V-MACS: Novel views of the Martian giant canyon system

Global tectonics on the terrestrial planets

Plate tectonics, which prevails on Earth since the Proterozoic at least, provides one of the possibilities to evacuate internal heat from the inner planets (Mercury, Venus, Earth, Mars). Internal heat needs to be in sufficient quantity, as well as water in the crust, to make possible plate overthrusting and subduction, and some mechanism to generate rigid plate boundaries. These factors partly depend on how and where the planet accreted in the Solar System, and how it survived the Late Heavy Bombardment.

Mercury, dry due to its proximity to the Sun, illustrates that horizontal plate mobility does not occur in the absence of water. The origin of deformation of the Mercurian crust is conjectural but could lie in shock waves related to a giant impact and volcanic loading tectonics.

Venus is a fascinating case because its diameter almost equals the Earth's diameter, it formed in an orbit close to the Earth's, and has therefore quite a similar composition. There is evidence of intense past crustal deformation, and plate tectonics has been advocated as a mechanism explaining the formation of mountain belts in the Ishtar Terra region, such as Freyja, Danu and Akna Montes around Lakshmi Planum (Fig. 1), that some authors compare to the Himalayas/Tibet subduction and collisional system. The existence of deformable plates (tesserae) showing a tectonic style akin to ductile tectonics of Archean cratons, such as the Dharwar in India, has led to the suggestion by the PI and co-workers that these terrains were similarly deformed by sagduction. Transition from sagduction tectonics to plate tectonics is possible by lowering the crustal thermal gradient, causing the crustal brittle-ductile transition to move from the surface downward. The possibility exists, therefore, that the early Venusian crust evolved in a way much similar to the Earth. Then, perhaps some ~1 Gy ago, deformation ceased. The extreme greenhouse effect that exists on Venus nowadays (90 atm and 460°C at the surface) would certainly not allow plate tectonics because of crust dehydration. The origin of the greenhouse effect is not known on Venus, and its understanding has consequences for the Earth within the framework of continuous supply of greenhouse effect gases by human activities. As long as the interplay between causes and consequences is not understood, whether greenhouse runaway is to be anticipated on Earth, causing the loss of mankind, is an open issue.

Mars is still another case, where the dominant stress source is connected to the evolution of the Tharsis volcanic rise (Fig. 1), which was shown to control not only the tectonic deformation of the planet, but also the main lines of its geomorphology and hydrology. In 1996 a plume tectonics model was proposed in which Tharsis is very similar to a continental large igneous province on Earth, such as the Ethiopian volcanic province, where flood lava eruption occurs at a "hot spot" in response to a buoyant plume rising through the mantle, impinging on the base of the lithosphere, and partial melting. In the brittle crust, the generated magma is horizontally channelled by huge swarms of vertical magma sheets (dykes). Most of dyke propagation occurs at a depth of several kilometres, controlled by magma buoyancy, and is associated with extensional tectonics (rifting) that breaks the weakened lithosphere.
Other stress sources may have existed. For instance, the growing Tharsis magmatic load in the Martian lithosphere, if not built at the equator where it is now located, may have modified the planet's rotation axis, until its present, stable, position. The Tharsis lithosphere would have stored elastic stress during axis reorientation, possibly until failure, producing deformation in a form that still needs investigations.
The main problem actually to understand global tectonics on Mars is that most of the deformation of the crust of Mars is extremely old, corresponding to the Archean eon on Earth. Understanding the tectonic events that occurred in this distant past requires examination of exposures of the earliest crust.

What the study of Valles Marineris on Mars reveals

The Valles Marineris giant equatorial trough (chasma) system, located on the flank of the Tharsis rise (Fig. 1), is an unique site to study such exposures. It provides a 700,000 km2 view into crustal processes that occurred over 4 Gy of planetary history through a window up to 10 km deep that exposes the oldest rocks that can be found on Mars. How this window opened is not clear but there is evidence that extensional tectonics played a significant role. Some authors have compared Valles

Marineris to a rift in the sense of continental terrestrial rifts, like for instance at the East African Rift System (Fig. 1).
The earliest geological events in Valles Marineris have been seldom investigated. Difficulties are diverse. Evidence of the oldest events lies in the deepest parts of chasmata, which are frequently masked by various more recent deposits. The area is really huge, covering it with high resolution orbital images (HiRISE data from the Mars Reconnaissance Orbiter spacecraft, 25-50 cm/pixel) takes time, and the number of geologists interpreting Valles Marineris is very small. As a result, most useful data have not yet been examined in detail. This project accepts the challenge of identifying these rocks and interpreting their deformation.

What's new in Valles Marineris? Recent findings

Considering that the key to understanding Valles Marineris evolution lies in its earliest rock exposures, a preliminary survey was undertaken in 2015 in order to identify such outcrops. It revealed the presence of many dykes on chasma floor having an orientation predicted by the plume tectonics model. The model is therefore confirmed, but also its limitations are revealed. The observed thickness as well as the dyke density are indeed evidence that the top of these dykes was removed by erosion of several kilometres of crust, similar to e.g. the Proterozoic Mackenzie dyke swarm of the Canadian shield associated to the opening of the Poseidon ocean, first formed as sub-rift intrusives, then exhumed by erosion. Therefore, the identified dyke swarm not only is consistent with tectonic extension, but also indicates that chasma floor lowering occurred through substantial erosion.
The preliminary work also identified an exhumed shear zone on chasma floor, revealing the first deep tectonics ever identified on Mars. Next to it, exposure of a crystalline body also points to crustal exhumation. All these observations point to a dual mechanism of chasma formation on Mars: by tectonic extension and crustal exhumation by erosion.
Finally, the preliminary survey also revealed additional dyke swarms on the chasma walls that do not follows the orientation predicted by any tectonic model. Dyke swarms are unique tectonic indicators because at regional scale they follow principal stress trajectories. They offer the potential to enrich dramatically our knowledge of Tharsis tectonics and therefore, Martian global tectonics.

Proposed research

Understanding the formation of Valles Marineris requires that the plume tectonics model be complemented by a mechanism for exhumation and an accurate characterisation of the changing stress field orientation with time. In the V-MACS project, the exhumation mechanism will be sought and quantified, the stress field successions will be mapped, and finally a new model of Valles Marineris formation and evolution will be proposed (the previous one is dated 1992), providing new constraints on the evolution of the early Tharsis rise and the characterisation of the Martian global tectonics system.
Martian tectonics was thought to be much more simple than the tectonics of the Earth and Venus; this project will reveal new aspects and may uncover unexpected complexity.