

## **The mud volcanoes of Pakistan**

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### **Abstract**

Mud volcanoes are geological structures formed as a result of the emission of argillaceous material on the Earth's surface or sea floor. Sufficient water and gas is incorporated to make it semi-liquid and force it up through long narrow openings or fissures in the crust to produce an out-flowing mass of mud slurry on the surface. In Pakistan mud volcanoes occur in the Makran Accretionary Belt and the Pishin Belt.

The Makran Accretionary Belt has larger number of mud volcanoes. Using high resolution satellite images, over 70 active mud volcanoes were identified, listed and plotted. They occur within a well-defined zone parallel to the regional trend of the accretionary belt; we called the Makran Zone of Active Mud Volcanoes (MZAMV). Within the zone mud volcanoes occur as clusters, which form linear belts parallel to the regional thrusts and anticlines.

The MZAMV also includes the offshore mud volcanoes found in the shallow shelf area, specifically the "Malan Island" that has been recurrently emerging for the fourth time since 1945 on their own fixed positions. The periodically emerging mud islands on shelf of the Arabian Sea along the Makran Coast of Pakistan and Iran are known to be submarine mud volcanoes.

The 1st known emergence, during November 1945, was concurrent with an earthquake (M8.0), the 2nd and 3rd emergences (March 1999 and November 2010), respectively, were not apparently relevant with large earthquakes. The 4th emergence concurred with Awaran earthquake (M7.7) of September 2013. Landsat images of March 1999 and November 2010 emergences indicate appearance of round-shaped island of 4.4-5.2 hectare size, followed by erosion and disappearance. The emerged island was composed of mud breccias along with circular vents extruding mud slurry and methane gas. We suggest that mud islands develop in response to the episodes of enhanced mud extrusion, which in-turn are related with the enhanced compressional and/or seismic events. These events are followed by periods of relative quiescence characterized by normal activity of mud extrusion and marine erosion.

We believe that the MZAMV developed and evolved in response to the continued compression within the Makran Accretionary Belt, which in turn is a response of the subduction process; mud diapirism has also been an ongoing phenomenon since Pleistocene or even earlier. Thick deposits of old mud volcanoes (Pleistocene or even older) are also present within the zone, which also display recognizable features that are characteristic of the fossil mud volcanoes. Mud volcanoes are also found in the Pishin Belt, Pakistan; 1) at the locality of Khutkandai, 35 km north-northeast of the town of Qila Saifullah, on the Qila Saifullah-Sharan Jogazai road, and 2) at a locality near the village of Sur Kach, 40 km west of the town of Zhob. These mud volcanoes are associated with a major thrust zone, known as the Sur Kach-Khutkandai Thrust. Mud volcanoes and associated features at Khutkandai cover ~ 0.75 km area and over 50 m thick deposits. Near the Sur Kach village several active vents and old mud volcano deposits are found.

At Khutkandai active mud volcanoes extrude mud-water slurry, along with hydrocarbon gases, from a cluster of vents. A clear-water carbonate spring is also present on top of a dome-shaped mound, which shows 1 m thick carbonate crust of clear-water spring deposit over the mud volcano deposit. Several occurrences of extinct mud volcanoes and clear-water carbonate spring deposits

also occur. Some very old mud volcano deposits, comprising mud supporting chaotically distributed angular to subrounded sandstone clasts resembling with the Dasht Murgha group and a cluster of chimney-shaped features composed of very coarse sandstone with intraclasts of the host rocks are also present.

In both localities mud volcanoes occur within the fluvial succession of the Miocene Dasht Murgha group, whereas the surrounding area comprises thick marine, deltaic and fluvial sedimentary succession of the Eocene through Pleistocene age. Based on their association with the Sur Kach-Khutkandai Thrust, we suggest that folding, thrusting and subsequent migration of methane from the underlying hydrocarbon source are the major controlling factors for the development of mud volcanoes in the region.