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Geology and geomorphology of Turkmenistan: A review

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Abstract

This article provides a background for scientists interested in a general overview of the geology and geomorphology of Turkmenistan, a subject covered only sparsely in the international geological literature despite the very attractive features of this important Central Asian country. The basement of Turkmenistan is a complex amalgamation of arc–related terranes developed in the Asiatic and northern Paleotethys oceanic domains during Late Paleozoic to Triassic times. A major part of the country coincides with the Turan Platform, where a thick sedimentary succession accumulated between Late Paleozoic and Cenozoic. Sedimentation rates culminated during Middle Jurassic times, being more eminent in the Kopeh–Dagh Province to the south due to backarc extension in remote regions of the Neotethys subduction zone. Closure of the Neotethys ocean and collisional events in the Iranian, Afghan and Indian regions to the south resulted in inversion of the tectonic regime into a compressional setting in Early Cenozoic. The Caspian Province in western Turkmenistan recorded a geological and tectonic history very similar to that of the South Caspian Basin in Cenozoic times. Major gas and oil fields have developed in different petroleum systems of the Turan and Caspian Provinces. Dynamics of the Karakum desert and evolving drainages across it have a major bearing on the geomorphology and environment of Turkmenistan. Major structural features of the country are described, and attractive geological features are introduced.

Keywords: *Turkmenistan, Turan Platform, Karakum Desert, Amu–Darya River, Kopeh–Dagh, South Caspian Basin, Geology, Hydrocarbon Potential.*

"Either thou shalt renounce thy vaunt and yield,
Or else thy bones shall strew this sand, till winds
Bleach them, or Oxus with his summer-floods,
Oxus in summer wash them all away".
Sohrab and Rustum by Matthew Arnold

Introduction

Located in the transition zone of the Cimmerian terranes in the south, and the stable Eurasian plate in the north, Turkmenistan is a very interesting country from the geological point of view, yet it has been studied in a very limited capacity. A major attractive aspect of the geology of Turkmenistan lies in its vast petroleum potential (The reader is addressed to the oil and gas reserve map of Turkmenistan by Crude Accountability, 2011). Turkmenistan is surmised as the second gas reserve of Eurasia and Europe after the Russian Federation. The proved natural gas reserves in the country is estimated at 17.5 trillion m^3 (Olcott, 2013).

Most geological studies in Turkmenistan were carried out by the former Soviet Union geologists (e.g., Kalugin, 1957; Volvovsky *et al.*, 1966; Rastsvetaev, 1966; Krymus & Lykov, 1969; Amursky, 1971), many of which are in Russian language, and are scarcely accessible to an international audience. More recent geological studies, dedicated specifically to this region include those by Lyberis *et al.* (1998), Lyberis and Manby (1999), and Garzanti and Gaetani (2002), whereas others have considered Turkmenistan in the wider framework of the regional geology of the "Turan Platform" and of Central Asia in general. The term "Turan platform" (sometimes used in conjunction with "South Kazakh platform") is applied for description of a large area between the Kopeh–Dagh and Caspian Sea in the west and the western Tien Shan/Pamir ranges in the east, which is mainly covered by upper Permian to Quaternary deposits, and is considered roughly stable since the Triassic times (Kazmin, 1990; Maksimov, 1992; Lordkipanidze, 1991; Sheikh–Zade, 1996; Thomas *et al.*, 1999; Natal'in & Sengör, 2005). According to Natal'in and Sengör (2005) the boundaries of Scythian and Turan platforms are defined by the extent of their Jurassic to Cenozoic cover, which, in the Turan case, oversteps onto the southwestern part of the Altaids. Compared to the rather sedimentological and physiographical concept of the "Turan platform", the term "Turan plate" is generally used for the tectonic realm situated between the Iranian plate to the south, and Altaids, Uralides and Ust–Yurt domains to the north. The Paleotethys suture and the Skytho–Turanian fault respectively delineate the southern and northern boundaries of the Turan plate. Thomas *et al.* (1999) provided structure–contour and isopach maps for five main stratigraphic intervals, Late Permian to Cenozoic in age, to reconstruct the paleogeographic and paleotectonic evolution of the southern margin of Eurasia. Natal'in and Sengör (2005) analyzed borehole and geophysical data, and distinguished different geological units within the Turan domain, including Bukhara, Chardjou, Karakum–Mangyshlak, Tuarkyr, and Karabogaz units. They suggested that the basement of these terranes, extending from northern Afghanistan and Turkmenistan to the Caucasus and the northern Black Sea, consists of a number of *en échelon* array of southwest–facing arc fragments of Paleozoic to Jurassic ages which were stacked into their present places by large–scale, right–lateral strike–slip transport in the Triassic and middle Jurassic, simultaneous with the subduction and elimination of the Paleotethys ocean.

Detailed studies by Lyberis *et al.* (1998) and Lyberis and Manby (1999) investigated the stratigraphic and structural evolution of the Turan continental block, suggesting that post–Triassic sediments were folded and uplifted in the Kopeh–Dagh mountains in response to the convergence between the Iranian and Turan plates. They inferred ca. 75 km of north–south shortening in the western part of the Kopeh–Dagh–Greater–Balkhan area, accommodated by oblique movement along the major Ashk–Abad fault zone and east–west structures south of it.

Sedimentologic and petrographic analysis of the Upper Paleozoic to Triassic Kizilkaya sedimentary succession in western Turkmenistan led Garzanti and Gaetani (2002) to conclude that the Turan Plate consists of an amalgamation of Upper Paleozoic to Triassic continental microblocks separated by oceanic sutures. In their reconstruction of the southern margin of Eurasia, Zanchetta *et al.* (2013) showed that this tectonically active region recorded several episodes of continental accretion and opening of arc–related basins associated with magmatic activity. Brunet *et al.* (2017) used geological and geophysical data to reconstruct the Late Paleozoic and Mesozoic evolution of the Amu–Darya basin in Turkmenistan and Uzbekistan.

This article reviews geological and geomorphological information from the Iranian Kopeh–Dagh and Gorgan plain, as well as the available regional geological maps, and combines them with ETM and Google Earth™ satellite images to illustrate and extrapolate major geological units and tectonic structures within the territory of Turkmenistan. A new general geological map of the region is compiled (see sections 2 and 3), and the geological evolution of the country is discussed also based on the mapping and surface features observed with the help of remote sensing data. Spectacular and enigmatic geological and geomorphological features of the country are described and discussed, and a comparison is made between Turkmenistan and the neighboring regions.

Basement, regional geology and geomorphology

The basement of the Turan platform in Turkmenistan is an assemblage of amalgamated magmatic arcs and forearc–accretionary wedge complexes (Fig. 1), suggested by Natal'in and Sengör (2005) to have resulted from strike–slip stacking of the "Silk Road Arc" in Late Paleozoic to Triassic times. The basement then developed into several extensional basins between Lower Jurassic and Paleogene (Lyberis & Manby, 1999). Basement of the western Turkmenistan, near the coasts of the South Caspian Basin (SCB) is suggested to be an extension of the oceanic–type crust which underlies the thick sedimentary cover of the SCB (Shikalibeily & Grigoriants, 1980; Brunet *et al.*, 2003; Golonka, 2007). Because of extensive Neogene to Quaternary cover, bedrock geology is limited to ca. 25% of the area of the country (Fig. 2). The cover materials include mostly the Karakum sand veneer, recent Caspian Sea deposits, and regoliths in alluvial fans and flood plains, as well regoliths produced by weathering of Neogene deposits. Bedrock crops out in three main regions, including the Kopeh–Dagh range in south, the Karabogaz (Balkhan) to Kharazm region in north (the Turan Province), and the Gowurdag in east (the Pamir Province).

We used geological evolution histories to distinguish regions within the Turkmenistan territory, and described here below their geology, petroleum potential, and peculiar geomorphological features; they include: 1) Kopeh–Dagh Province, 2) Caspian Province, 3) Turan Province, and 4) Pamir Province. Three hydrocarbon provinces also can be identified in Turkmenistan: a) the Amu–Darya basin, b) the Gograndag–Okarem Zone, and c) the Kopeh–Dagh basin. Except for the northern Kopeh–Dagh range to the south, and the western Pamir range to the east, Turkmenistan is dominated by low–lying, low–relief landforms. In southeast, large alluvial fans of Murghab and Harirud (Tejen in Turkmenistan) rivers form the Mary (Merv) and Tejen oases respectively. The Karakum desert covers a vast central part of the territory with an average elevation of ca. 100 m asl.

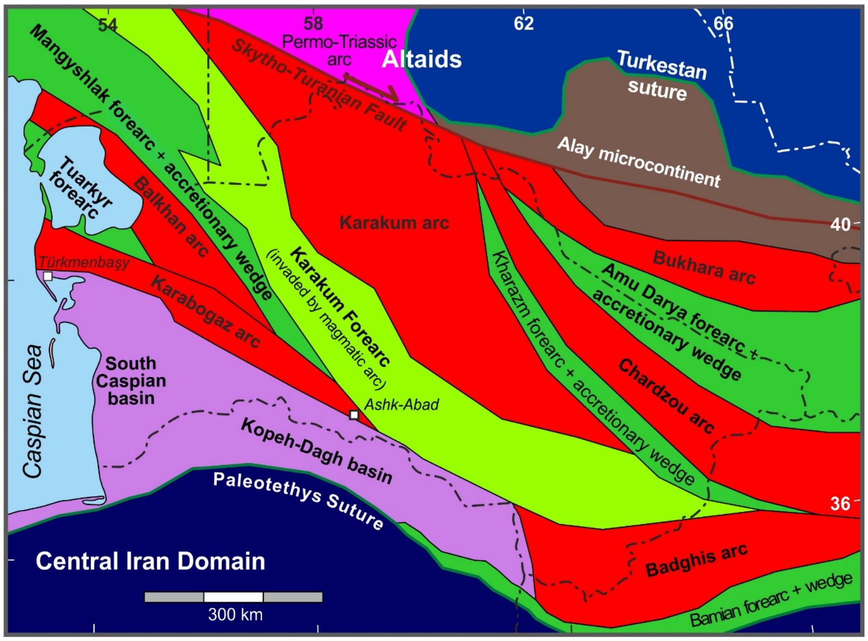

Figure 1. The Paleozoic–Triassic basement of Turkmenistan. Modified after Natal'in and Sengör (2005) and Zanchetta *et al.* (2013). International boundaries are indicated.

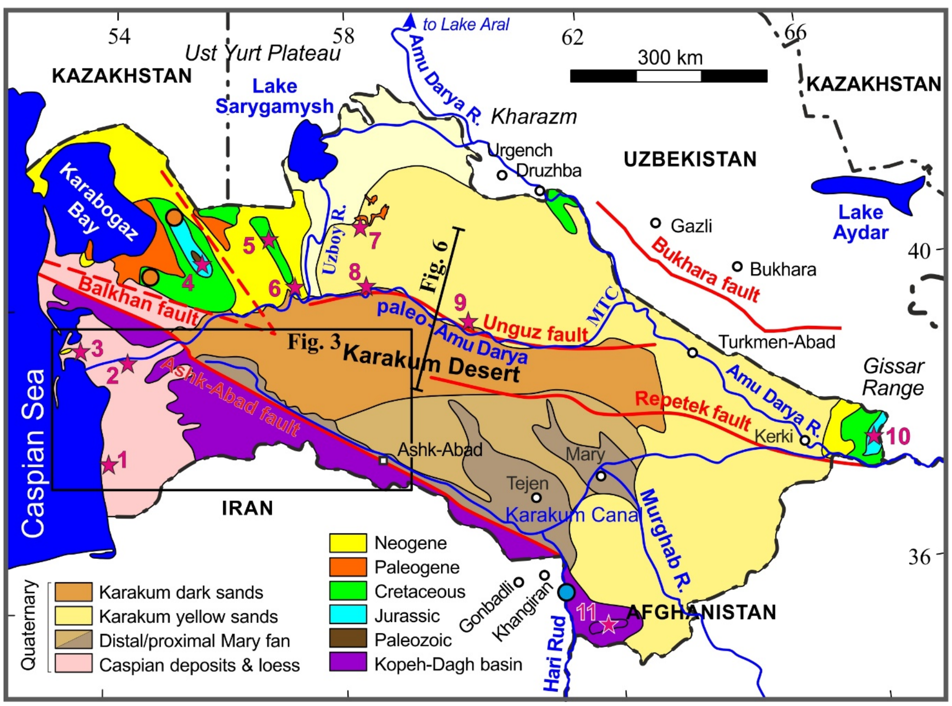

Figure 2. General geological map of Turkmenistan, compiled from small–scale maps provided by the Russian Geological Research Institute (VSEGEI) and available at One Geology Portal, integrated with geological data in Iran and ETM and Google EarthTM satellite images. Stars indicate features discussed in the text: 1: Gyeok Patlavuk mud volcano; 2: Monzhukly diapiric structure; 3: Cheleken Peninsula; 4: Kizilkaya erosional window; 5: Altyn Asyr Lake; 6: Uzboy River deflection; 7: lowest point in Turkmenistan (81 m b.s.l.); 8: Darvaza; 9: Neogene strata N of the Unguz fault; 10: dinosaur plateau; 11: Yeroylanduz depression. MCT: Main Turkmen Collector.

The highest elevations in Turkmenistan belong to the Gowurdak zone, where Pamir mountains on the border with Uzbekistan have a peak of 3138 m height. In the central Kopeh–Dagh zone, elevation reaches to ca. 2770 m on the border with Iran. The highest elevation in the Balkhan zone is ca. 435 m, close to the lowest elevations near the Caspian coast with an elevation of ca. –27 m. The lowest point in the country is –92 m in the Akhchakaya Depression – southeast of the Sargamysh Lake and the northwestern part of the Trans–Unguz Karakum (Babaev, 1994).

Kopeh–Dagh Province

Southern part of Turkmenistan coincides with the Kopeh–Dagh (Kopet–Dag) Province, which is separated from the Turan Province along the major Ashk–Abad fault zone. The word “kopeh” means “pile”, “heap” or “ridge” in Persian, and the word “dagh” means “mountain” in Turkic. Therefore “Kopeh–Dagh” may refer to gentle ridges which are produced by long anticlines in this province. A vast part of this geological province is located within the Iranian territory, evolution of which is described here as an inverted extensional basin.

The inverted basin

The Kopeh–Dagh mountains are the result of folding and faulting of a Mesozoic extensional basin in the northeastern part of the Iranian Plateau. Nature of the basement in the Kopeh–Dagh basin is not well–understood. The oldest rocks are revealed in an erosional window in easternmost part of the mountain belt in Iran (the Aghdarband window), where a Lower–Middle Triassic basin, consisted of deformed arc–related marine succession were deposited along the southern margin of Eurasia (Ruttner, 1991; Baud *et al.*, 1991; Zanchi *et al.*, 2016). Deformed and moderately metamorphosed Upper Paleozoic carbonate and siliciclastic rocks, in fault contact with abovementioned Mesozoic rocks, appear to form a basement to the basin fill. An extensional tectonic event in the backarc setting of the remote Neotethys subduction zone incepted the Kopeh–Dagh sedimentary basin in Middle Jurassic times. Sedimentation continued without magmatic activity (Afshar–Harb, 1979) and ca. 7 km (data from the Iranian side of the basin) of carbonate and siliciclastic deposits accumulated by the Late Eocene, when marine deposition ceased and compressional inversion of the basin began (Robert *et al.*, 2014). Lyberis and Manby (1999) suggest that the post–Triassic succession of the Kopeh–Dagh appears to become even thicker in Turkmenistan, and reaches to ca. 17 km. The extensional stresses gradually diminished, and the first signs of inversion of the basin into a compressional setting appeared in Late Eocene (Robert *et al.*, 2014). Major shortening of the basin, incepted in Oligocene to Miocene times, stopped the marine sedimentation, and folded and faulted the inverted basin sequence. A simplified map of the Kopeh–Dagh basin, produced by use of remote sensing data and extrapolation of the geological units in Iran across the border with Turkmenistan is shown in Fig. 3.

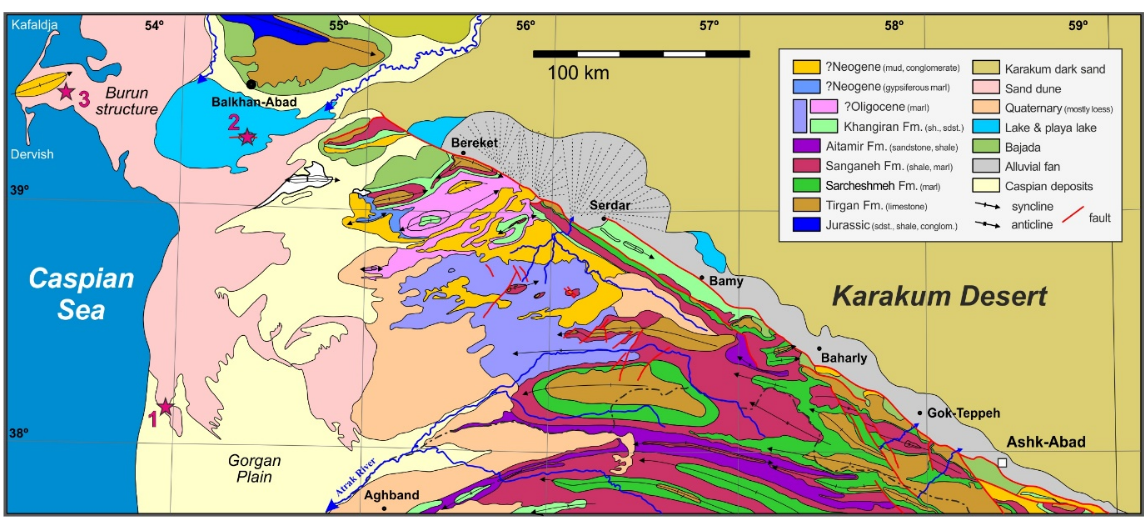

Figure 3. Geological map of the Kopeh–Dagh province (compiled from geological maps of northeastern Iran and extrapolated by satellite imagery to southern Turkmenistan). Formation names and lithologies are after the Iranian stratigraphic nomenclature. Stars are numbered as in Fig. 2.

Folds and thrust faults in northern Kopeh–Dagh province show a vergence towards north (Lyberis & Manby, 1999). The southern margin of the Turan Platform is bent downward along the front of the Kopeh–Dagh belt, as shown by increasing basement depth and thickness of cover strata as well as by gravity anomalies (Thomas *et al.*, 1999; Jackson, 2002). The southern margin of the Turan Platform therefore represents the northern foreland of the Kopeh–Dagh fold–and–thrust belt, whereas south–verging folds and faults in southern part of the belt face towards the southern foreland in the Iranian territory.

Hydrocarbon potential

The petroleum potential of the Kopeh–Dagh basin in Turkmenistan is poorly known; however some major gas fields occurring in the easternmost Kopeh–Dagh region of northeastern Iran, notably the Khangiran and Gonbadli fields, probably extend eastward into Turkmenistan. The reservoir rocks in these fields, located in anticlinal traps (Moussavi–Harami & Brenner, 1992), are Upper Jurassic carbonates (Mozduran Formation) and Lower Cretaceous siliciclastic (Shurijeh Formation; Afshar–Harb, 1979; Aghanabati, 2004; Kavoosi *et al.*, 2009). The main source rocks for the gas are considered the Middle Jurassic shales and carbonates of the Chaman–Bid Formation and the Upper Bajocian to Bathonian shales of the Kashafrud Formation (Robert *et al.*, 2014).

The Yeroylanduz depression

The 38 km–long and ca. 10 km–wide Yeroylanduz depression, a most spectacular geomorphological feature carved into Cenozoic strata of the easternmost continuation of the Iranian Kopeh–Dagh, is located in southernmost Turkmenistan near the border with Iran and Afghanistan (star 11 in Fig. 2). Yeroylanduz in Turkmen language means "*the salt that has ornamented the land*", referring to the small salt lakes formed by evaporation of internally drained water (Fig. 4A).

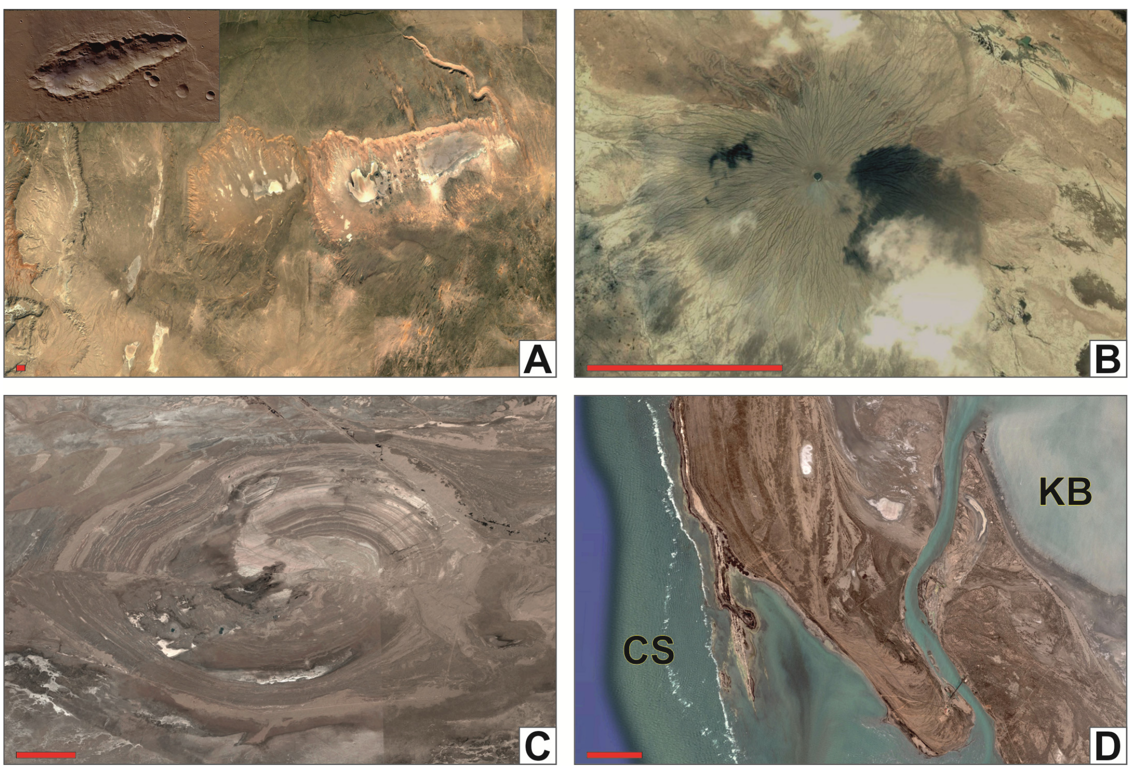

Figure 4. Geomorphological features of the Kopeh–Dagh and Caspian provinces. A) Yeroylanduz depression in southernmost Turkmenistan (N 35°40' E 61°46'). Inset figure is example of an oblique impact crater on Mars (European Space Agency, 2011). Drainage at the eastern end of the Yeroylanduz depression also recalls channel on Mars. B) Gyeok Patlavuk mud volcano close to the east coast of the Caspian Sea (N 38°09' E 53°58'). C) Monzhukly diapiric structure in the Akchagyl and Apsheron Formations along the Burun structure (N 39°17' E 54°21'). D) Very narrow channel connecting the Karabogaz Bay (KB) to the Caspian Sea (CS) (N 41°05' E 52°54'). Scale: red bar = 1 km.

The three parts of this east–west–trending depression, which includes a long trough in the east and a smaller pit in the west, are given the local names of Kagazly, Tekeduz, and Nemeksar. The depression, reaching a maximum depth of ca. 450 m in its central part, is closed on all sides, therefore precipitation water in it is internally drained. A partial exception is an 18 km long relatively young ravine with steep walls which drains seasonal water into the depression form the eastern end. Hillocks within the eastern trough are topped by what appear to be volcanic or other igneous rocks. Because volcanism is not recorded in the area, and neither the occurrence of subsurface salt nor related diapiric structures have been reported – which may explain development of such depression via extrusion of a salt dome, we suggest here that the depression might have been developed as an oblique meteorite impact crater, and that the supposed volcanic rocks inside the depression may represent instead the meteorite remnants.

Caspian Province

Western Turkmenistan represents eastern margin of the South Caspian Basin (SCB), a rapidly subsiding basin which has accumulated up to 25 km of sediments with a major contribution in Late Cenozoic times (Brunet *et al.*, 2003). This part is therefore named as "Caspian Province", and shares many of the geological features of the SCB.

Cenozoic sedimentation history

A regional retreat of the sea from the Turan Platform at the end of the Cretaceous was followed by a marine transgression during the Danian, when shallow–marine carbonates were deposited in subsiding regions within the Turan domain, including the Kopeh–Dagh and Amu–Darya basins (Maksimov, 1992; Thomas *et al.*, 1999). In the western regions of the Turan Platform, Oligocene and Miocene sediments exposed along the Caspian Sea coast and north of the Karabogaz, are largely marls and clays – surmised to be equivalents of the Maykop Series in Azerbaijan – deposited in lagoonal to shallow–marine environments (Thomas *et al.*, 1999).

The Caspian Sea was completely isolated from the major Paratethys Sea by Early Pliocene time (late Pontian in Russian literature or early Zanclean in standard Stages). The Pliocene Productive Series, known as "Red Beds" or "Cheleken Series" in Turkmenistan, were deposited in this period, and include fluviodeltaic to lacustrine cyclothems of interbedded sandstone, siltstone, and shale including layers with reworked Paleogene and Neogene foraminifera and ostracods (Reynolds *et al.*, 1998; Devlin *et al.*, 1999; Smith–Rouch, 2006). This unit testifies to the rapid accumulation of large volumes of sediments supplied by major fluviodeltaic systems, including the Amu–Darya paleodelta (Smith–Rouch, 2006).

The Akchagyl Formation marks the last major transgression of the Caspian Sea in the Paratethys domain during which the sea occupied a much larger basin, which extended between the northern Greater Caucasus region in the west and the Amu–Darya–Aral region in the east. Paleogeographic reconstruction of the Paratethys basin during middle Late Pliocene (see Popove *et al.*, 2006; van Bak *et al.*, 2013) indicates that the sea covered the whole Karakum area, and was connected to the Aral Sea through a N–S corridor. A major part of Turkmenistan, including the entire Karakum Desert, is thus suggested to be floored by the Akchagyl Formation. Magnetostratigraphic studies by van Bak *et al.* (2013) dated the Akchagylian, Apsheronian and Bakunian transgressions of the Caspian Sea as ca. 3.2 Ma, ca. 2.0 Ma and 0.85–0.89 Ma respectively.

Hydrocarbon potential

The first discovery of oil in western Turkmenistan occurred on the Cheleken Peninsula in 1876 (Smith–Rouch, 2006). The Gograndag–Okarem hydrocarbon Zone in the Caspian Province of Turkmenistan is easternmost extension of the South Caspian Basin (SCB). Gas and oil fields in this zone are developed in anticlines cored by shale diapirs. The main source rocks for hydrocarbons are Oligo–Miocene mudrocks equivalent to the Maykop Series in Azerbaijan, whereas the major reservoirs and seals are mostly found in the upper part of the lower to middle Pliocene "Red Bed" Series. Reservoir facies are fluviodeltaic, slope, and turbidite sandstones interbedded with siltstones and shales (Smith–Rouch, 2006). The relatively cool temperature gradient in the southeastern part of the SCB places the Maykop and Diatom Suites source rocks in the oil–generating window at greater depths as compared to other parts of the basin.

Mud diapirism

Mud diapirism is a widespread feature both offshore and onshore of the SCB. Within the

Caspian Province of Turkmenistan, the diapirism is well documented by exploration seismic data, and is manifested as mud volcanoes at the surface, locally associated with sand intrusions (Oppo & Capozzi, 2015). Best–known examples reported from the oil fields in Azerbaijan (Huseynov & Guliyev, 2004) suggest that mud diapirism in the SCB began in Early Miocene times. Mud diapirs may originate from as deep as 14 km (Cooper, 2001), as testified by fragments of Mesozoic and Paleogene rocks contained in the mud breccia generated in larger mud volcanoes during catastrophic events (Kholodov, 1987; Inan *et al.*, 1997). Most of the erupted mud, however, is derived from the pelitic parts of the Oligocene–Miocene Maykop Series, the major petroleum source rock in the SCB (Inan *et al.*, 1997; Kireeva & Babayan, 1985; Fowler *et al.*, 2000; Planke *et al.*, 2003). Mud volcanoes in the Gograndag–Okarem province commonly pierce anticlines hosting hydrocarbon accumulations, allowing the partial leakage of the fluids (Oppo & Capozzi, 2015). More than twenty mud volcanoes are located in the eastern onshore area of the SCB in Turkmenistan, some of which are associated with seepage of oil and gas (see Fig. 1 in Oppo *et al.*, 2014). They display a variety of morphological and geological features, including inactive centers subjected to erosion, cones associated with gryphons (gryphon – gas–mud vent generally occurring at the flanks of a main dome or crater) and salsa lakes, and negative caldera–like morphologies filled with saline water (Oppo *et al.*, 2014). The most spectacular one is the Gyeok Patlavuk, with a cone very similar to magmatic volcanoes, rising ca. 73 m above the nearby coastal plain located at –20 m (star 1 in Fig. 2; Fig. 4B).

Mud diapirism has induced doming of the Plio–Pleistocene Akchagyl and Apsheron Formations in the Monzhukly area (star 2 in Fig. 2; Fig. 4C), where the structure is cut by several faults as in salt diapirs of north central Iran (compare with Fig. 1.10 in Jackson *et al.*, 1990). A few mud volcanoes occur along the southwestern rim of the diapiric structure, which is part of the so–called Burun structure, a set of *en échelon* folds hosting a major gas field and extending from the Cheleken peninsula in the west to the Nebit–Dagh in the east. The Burun structure is the eastern continuation of the Apsheron–Balkhan sill, a shallow structure linked kinematically to the Ashk–Abad fault system and separating the South Caspian from the Middle Caspian basin (Jackson *et al.*, 2002).

Cheleken peninsula

The Cheleken peninsula is located at the western end of an *en échelon* array of folds named as Burun structure, and at the eastern end of the Apsheron–Balkhan sill. The backbone of the peninsula is the Cheleken anticline, formed by Pliocene Red Beds and by the Pleistocene Apsheron Formation pierced by several mud volcanoes. The Cheleken peninsula – marked as “Chereken Island” on a map by A. Bekovich–Cherkassky in 1715 – used to be an island in historical time, and becomes an island again from time to time when Caspian waters rise (star 3 in Fig. 2). The peninsula was linked to the mainland in 1937, when sea–level dropped and the shallow area between the island and the mainland dried out (Zonn *et al.*, 2010). The two nearly symmetrical spits in the west, the northern Kafaldja Peninsula and the southern Dervish Peninsula pointing towards Ogurja Ada 17 km farther south, make it very similar to the Ebro river delta in Spain.

Karabogaz Bay

The Karabogaz Bay (area ca. 18,000 km^2, average depth 8–10 m) is the saltiest water body on Earth and hosts the world's largest deposit of marine salt. Its water surface lies several meters below that of the Caspian Sea, to which the Bay is connected by a 7 km–long and only 200–350 m–wide strait (Fig. 4D). There is a great contrast in salinity between the Caspian Sea (12 g/l) and the Bay (350 g/l), which acts as a regional regulator of both water level and salinity (Zonn *et al.*, 2010). The water level of the Caspian Sea reached – 29 m in 1977, the lowest level in the last 400 years. To reduce water loss, the strait was dammed in March 1980. In response to damming, however, the Bay dried up completely by November 1983, and the dam was destroyed in 1992. Until 1996 the Karabogaz bay filled up with Caspian water at a rate of 1.7 m/yr, and evolved in a similar way as the Sea since then (Kosarev & Kostianoy, 2005).

Turan Province

Exposed in the Balkhan zone of the western Turan Province are Jurassic to Neogene strata displaying major open NW–SE–trending folds. Upper Paleozoic to Triassic rocks are exposed only in the central Balkhan zone, in the small Kizilkaya dome–like structure surrounded by younger rocks (star 4 in Fig. 2; Fig. 5A; Garzanti & Gaetani, 2002). Sub–horizontal Cenozoic strata crop out southeast of Lake Sarygamish (star 9 in Fig. 2), where the lowest elevations in the country occur. Cretaceous and Paleogene sedimentary rocks are exposed in a NW–trending, SE–plunging anticline in the Druzhba area of northeasternmost Turkmenistan, near the Uzbekistan border. A NW–plunging syncline and a SE–plunging anticline floor the Karabogaz and Karakum lakes, respectively.

Hydrocarbon potential

The Amu–Darya basin of central and eastern Turkmenistan, underlying the Karakum Desert and straddling the Uzbekistan border, is a hydrocarbon province with great productive potential and discovered gas reserves. Modeling of the reserves indicate that the total undiscovered resources in the Amu–Darya basin are about 3.31 billion t, in which gas accounts for more than 98 percent (Clarke, 1994; Yixin *et al.*, 2015). Discovered gas reserves are estimated between 6.5 and 7.9 trillion cubic feet. The basement, consisting of Paleozoic rocks deformed and metamorphosed during the Variscan orogeny, is overlain by an Upper Permian–Triassic rift–graben fill followed in turn by thick coal–bearing continental rocks of Early to Middle Jurassic age. The late Middle Jurassic carbonates are overlain by the thick Late Jurassic evaporites of the Gaurdak Formation (Osichkina, 2006), followed in turn by Cretaceous to Paleogene largely marine clastic and carbonate rocks. Old faults were reactivated and new faults and structural traps formed during the Alpine orogeny (Ulmishek, 2004), when continental clastic rocks were deposited along the basin's margins.

The main source rocks for gas are Lower Jurassic coal and black shales interbedded within clastics, whereas gas reservoirs mostly occur in mid–Jurassic carbonates and Neocomian clastics. Seals include the Upper Jurassic Gaurdak evaporites and subordinately Lower Cretaceous marl and shale. Traps may be structural, paleogeomorphic, stratigraphic, or a combination of these types (Ulmishek, 2004).

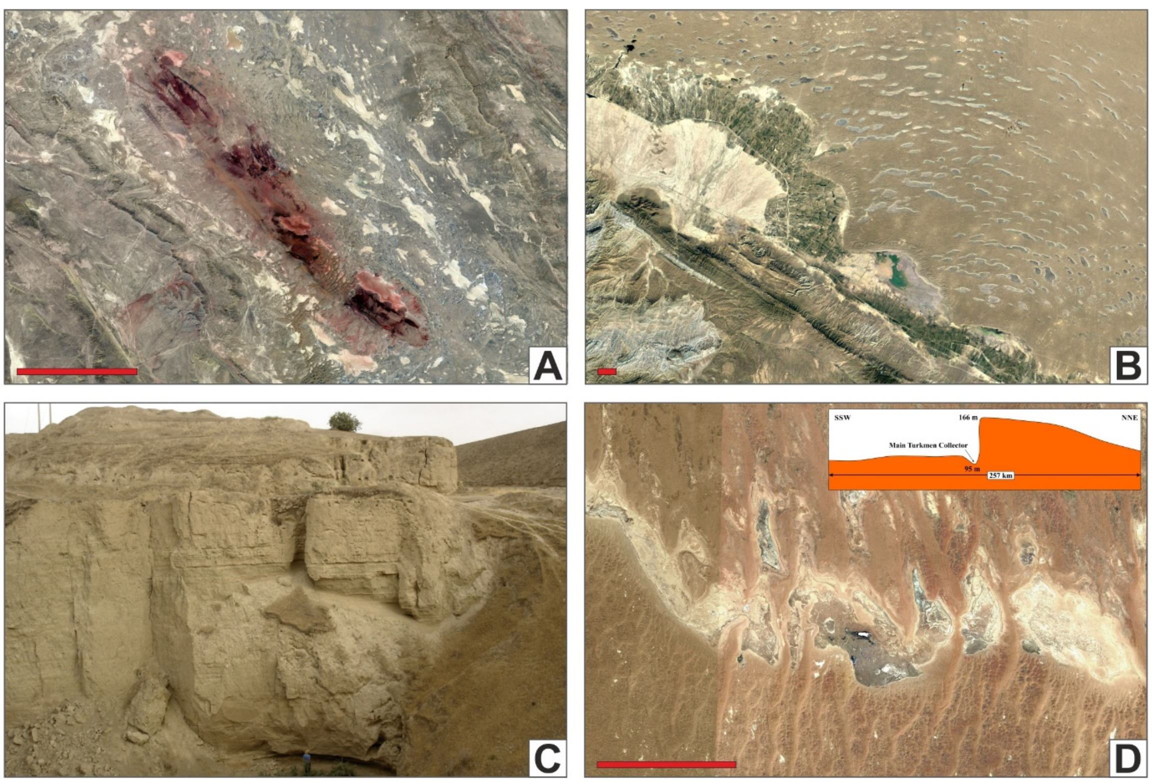

Figure 5. Geological and sedimentological features of Turkmenistan. A) Kizilkaya domal structure exposing Upper Paleozoic volcaniclastic red beds (N 40°36' E 55°28'). B) Salt pans within the sand dunes of the southern Karakum Desert near Serdar. The pans are filled seasonally with water leaking from the irrigated fields in the lower–left corner of the picture (N 39°07' E 56°46'). C) Loess deposits in the northwestern Kopeh–Dagh region of Iran, near the Turkmenistan border. D) Salt marshes formed along the Unguz fault (N 39°45' E 59°28'); inset shows E–W scarp–like topography associated to the active Unguz fault. Neogene strata exposed to the north may be upthrown by several tens of meters. Location of the profile, which has very strong vertical exaggeration, is shown in Fig. 2. Scale: red bar = 5 km in A, B, and C; man at the base of picture in D.

In the middle of the Amu–Darya hydrocarbon province, there is a 30 m–deep pit of fire called Darvaza (or "door to hell"; in Persian darvaza = gate; star 8 in Fig. 2). It is said that a Soviet oilrig fell into the crater in 1971, and a geologist decided to get rid of the rig by setting the pit on fire. The resulting gas–fed flames are still burning.

Pamir Province

The Gowurdag (Koytendag) zone in easternmost Turkmenistan represents the western termination of the Pamir mountains in Tajikistan and Uzbekistan. Jurassic to Neogene sedimentary rocks are exposed in a NE–trending folded structure, cored in Uzbekistan by Proterozoic and Paleozoic rocks thrusted over Neogene strata towards the SE. Jurassic strata host the world's longest dinosaur trackways, hence the Koytendag is called "dinosaur plateau" (star 10 in Fig. 2).

Wind, water and earth

Being covered by the vast Karakum desert, a major part of Turkmenistan's surface geology and geomorphology is sculpted by action of wind and drift of sand and dust in an arid environment. Turkmenistan also has a long history of major natural and human modifications of rivers and drainage systems which is discussed under this section.

Karakum desert

As the most important geomorphologic feature of Turkmenistan, the Karakum (black sand) desert occupies ca. 70% of the country's area. The entire territory of Turkmenistan is divided into different deserts, including sand, clay, loess, stony and salt types (see Fig. 2 in Babaev, 1994). The neighboring mountains, including Kopeh–Dagh, Hindu–Kush and Pamir, may be considered as the sources for sands within these deserts, however prevailing wind systems of the region suggest that the major source area may be in the Kazakhstan steppe and beyond. For a more detailed account of provenance of the Karakum desert sands see Garzanti *et al.* (2019).

The Karakum desert has a general low elevation with a maximum of ca. 220 m in the eastern part which reduces to ca. 0 m amsl in the west near the Caspian Sea; it drops to ca. –92 m in a small depression to the southeast of the Sarygamish lake (star 7 in Fig. 2). Abundant desert pans occupy the southern part of the Karakum desert in vicinity of Kopeh–Dagh mountains, some of which appear to be seasonally filled by water leaking from the Karakum canal and farms which are irrigated by the canal (Fig. 5B). Most of the onshore oil and gas fields of the country are hosted in central and eastern parts of the Karakum desert.

Turkmenistan records the highest frequency dust storms in Central Asia. Dust storms exceed 40 per year in the Karakum desert and near the Caspian Sea. The largest source area for these storms is the Karakum desert, however there is a large dust belt that extends from west to east, lying north of the Caspian Sea, south of Lake Balkhash and in the Aral Sea region (Indoitu *et al.*, 2012). The real dark sands of Karakum occur in a central belt of the desert, which extends between Turkmen–Abad in the east and Serdar in the west. Other parts of the desert are covered with lighter–colored sands. The Amu–Darya river separates Karakum sands in its southwest from the Kyzyl–Kum (red sand) sands in its northeast within the Uzbekistan and southern Kazakhstan.

Results of the study by Maman *et al.* (2011) suggest that the ergs in the Karakum are mostly stabilized. They also argue that a low wind power environment and sufficient rainfall (>100 mm) support vegetation over the ergs. A sample from the northern margin of the Karakum desert near Kharazam yielded an Optically–Stimulated Luminescence (OSL) age of 7.3 ± 0.8 ka (Maman *et al.*, 2011).

It is suggested that the parallel extension of the dune ridges does not correspond to the prevailing wind direction. On the other hand some researchers believe that the major part of sand material in the Lower Karakum have never been affected by aeolian processes, and even attribute relief of the longitudinal valleys and ridges to activity of fluvial processes (Shahgedanova, 2002). Longitudinal N–S–trending sand dunes are specially visible in southern Karakum resting over the Mary fan with a maximum relief of ca. 30 m, and an average spacing of ca. 2.5 km. The Murghab river fan hosts the Merv (Mary) oasis. Distal parts of this fan is composed of fine–grained fluvial silt and clay material, interspersed with planes of muck. These fine–grained materials are sculpted by yardangs (yardang – a long, irregular, sharp–crested, undercut ridge between two round–bottomed troughs, carved on a plateau or unsheltered plain in a desert region by wind erosion; has a Turkic origin) and lie below the mobile dunes of the southern Karakum desert (Stoppato *et al.*, 2003).

Loess

Loess in Turkmenistan is part of the Eurasian loess belt which extends between the Pacific to Atlantic coasts in mid–latitudes. The formation of continuous loess–paleosol sequences by dust deposition began 22 My ago (Guo *et al.*, 2002), however a major volume of the loess was deposited in Pleistocene times. Most of the studies (e.g. Sun, 2002) suggest that the Chinese loess deposits have their provenance from the Gobi (stony) desert of northern China. Equivalent of Gobi desert in Turkmenistan may be the stony deserts, which are mostly located in the northwestern part of the country. The Loess deposits of northern Iran close to the border with Turkmenistan is composed of a large fraction of silt size material (more than 80%) and smaller fractions of clay and sand size grains (Frechen *et al.*, 2009) (Fig. 5D). These are homogeneous windblown geological materials interspersed with some paleosol horizons. The sequence in general records an alternation of comparatively dry and cool climate phases with increased dust accumulation including loess formation, and moist and warm phases with soil formation, respectively (Kehl *et al.*, 2006). Different horizons of loess deposits in Aghband section of northern Iran near the border with Turkmenistan were dated between 145 and 9.5 ka (Frechen *et al.*, 2009).

Amu–Darya River, Karakum Canal and MTC

The Amu–Darya River (Oxus in Latin) is a major river (the largest river basin in Central Asia) formed by the junction of Vakhsh, Panj and Kunduz rivers which originate in the Pamir mountains. Flowing for ca. 2400 km towards northwest, the river drains into the previous Aral Sea at an elevation of ca. 30 m.

It is believed that the precursor of the Amu–Darya River ran into the Caspian Sea instead of the Aral Sea. The junction to the Caspian Sea was located in the south of the present Karabogaz Bay. The river drastically changed its course in Pleistocene or early Holocene times into the Aral Sea, leaving the old course in the Uzboy valley (Zavialov, 2005). Similar changes in historical periods have also been reported. According to Ptolemy (in the 2nd century A.D.) and Biruni, the river flowed towards west from modern Kerki (a city in Lebap Province of Turkmenistan) – not northwesterly as in present time – and evaporated in the Karakum desert. It is also suggested that the Amu–Darya had flowed through the Uzboy into the Caspian Sea at the time of the Mongol conquest of Gorganj (later Urgench) in 618–1221 AD, and had turned back towards Lake Aral only about 1575 AD (Encyclopedia Iranica). Possible old courses of the Amu–Darya River are shown in Fig. 2.

The Karakum canal was designed by the Soviet Union government, and was built between 1954 and 1988 to transfer water from Amu–Darya into western Turkmenistan. The canal is among the largest water supply and irrigation canals of the world. It is navigable over much of its 1375 km length, and carries 13 km^3 of water annually from the Amu–Darya River across the Karakum desert. The canal opened up huge new tracts of land to agriculture, especially to cotton monoculture heavily promoted by the Soviet Union, and supplying Ashk–Abad with a major source of water. Unfortunately, the primitive construction of the canal allows almost 50 percent of the water to escape en route, creating lakes and ponds along the canal, and a rise in groundwater leading to widespread soil salinization problems. The canal is also a major factor leading to the Aral Sea environmental disaster (Wikipedia; Kharin, 2002).

Northern part of the Karakum desert is separated from the rest of it along the so–called Main Turkmen Collector (MTC). The MTC was planned in 1970s as a 720 km long drainage to be built from Turkmen–Abad through the center of the Karakum Desert along the ancient river bed of the Amu–Darya (along the Unguz salt marshes) (Zonn & Kostianoy, 2014). The collector occupies the lowest elevations in the middle of the Karakum desert.

Structure and seismotectonics

Structural features in the basement rocks of Turkmenistan and in the Caspian Province are mostly documented by geophysical data, whereas surface structures are best displayed in the Kopeh–Dagh Province and partly in the northern Turan Province.

In the Kopeh–Dagh zone, spectacular E–W trending folds of Mesozoic to Paleogene strata form an orocline convex towards the north (Fig. 3). The folds developed since the early Neogene in response to N–S shortening of the sedimentary basin located between the Central Iran and Turan blocks. Fold wavelength decreases from 25–30 km in the central part of the zone to ≤ 12 km towards its margins. In the northern Kopeh–Dagh, fold–trends become parallel to the Ashk–Abad fault zone, indicating that fold geometry is controlled by the fault (Lyberis & Manby, 1999). Right–lateral strike–slip motion at depth along the western end of the Ashk–Abad fault zone is suggested by the right–stepping *en échelon* pattern of anticline axes in the Pliocene Red Series and younger sediments (Jackson *et al.*, 2002).

The presence of folded structures beneath onshore areas of the eastern South Caspian Basin (Gograndag–Okarem petroleum province) was highlighted by hydrocarbon exploration during the Soviet Union period. Folds are parallel to the coastline and have thus a different trend than in the adjacent Kopeh–Dagh basin where shortening is N–S (Fig. 1 in Oppo *et al.*, 2014). Such a 90° difference in shortening direction needs an explanation. One possible mechanism is the westward extrusion of the Kopeh–Dagh (Hollingsworth *et al.*, 2008), which may have induced fold–thrust deformation in Neogene sediments of the easternmost SCB. An alternative mechanism is large–scale gravitational collapse of cover strata, as observed in the Gulf of Mexico (Worrall & Snelson, 1989). The offshore region, called Turkmen Block or Turkmen Step, is a relatively shallow region compared to the rest of the SCB, and is characterized by slumps and growth faulting (Smith–Rouch, 2006).

In northern Turkmenistan, including the Balkhan zone, NW–trending folds indicate NE–SW shortening. This regional structural trend continues northwards into Kazakhstan abutting against the Skytho–Turanian fault (Fig. 1).

Major Faults

The ca. 845 km–long, NW–SE–striking (N62W) Ashk–Abad fault system, the largest in Turkmenistan, separates the Kopeh–Dagh mountains in the south from the Karakum Desert in the north (Fig. 3). Its linear surface signature, and the notable change in elevation across the fault, indicate a steep structure with a major strike–slip component but with a large dip–slip component as well. Several moderate–size earthquakes of both right–lateral strike–slip and thrust mechanisms (Vannucci *et al.*, 2004) confirm that oblique shortening across the Ashk–Abad fault zone is partitioned between thrusts and strike–slip faults. Considering a N–S shortening of ca. 75 km in the western Kopeh–Dagh, starting at the Miocene–Pliocene boundary, Lyberis and Manby (1999) calculated a convergence rate of 13–15 mm/yr between the Iran and Turan plates. If such a shortening is applied to the Ashk–Abad fault zone, representing the boundary between the two plates, and resolved into components parallel and perpendicular to the fault, these authors concluded that shortening orthogonal to the eastern Kopeh–Dagh is twice as large as the right–lateral strike–slip movement. Rather than purely N–S shortening, more recent geodetic estimates (Tavakoli, 2007) suggest maximum velocities relative to Eurasia of ca. 11 mm/yr in northwestern direction, which is consistent with NE–trending folds in the western Kopeh–Dagh (Fig. 3). Such a velocity field implies that strike–slip motion on the Ashk–Abad fault prevails over its thrust component, with rates of 5 ± 2 mm/yr and 2.5 ± 2 mm/yr, respectively (Tavakoli, 2007). Other estimates of slip rate on the fault zone range between 1.5 and 12 mm/yr (see Mousavi *et al.*, 2013).

Some folds in the Kopeh–Dagh zone are probably cored by thrusts, and many are cut and displaced by relatively small NW– and NE–trending strike–slip faults. Similar structures accommodate part of the shortening in the Iranian Kopeh–Dagh (Hollingsworth *et al.*, 2006).

Faults parallel to NW–trending folds are mapped by the Russian Geological Research Institute (VSEGEI) in the Balkhan zone. A ca. 670 km–long, WNW–striking fault across the central Karakum Desert is shown in geophysical maps produced for hydrocarbon research (Ulmishek, 2004). Another 560 km–long and WNW–striking fault is inferred to exist along the Unguz salt marshes based on topographic features and surface geology (Fig. 5B). A 380 km–long, WNW–striking fault runs along the southern margin of the Balkhan zone. The NNW–trending structure occupied by Lake Altyn–Asyr in northwestern Turkmenistan (star 5 in Fig. 2) is cored by Cretaceous to Paleogene strata and interpreted as a right–lateral strike–slip fault that diverted the Uzboy River around its southern tip (star 6 in Fig. 2). The gradient of uplift is estimated as greater than 0.03–0.04 mm km^{-1} yr^{-1} (Jaboyedoff *et al.*, 2005).

Seismicity

Central part of the Turkmenistan shows very rare instrumental seismic activity, and most of the earthquakes inside the country occur along the northern margin of the Kopeh–Dagh region (Fig. 6). The Ashk–Abad earthquake of 6^{th} October 1948 had a magnitude of 7.3, and claimed ca. 110,000 lives, most in Ashk–Abad city (Tchalenko, 1975).

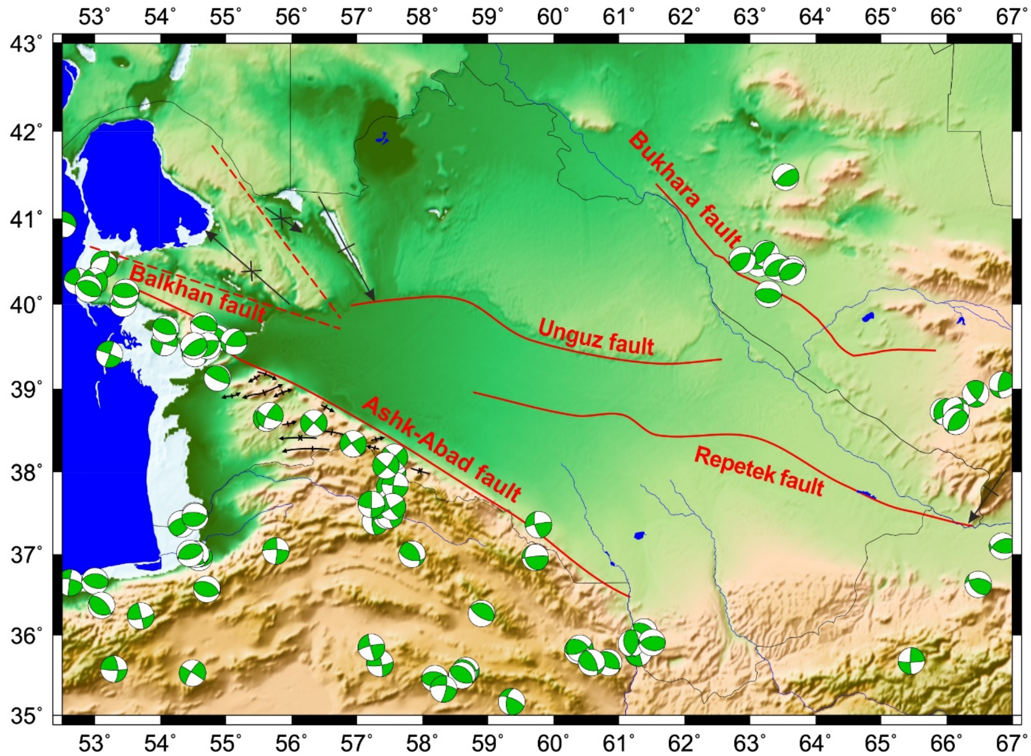

Figure 6. Seismotectonic map of Turkmenistan. Note dominance of strike–slip and thrust earthquake focal mechanisms in the hanging–wall of the Ashk–Abad fault and near the central part of the Bukhara fault respectively.

The rupture did not occur along the surface trace of the main fault, but on the nearby faults (Berberian & Yeats, 2001). The poorly constrained hypocenter was located at a depth of ca. 15 km (Engdahl catalogue). The focal mechanism (Earthquake Mechanisms of the Mediterranean Area database) and local geology suggest a shallow–dipping thrust movement by 20° to the SW. The epicenter of the 1895 Krasnovodsk (Ms 7.4) and 1946 Kazandzhik earthquakes (M 7.0) was located at the northwestern end of the Ashk–Abad fault system near the Caspian Sea (Ambraseys, 1997; Balakina & Moskvina, 2007). Another major source of hazard for eastern Turkmenistan is the Bukhara–Gazli seismic zone (BGSZ)located to the northeast of the Bukhara (Bukhara–Gissar) fault in southern Uzbekistan, which has generated earthquakes of magnitude ≥ 7 in historical and recent times (Artikov *et al.*, 2015). The Bukhara fault is a major NW–striking normal fault of Permo–Mesozoic age which shows evidence of Tertiary reactivation (Thomas *et al.*, 1995, 1999), while the BGSZ occupies a relatively small area in the central vicinity of the earlier fault, and is associated with earthquakes of thrust mechanism on fault planes which are highly oblique to the Bukhara fault (Fig. 6).

Conclusions

The geology and geomorphology of Turkmenistan is still underexplored. Basement units were assembled during the Variscan and Cimmerian orogenies in Late Paleozoic to Triassic times by subduction of oceanic domains and collision of magmatic arcs and accretionary complexes within the Paleotethys and northern Asiatic oceanic realms. After closure of the Paleotethyan seaways and amalgamation of peri–Gondwanan microblocks with the Turan platform, thick sedimentary successions accumulated in extensional basins that started to subside rapidly in the backarc region of the Neotethys ocean during Middle Jurassic. Based on the Mesozoic–Cenozoic evolution, the four Kopeh–Dagh, Caspian, Turan, and Pamir geological provinces are identified, hosting the three Kopeh–Dagh, Gograndag–Okarem (South Caspian), and Amu–Darya hydrocarbon–prone basins.

Up to 17 km of Middle Jurassic to Neogene carbonate and siliciclastic rocks accumulated in the Kopeh–Dagh extensional basin, supplied with sediments derived from magmatic arcs in the Asiatic–Paleotethys oceanic realms. Compressional inversion induced by collisional events underway in Neotethyan realms to the south took place in

Cenozoic. Hydrocarbon potential appears limited to the easternmost part of the Kopeh–Dagh basin.

The Caspian province of Turkmenistan shares the rapid Cenozoic subsidence of the South Caspian Basin. The Caspian Sea encroached onto most of Turkmenistan as far as the Aral Sea in the Upper Pliocene, when the Akchagyl Formation was deposited. The temperature gradient of the southeastern SCB, cooler than in Azerbaijan, places the Oligo–Miocene Maykop and Diatom Suites source rocks in the oil–generating window at greater depths. North–south structural trends in the Gograndag–Okarem Zone may have resulted either from westward extrusion of the western Kopeh–Dagh or from gravitational collapse of young cover strata. Mud diapirism started in the early Miocene, and is still forming spectacular mud volcanoes mostly sourced in the Oligo–Miocene Maykop Series along the Caspian shores. The Cheleken peninsula lies at the western end of a series of *en échelon* folds related to dextral strike–slip motion along the western Ashk–Abad fault system. These structures represent the eastern continuation of the Apsheron–Balkhan sill separating the South Caspian from the Middle Caspian basin. The Karabogaz Bay, the saltiest water body on Earth, acts as a regional regulator of both water level and salinity in the Caspian Sea.

The Turan Province is characterized by NW–SE–trending folds affecting Jurassic to Neogene cover strata. Upper Paleozoic to Triassic siliciclastic rocks are exposed only in the Kizilkaya dome–like structure. Towards the east, the basement is buried under the Upper Permian to Neogene, marine to continental succession of the Amu–Darya basin, which hosts major hydrocarbon reserves in Upper Jurassic carbonates and Neocomian clastic rocks. Folded Jurassic to Neogene strata occur in the westernmost Pamir mountains.

Vast sands in the Karakum desert covers ca. 70% of the Turkmenistan territory mostly in central and eastern parts, and conceals the underlying Amu–Darya basin which is very important in terms of hydrocarbon reserves. Sands within the desert probably source from the steppe in Kazakhstan and beyond, and generate frequent dust storms within the country. Sediments in loess deposits located in southern part of Turkmenistan are finer–grained and older as compared to the sands in Karakum. Amu–Darya, the largest river in Central Asia, has experienced major changes in historical and modern times. The Turkmen Canal and Main Turkmen Collector are two major projects of Soviet Union period aimed at reorganization of drainage in this arid region.

The most prominent tectonic feature and major source of seismic hazard in Turkmenistan is the Ashk–Abad fault system, which accommodates oblique shortening between the Kopeh–Dagh province and the Turan platform.

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