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Similar Ring Structures on Mars and Tibetan Plateau confirm recent tectonism on Martian Northern polar region

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Abstract: The polar regions of Mars feature layered deposits, some of which exist as enclosed zoning structures. These deposits raised strong interest since their discovery and still remain one of the most controversial features on Mars. Zoning structures that are enclosed only appear in the Northern polar region, where the disappearance of water bodies may have left behind huge deposits of evaporate salts. The origin of the layered deposits has been widely debated. Here we propose that the enclosed nature of the zoning structures indicates the result of recent tectonism. We compared similar structures at an analogue site located in the western Qaidam Basin of Tibetan Plateau, a unique tectonic setting with abundant saline deposits. The enclosed structures, which we term Ring Structures, in both the analogue site and in the Northern polar region of Mars, were formed by uplift induced pressurization and buoyancy of salts as the result of recent tectonic activity.

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Introduction

The layered deposits detected by the Mariner 9 and Viking missions remain one of the most controversial features of the Martian surface to date (Murray *et al.* 1972; Cutts 1973; Kargel 2004; Carr 2006). A wide range of interpretations has been proposed for their origin, such as a result of the orbital and rotational perturbations of the planet (Carr 2006), formations related to ice sublimation (Ivanov & Muhleman 2000), layers formed by spiral troughs (Howard *et al.* 1982), or formations by variations in the deposition of ice and dust (Milkovich & Head 2005). Although evidence of young tectonic activity and related faulting (<2 million years) have been identified on Mars (Roberts *et al.* 2012), the layered deposits have never been considered as a result of recent tectonism.

The layered deposits have been identified in both polar regions by high-resolution images taken by Mars Orbiter Camera (MOC) on board the Mars Global Surveyor mission and Thermal Emission Imaging System (THEMIS) on board Mars Odyssey Mission. In the northern and southern regions, the layers are composed of alternating bright and dark materials; however, in the South the deposits are less symmetrical and not enclosed (Carr 2006). In the North, where the evaporation of ancient bodies of water may have resulted in extensive saline soils dominated by halite and gypsum (Clark & Vanhart 1981; Di Achille & Hynek 2010), some of the layered deposits are enclosed structures and form a mound (Carr 2006), such as a contour structure of a hill. We name these enclosed structures made of layered deposits that form mounds as Ring Structures.

To interpret the genesis of the Ring Structures from the Northern polar region of Mars, we examined an analogue site in the north western Qaidam Basin located in Northern Tibetan Plateau (Fig. 1). The Qaidam Basin is a tectonic region where over 4 million years of dramatic environmental evolution saw isolated mountain lakes turn to hyper-arid playas due to the drying up of sulphate brines (Zheng 1997; Kong *et al.* 2014). The basin has an irregular rhombic profile, measuring roughly 850 km from west to east and 150–300 km from south to north (Fig. 1) (Fang *et al.* 2007). The basin has an average elevation of 2800 m above the sea level, in contrast to the surrounding mountains that are averagely 5000 m high (Yin *et al.* 2008). The exceptionally high elevation of the basin and high levels of solar irradiation received induce tremendous diurnal and seasonal temperature fluctuations (Wang & Zheng 2009). The basin was formed in the core of an extensive synclinorium that was created by the compression between the South Qilian Mountain thrust belt of 65–50 Ma in the northeast margin and the younger Qiman-Tagh-Kunlun Mountain thrust belt of 29–24 Ma in the southwestern margin (Fig. 1) (Yin *et al.* 2008). The differential uplift of the Tibetan Plateau since the early Pleistocene 1.8 Ma (Zheng 1997) resulted in the breaking of the giant lake that existed since the Eocene 55 Ma ago (Dewey *et al.* 1988; Zheng 1997), and a long trend of hyper-arid climate caused increased water salinity and a gradual transformation of the lake areas to dry lake basins (Zheng 1997).

Ring Structures

The compression between both major thrust belts in the Qaidam Basin resulted in the formation of a series of Ring Structures in the dried lake areas. For example, the Ring

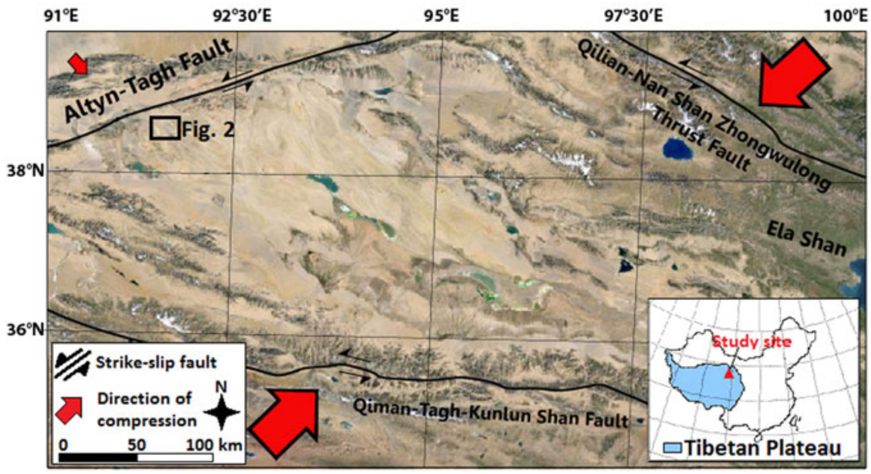

Fig. 1. Tectonic configuration of Northwest Tibetan Plateau and its surrounding mountains and faults. The directions of compression of Qiman-Tagh-Kunlun Mountain Fault, Altyn-Tagh Fault and Qilian-Nan Mountain-Zhongwulong Fault are indicated by red arrows. Bigger arrows show stronger compression.

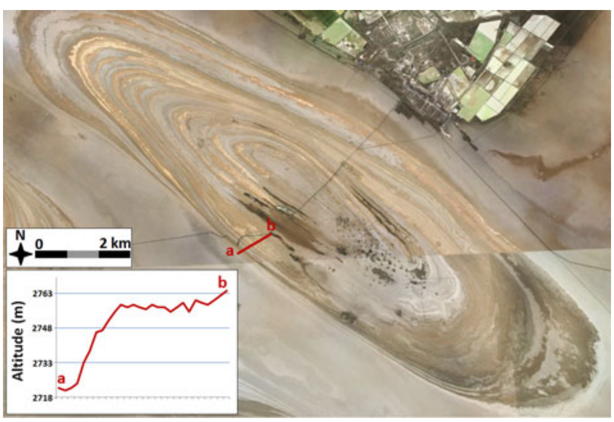

Fig. 2. Ring Structure of Xiaoliang Mountain. Image centred at 38.49°N, 91.37°E with an altitude of 2782 m at the centre. The inset displays the Ring Structure uplift towards the centre.

Structure of Xiaoliang Mountain is characterized by its <30 m altitude, ~20 km along the major axis, ~5 km along the minor axis and the enclosed zoning structures (Fig. 2). The Ring Structures display a striped stratigraphy all around, alternating from salt-rich (brighter) to clay-rich (darker) compositions. The X-ray diffraction measurements and scanning electron microscopic observations show that the surrounding mountains of Pliocene in age are clayey deposits with major mineral composition of gypsum and halite (<5% of clay). Ephemeral accumulation of ice during winter gives rise to hydration and dehydration of the salts due to freeze–thaw processes.

The uniqueness of the Ring Structures is their formation mechanism which is caused by tectonic forces from the surrounding thrust belts in all directions. The layered evaporites and their different mechanical properties to that of rocky silicates is a key feature of the structures. Our theory proposes the Ring Structures are formed by surrounding thrust belts causing tectonic pressure resulting in a localization of concentrated salts (Jackson & Talbot 1991; Jackson 1997; Hudec & Jackson 2007; Chan *et al.* 2013) where the force is at its maximum. The concentration and increased buoyancy of the salts within the clay substrate cause the salt to rise until the crust is arched as the salt is brought to the surface. Strong wind erosion (Phillips *et al.* 1993) and occasional episodic flooding weaken the crust as the underlying layer of clay is compressed and forced upwards by a new layer of concentrated salts building up below. The constant compressional forces from the thrust belts cause these layers to be formed alternatively as the Ring Structure grows taller due to new layers being formed below (Fig. 3). As observed in the Qaidam Basin, the Ring Structures have their longitudinal axis in the northwest direction as a result of the greater tectonic compression from the South Qilian Mountain and the Qiman-Tagh-Kunlun Mountain thrust belts (Yin *et al.* 2008).

Occasionally compression forces result in squeezed layers in a direction perpendicular to the compression (Fig. 4(a)). Stronger deformation can lead to a normal fault, where the displaced walls result in the disjunction of adjacent Ring Structures (Fig. 4(b)). Figure 4(c) clearly displays the division of two Ring Structures and the elevation towards the centre of the normal fault.

Ring Structures in the Qaidam Basin offer a unique analogy to the Martian morphologies. Alternating layers of salts and clays, together with small amounts of ice as a result of variations in obliquity (Head *et al.* 2003), are observed in the Northern polar region of Mars. We suggest that those Martian enclosed zoning structures (Fig. 5(a)) are similarly the result of the surface manifestation of surrounding thrust belts forming salt-layered mounds as those found in the Qaidam Basin. S-folding resulted in parallel hinge lines in the Qaidam Basin (Fig. 5(b)), which bear a strong resemblance to a pair of Ring Structures observed in the Martian northern cap (Fig. 5(c)). They could be a result of shear forces that cause a rupture of the initial Ring Structure perpendicular to the direction of the main compressional forces, resulting

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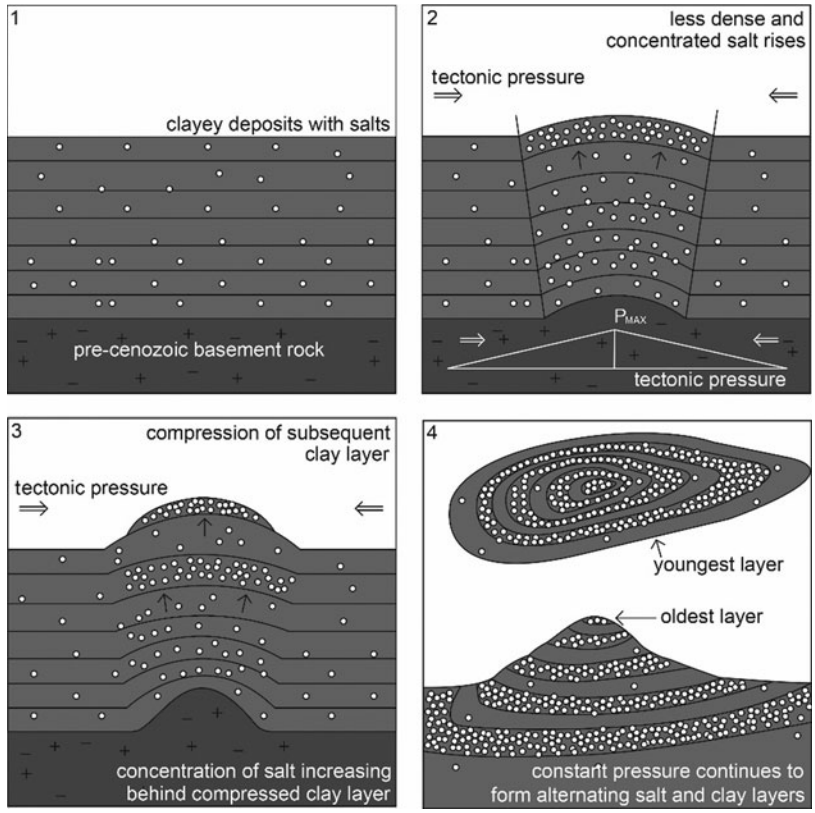

Fig. 3. Formation of Ring Structures. 1. Clayey deposits were originally mixed with salts. 2. Regional pressurization causes a localization of concentrated salts. The increased salt concentration applies pressure to the overburden. 3. The overburden is weaken until the crust arches and a salt-rich layer forms. 4. Ring Structure as seen from above. Salt- and clay-rich layers continue to form as long as there is tectonic pressurization.

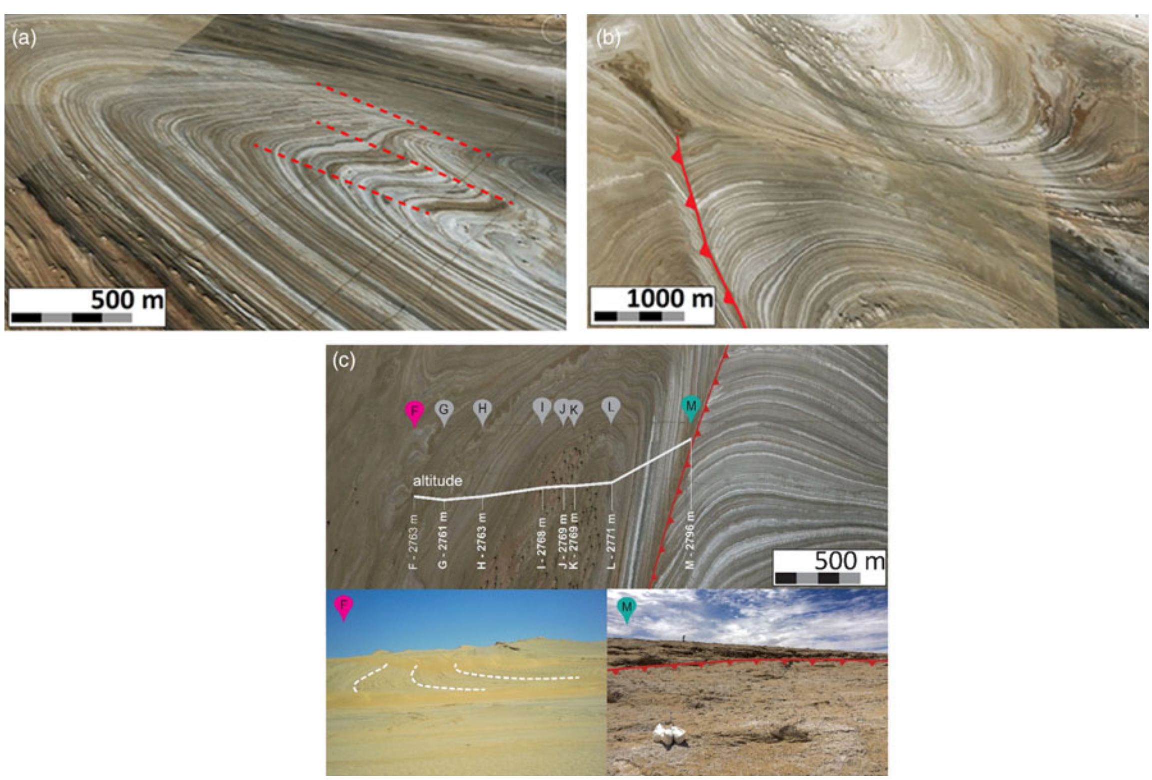

Fig. 4. Ring Structures in the Qaidam Basin. (a) The dashed lines show a small NW–SE compression force in the layered stratification in one of the Ring Structures. Image centred at 38.06°N, 91.38°E with an altitude of 2819 m at the centre. (b) A normal fault intersects two Ring Structures. Image centred at 38.11°N, 91.35°E with an altitude of 2763 m at the centre. (c) Altitude profile and expedition images of the normal fault.

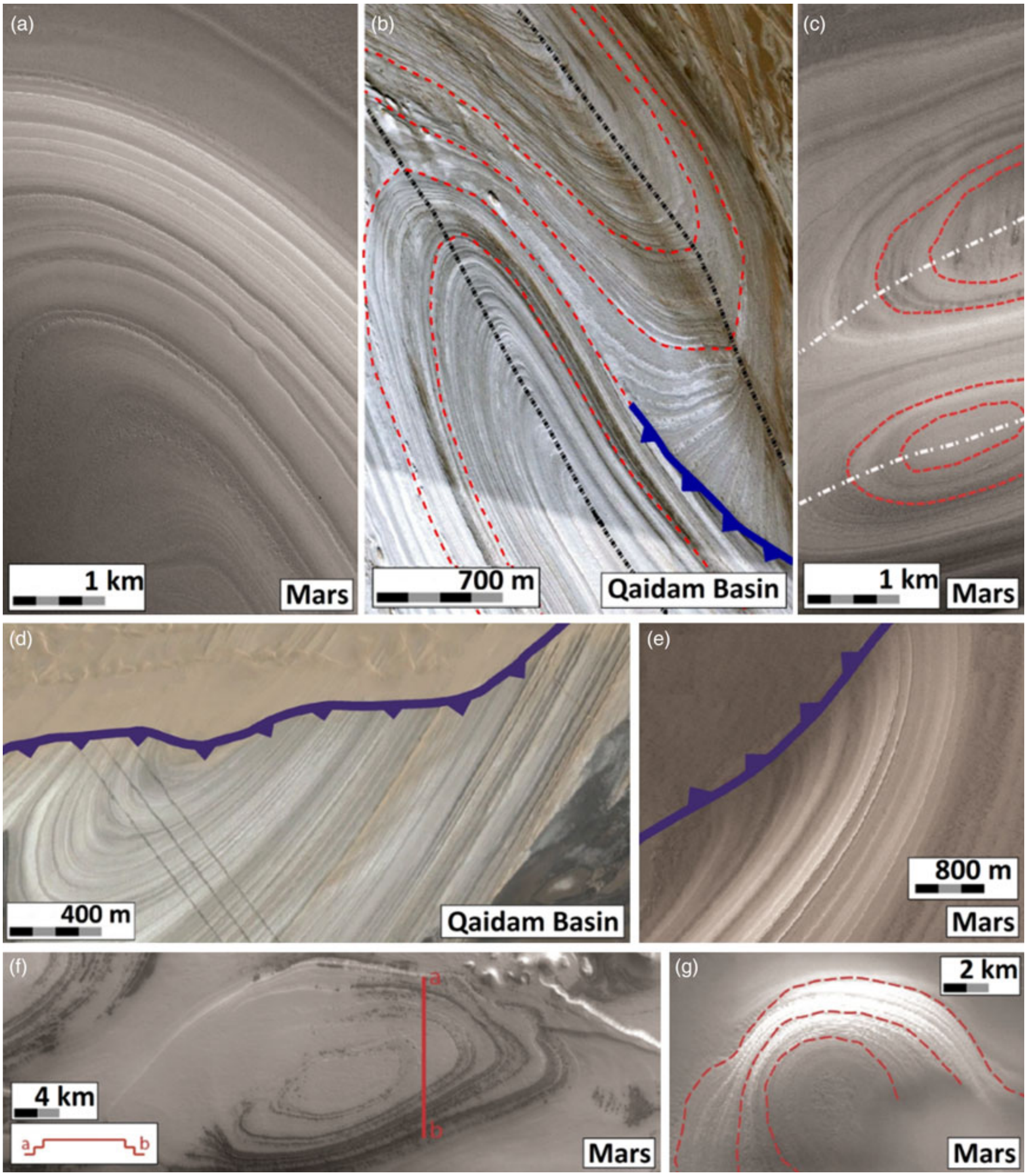

Fig. 5. Ring Structures in the Martian polar regions and the Qaidam Basin. (a) Ring Structures exposed in the Martian Northern polar region, near 84.90°N, 263.30°W. (b) Parallel Ring Structures in the Qaidam Basin, centred at 38.21°N, 91.45°E with an altitude of 2822 m at the centre. (c) Parallel Ring Structures on Martian Northern polar region, near 85.70°N, 21.00°W. (d) Thrust movement in the Qaidam Basin at the edge of Ring Structures, centred at 37.58°N, 91.12°E with an altitude of 2881 m at the centre. (e) Thrust movement in the Martian Northern polar region, near 81.40°N, 352.20°W. (f) Flat structure in the Martian Southern polar region, near 82.28°S, 275.13°W. (g) Martian Southern polar region structure showing multitude of open layers near 84.26°S, 315.20°W.

in a few small synclines between them. Both the Northern polar region of Mars and the Qaidam Basin show the Ring Structures being divided by the tectonic compressions (Fig. 5(d) and (e)).

By contrast, similar structures identified in the Martian Southern polar region differ from Ring Structures due to a number of factors. As shown in Fig. 5(f), the topography of the structure is uplifted and levelled in the centre and the stepping contours are flat with steep margins, while those Ring Structures peak in the centre and have undulating contours. Structures with open contour lines are also observed (Fig. 5(g)), which are most likely created by the receding floods or lake shorelines. The circular nature of these similar structures is a critical factor showing that they are not Ring Structures as the tectonic compression would result in a more elongated and stretched structure.

Discussion

The Ring Structures are the surface expressions of an uplift process originated by the pressurization of surrounding faults that have been active recently. The unique resemblance of the Ring Structures observed in the Qaidam Basin and the Martian Northern polar region is remarkable, offering an exceptional verification of recent tectonic activity on Mars. The scenario comparing the relationship between thick salt deposits and tectonics on a Martian analogue has not been investigated to date. Other than the Ring Structures in the Qaidam Basin, no other examples are known on Earth. Although an accurate knowledge of local and regional deformation on Mars is still unknown, the similarity of both planets' Ring Structures is a confident proof that tectonism in the Martian Northern polar region has been active in recent geological times.

Methods

Martian Northern polar region

For the analysis of the Martian Northern polar cap we used imagery data from MOC on board the Mars Global Surveyor mission. MOC2-1568 (Fig. 5(a)) was acquired on 28th August 2006 in a location near 84.90°N, 263.30°W and covers an area of 3 km across. MOC2-917 (Fig. 5(c)) was taken on 21st November 2004 in a location near 85.70°N, 21.00°W and covers an area of 3 km across. MOC2-1512 (Fig. 5(e)) was acquired on 3 July 2006 in a location near 81.40°N, 352.20°W and covers an area of 3 km across. All images were taken in the northern spring, minimizing distortions due to different sunlight illumination conditions and possible shadows.

Martian Southern polar region

The images examined in the southern region were captured by the High-Resolution Imaging Science Experiment (HiRISE) camera on board the Mars Reconnaissance Orbiter spacecraft. THEMIS V48151009 (Fig. 5(f)) was acquired on 21 October 2012 in a location near 82.46°S, 274.22°W and covers an area of $\sim$17 km across. THEMIS V56524003 (Fig. 5(g)) was taken on 10 September 2014 in a location near 84.43°S, 315.33°W and covers an area of $\sim$17 km across.

The Qaidam Basin

The Qaidam Basin images were acquired from Ovitalmap-Google satellite (Beijing Ovital Software Co. Ltd.) and by field trips to the Qaidam Basin. Samples from the layers in the Ring Structure of Xiaoliang Mountain (Fig. 2) were analysed using a Siemens D500 X-ray diffractometer at Guangzhou Institute of Geosciences (Chinese Academy of Sciences) and processed using MDI JADE 8 software to confirm their alternating salt and clay compositions.

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