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Research paper

Origin of the mud volcanoes in the south east Caspian Basin, Iran

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ABSTRACT:

The Gorgan Plain (SE Caspian Basin) contains several mud volcanoes. The Gharenyaregh, Neftlijeh, Sofikam and Inche mud volcanoes are active and erupting mud and gas. Mud volcanoes occur in an area characterized by seismic activity. The Sofikam mud volcano consists of five craters that define a NE-directed (60°) linear arrangement, which coincides with a subsurface anticline of the western Kopeh Dagh fold-thrust belt. The main craters of the Inche and Neftlijeh mud volcanoes are submerged. The Gharenyaregh mud volcano is an active mud volcano whose crater is nearly 500 m in diameter. Clasts collected from the Gharenyaregh mud volcano (GMV) mainly consist of glauconite-sandstone, limestone (± ammonite), marl, and fossiliferous limestone (lumachelle) with bioclasts ranging in size from millimeters to centimeters. X-ray diffraction (XRD) analyses revealed quartz, calcite, feldspar, chlorite, illite, glauconite, halite and gypsum minerals in the clasts and soft materials of the GMV. The clasts are comparable with rock fragments originating from the underlying Kopeh Dagh related formations and the uppermost Caspian basin sediments. Regression of the South Caspian Sea shoreline from east to west (across modern-day Golestan province), seismic activity and buried folds indicate that the south east Caspian basin mud volcanoes are located in a tectonically active area and generated from deeper parts of the Gorgan Plain. Some large, conical hills with a record of historical human activity, located between the Kopeh Dagh zone and the South Caspian Sea, seem to be inactive mud volcanoes.

1. Introduction

Mud volcanoes, like magmatic volcanoes, are a natural phenomenon that can give direct information from beneath the Earth's surface. Mud volcanoes have been reported from several different geologic settings, including: active subduction zones (e.g., Makran mud volcanoes: Delisle et al., 2002), compressive settings (e.g., South Caspian Sea: Bonini et al., 2013; Oppo et al., 2014), and environments with high sedimentation rates (such as modern fans; e.g. Aslan et al., 2001). Approximately 80% of all mud volcanoes occur on convergent and transform continental margins (Milkov, 2005). Mud volcanoes, mud domes, sedimentary volcanoes and mud pies are terms that describe features where fluid-rich, fine-grained sediments ascend through the upper lithologic succession (Kopf, 2002). Based on their outcrop structures, mud volcanoes are divided into mud pies and mud domes. ‘Mud pie’ refers to mud volcanoes with a low cone slope (< 5%), whereas the term ‘mud dome’ refers to structures with a higher slope (Kopf, 2002). The size of a mud volcano is mainly a function of the size of the conduit and the driving force of the mud volcanism in the area (Satyana and Asnidar, 2008), volumes and type of extruded sediments.

Mud volcanoes can be essentially divided in two groups: those associated with magmatic complexes and those related to petroleum provinces (Mazzini, 2009). Several factors can trigger the generation of a mud volcano, such as: 1) a rapid sedimentation rate; 2) a thick sedimentary cover; 3) the presence of a plastic layer in the subsurface; 4) a high gas supply and petroleum potential; 5) abnormally high formation pressure; 6) a compressional tectonic setting; 7) high seismicity; and 8) the occurrence of faults (Milkov, 2000). The mentioned factors often don't occur all together. Gas supply is the most important factor. Mud volcanism is generally controlled by brittle elements (fault, joints) associated with fold anticlines (Bonini, 2012). Depending on both the magnitude and epicentral distance, earthquakes with magnitude $M_w > 4$ are considered sufficiently large to initiate mud volcano eruptions (Aliyev et al., 2003; Wang and Manga, 2010). Mud volcanoes around the South Caspian Basin (SCB) are among the most important mud volcanoes in the world because of their frequency, relief, and oil/gas links (e.g. Yusifov and Rabinowitz, 2004; Feyzullayev, 2012; Bonini et al., 2013; Oppo et al., 2014; Oppo and Capozzi, 2016).

The aim of this study is to remedy the lack of scholarship on the mud volcanoes in the Iranian sector of the SCB, to investigate the erupted material of mud volcano with the aim of better understanding its buried plumbing system, and to compare the result of the current work with other mud volcanoes of SCB.

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2. Material and methods

One of the important benefits associated with the study of mud volcanoes is obtaining information about the areas underlying the mud volcanoes. This study investigates the SE portion of the Caspian basin (Iranian part), where four active mud volcanoes and some inactive/silent mud volcanoes, known as *ancient hills,* occur. In this study, we focused mostly on the Gharenyaregh mud volcano (GMV), which is an active mud volcano with the largest crater (500 m) among the ones we have studied. Among the erupted materials of GMV, there is a high quantity of chaotically distributed angular to rounded rock clasts. Different clasts were collected to study the root of the mud volcano, where the mud volcano conduit crosses different lithostratigraphic units. Hand specimens, petrography and thin section studies, and X-ray diffraction (XRD) have been employed to identify the characteristics of the clasts and to gain information on the stratigraphic units that the conduit crosses at the root of the mud volcano. Geophysical and seismic data (from 1950 to 2017) have been employed to identify the link between the studied mud volcanoes with the surface and buried structures. The seismic data (from 1950 to 2017) are adopted from International Seismological Center (ISC) bulletin (http://www.isc.ac.uk/).

3. Geological setting

3.1. Mud volcanoes of South Caspian Basin

The south Caspian basin (SCB) mud volcanoes are among the most famous natural phenomenon on the Earth. Since 2002, approximately 1700 individual mud volcanoes have been reported around the world, including over 900 terrestrial and 800 offshore mud volcanoes (Dimitrov, 2002). More than 50% of the total number of mud volcanoes is situated along the Alpine-Himalayan active belt (Dimitrov, 2002). Around 400 onshore mud volcanoes are reported within the SCB, from eastern Azerbaijan to southwestern Turkmenistan (Rashidov, 2014). Around 50 mud volcanoes with different morphologies and characteristic are reported from the lowlands of the SE Caspian basin (Western Turkmenistan; Oppo et al., 2014).

Mud volcanoes of the western Caspian Sea are related to anticlines and trapped oil/gas fields (Jakubov et al., 1971; Oppo et al., 2014). The South Caspian basin is a deep sedimentary basin hosting a sediment pile up to 20 km thick, ranging from Oligocene to Holocene in age (Zonenshain and Pichon, 1986; Abrams and Narimanov, 1997; Brunet et al., 2003). It is bounded by the Khazar fault to the south, in northern Iran, and by the Apsheron-Balkan fault in the north, south of the central Caspian Sea (Fig. 1A). To the west it is bounded by the Astara fault and the Kura basin, and to the east it is bordered by the Turkmenistan plain (Fig. 1). The term *"the land of eternal fire"* (Yergin, 1991) has been used for many parts of the SCB, where natural gas seeps from fractures and mud volcanoes. One of the best locations to observe natural gas seepage is *"The Gate of Hell*" in Turkmenistan.

The uplift and the subsequent erosion of the Caucasus, Alborz and Kopeh-Dagh ranges since the late Eocene caused high sedimentation rates, up to 4.5 km My^{-1}, in the whole basin (Oppo and Capozzi, 2016). Most of the SCB mud volcanoes were generated from the Oligocene-to Miocene-age Maykop Shale Formation (Devlin et al., 1999; Feyzullayev et al., 2001; Kopf et al., 2003). In the western SCB, the Maykop Formation is located at a depth of 3–7 km (Davies and Stewart, 2005). Fluids (gas/oil and saline water) that have originated from the deeper Jurassic and Cretaceous stratigraphic layers migrate into fold cores and accumulate at shallower reservoirs in the Productive Series (Bonini et al., 2013). Jackson et al. (2002) estimated the present-day motion of the SCB to be ~13–17 mm yr^{-1} to the SW relative to Iran and ~8–10 mm yr^{-1} to the NW or NNW relative to Eurasia. Radjaee et al. (2010) found that the focal depth of earthquakes is more than 30 km along the Alborz mountain ranges. Tectonic activity has produced faults, and tectonic loading favors the development of fluid overpressure (e.g. Jackson et al., 2002). Upward transport of a mixture of muddy gas-bearing materials can bring a variety of different clasts to the surface in the form of mud breccias, which contain clasts of variable composition, size, shape and abundance (Kopf et al., 2003).

3.2. Geodynamic history of study area

Following the closure of Paleotethys between the Central Iranian Microcontinents (CIM) and the Eurasian plate (Omrani et al., 2013a) and subsequent uplift and collapse, the Kopeh Dagh basin opened (Berberian and King, 1981; Lasemi, 1995; Robert et al., 2014). The Middle Jurassic Kashafrud Formation (Kopeh Dagh basin) with evidence of syn-rift normal faulting outcrops to the north of the ophiolitic complex of the Paleotethys (Alborz Mountain Ranges) (Robert et al., 2014). The Kopeh Dagh Mountains form a NW-SE-trending range composed of folded Mesozoic and Tertiary sediments (Shabanian et al., 2010).

The closure of Neotethys branch in north of the CIM during the Eocene (Sabzevar Zone; Omrani et al., 2013b) caused the collision of the CIM with the Alborz continental block and subsequent folding, uplift and erosion in the Kopeh Dagh basin. The South Caspian oceanic/continental crust is restricted by the northward-dipping Apsheron-Sill fault to the north and the southward-dipping Khazar fault to the south (Fig. 1A). This set of structures in a compressional area led to subsidence of the SCB and adjacent areas (the future Gorgan Plain) and sedimentation within the SCB (Berberian, 1983; Jackson et al., 2002; Brunet et al., 2003).

Conjugate right-lateral and left-lateral components are reported along the Kopeh Dagh and eastern Alborz respectively, which suggest that the SCB has a westward component of motion relative to both Eurasia and Iran (Jackson et al., 2002). This movement could be an effect of the northward motion of the central Iranian Microcontinent relative to the South Caspian Sea (Fig. 1A).

Lyberis and Manby (1999) constructed balanced geological sections across the western part of the Kopeh Dagh and estimated ~75 km of N-S shortening, which they assumed had occurred over the last 5 Ma, yielding a shortening rate of ~16 mm yr-1. Due to N-S shortening, the west of Kopeh Dagh is being expelled to the west (Fig. 1A; Hollingsworth et al., 2006).

3.3. South Caspian and Kopeh Dagh basins

The study area is a part of the Gorgan Plain in Golestan Province, NE Iran. It is situated between the Alborz mountain ranges, the Kopeh Dagh Mountains and the South Caspian Sea (Fig. 1A). Seismic sections of the Gorgan Plain indicate that the area is composed of two units (Robert et al., 2014). The lower unit consists of Kopeh Dagh-related formations (Jurassic to Eocene) that have been folded and eroded (Fig. 1B). The upper unit (Pliocene to Pleistocene) consists of South Caspian Basin sediments and river deltas (Fig. 1B). The boundary between these units is an angular unconformity (Robert et al., 2014). The main characteristics of these units are summarized below:

3.3.1. Kopeh Dagh Basin units

Five transgressive-regressive sequences are recorded in the Kopeh Dagh region, dating from the Jurassic up to the Eocene (Raisossadat, 2004; Sharafi et al., 2013). Up to 10 km of sediments were deposited from Jurassic to Oligocene time through subsidence (Berberian and King, 1981). Lower Cretaceous sedimentary rocks begin with the conglomerates and sandstones of the Shurijeh Formation and end with the dark grey shales and siltstones of the Sanganeh Formation (Raisossadat, 2004). The Upper Cretaceous sequence begins with the Aytamir glauconite sandstones and ends with limestone units of the Kalat Formation (Kalantari, 1987; Immel et al., 1997). These sediments were folded into parallel, asymmetric folds during the Oligo-Miocene orogenic phases