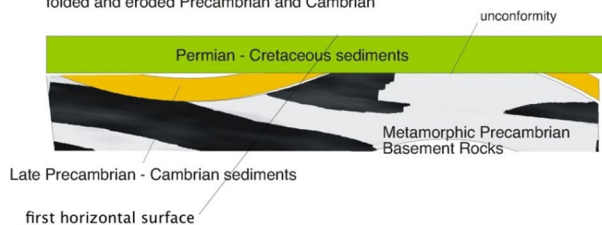
Late PreCambrian - Cambrian

Marine transgression; sediments deposited on a peneplained basement



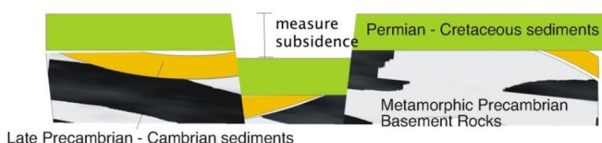
Permian - Late Cretaceous

Marine transgression; Mesozoic sediments deposited on peneplain of folded and eroded Precambrian and Cambrian



Eocene

Lake Urmia basin formed by faulting

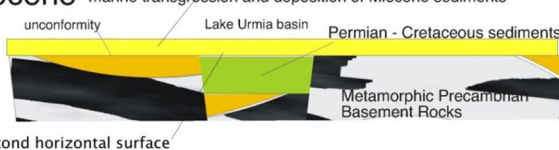


followed by erosion and formation of a peneplain.



Qom Formation

marine transgression and deposition of Miocene sediments



second horizontal surface



Fig. 7 Tectonostratigraphy evolution model for the Urmia Lake (not to scale)

areas where Cretaceous is still present, was hardly elevated at all.

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Compliance with ethical standards

Conflict of interest The authors declare that he/she has no competing interests.

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