NEW INSIGHT ON THE ORIGIN OF SPIRAL TROUGHS IN MARTIAN POLAR ICE CAPS. Zuoxun Zeng[1,2,3,4], Hongjie Xie[1], Stuart Birnbaum[1], Lilin Liu[2,4], Weiran Yang[2,4], [1]Department of Earth and Environmental Science, University of Texas at San Antonio, Texas, 78249, U.S.A., zuoxun_zeng@hotmail.com, [2]Faculty of Earth Sciences, China University of Geosciences, Wuhan, 430074, P.R.China, zuoxun.zeng@126.com, [3]Space Center, China University of Geosciences, [4]Tectonomechanical Research Center, China University of Geosciences

Introduction: Large-scale spiral troughs are characterized by lower albedo equator-facing dusty scarps of the troughs intervening higher albedo ice-rich smooth terrains, with an anticlockwise of the spiral troughs for the north ice cap (Fig. 1) and clockwise for the south ice cap (Fig. 2). The origin of spiral troughs has been studied for more than three decades. They have been firstly interpreted as erosional features formed via aeolian stripping by Coriolis-deflected winds [1]. Contradicting this hypotheses is that wind spiral out clockwise in northern pole and that wind spiral out anticlockwise in southern pole according to the influence of Coriolis force. These are just opposite to the arrangement of the troughs in both polar ice caps. Then, a mass balance explanation due to ablation-driven erosion and redeposition and aeolian erosion of polar layered deposits (PLD) and poleward migration of the troughs proposed by [2,3,4,5,6]; but a slow migration rate of the troughs has not been measured [7]. [8] simulated the 2D features of the spiral trough by fueling instability of the ice surface; however, it lacks a strong physical basis [7]. [7] presented a mathematical theory based on albedo pattern developed from spatial instability and then drive trough evolution, with a precondition of ancient albedo imprint; but how the ancient albedo imprint formed is a new problem? In this paper, we propose a vortex fracture system caused by differential rotation between the inner part and the outer part of the ice caps, to explain the origin of spiral troughs in both polar caps of Mars.

Vortex Fracture System on Earth: To understand the formation of the spiral troughs on Mars, let's examine two examples of vortex structures on Earth. The first example is a vortex fracture system developed in Nalinggou, Daqingshan, Inner Mongolia of China shown in Fig.3. It consists of five arcuate fractures arranging in a turbine-like pattern (After the Writing Group of the Lecture of Geomechanics, From [9]). This is similar to the spiral trough system in the Martian polar ice caps (Fig. 1). A current stress field showing spiral or vortex principal stress axes is shown in Fig. 4. It is obtained from focal mechanism in the Western Alpine arc. The center of the vortex stress field is located around Torino. In fact, there are many vortex structures founded on Earth in very different scales.

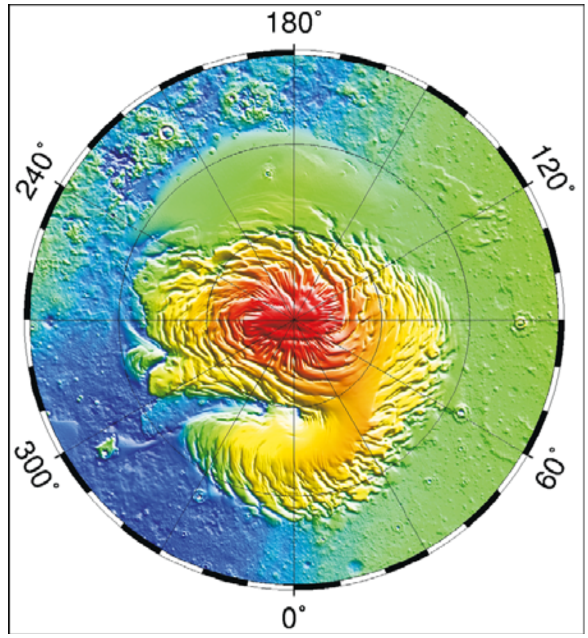

Fig. 1 Spiral troughs in northern polar ice cap of Mars. Source from [7]

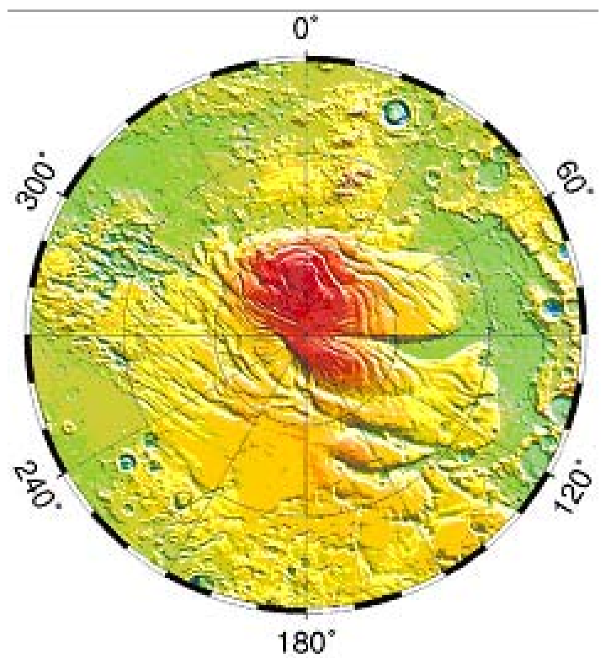

Fig. 2 Spiral troughs in southern polar ice cap of Mars. Source from [7]

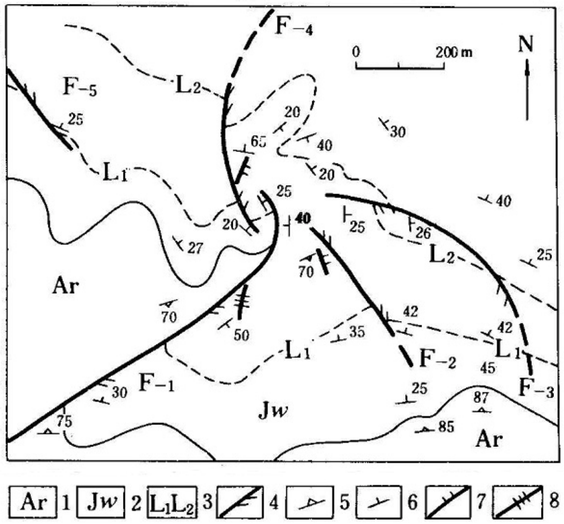

Fig. 3. Vortex fracture system developed in Nalinggou, Daqingshan, Inner Mongolia, China (After the writing group of the Lecture of Geomechanics, 1972, From [9])

Analytic solution for the stress field forming vortex fracture system: To explain the formation of vortex structures, we can develop an analytic solution for the stress field [9]. The geometric model for the analysis is a disc with an inner core at its center. The idea of the inner core is come from the permanently-frozen region as Kostrikov and Garagash, and [8] suggested. While the inner core has an anticlockwise rotation, the outer part of the disc should have a relative clockwise rotation (Fig.5). In polar coordination system, we select a stress function

$$\varphi = c\theta \tag{1}$$

where c is an undetermined coefficient.

Introducing Eq.(1) into the biharmonic equation:

$$\nabla^2\nabla^2\varphi = \left(\frac{\partial^2}{\partial^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}\right)\left(\frac{\partial^2\varphi}{\partial^2} + \frac{1}{r}\frac{\partial\varphi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\varphi}{\partial\theta^2}\right) = 0 \tag{2}$$

We obtain

$$\begin{aligned}
\sigma_r &= \frac{1}{r}\frac{\partial\varphi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\varphi}{\partial\theta^2} = 0 \\
\sigma_\theta &= \frac{\partial^2\varphi}{\partial r^2} = 0 \\
\tau_{r\theta} &= -\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\varphi}{\partial\theta}\right) = \frac{c}{r^2}
\end{aligned} \tag{3}$$

By using the condition that the moment is M when r = a or b, and assuming the uniform distribution of shear stresses on the circular section of the disc, we can determine the coefficient

$$c = \frac{M}{2\pi h} \tag{4}$$

Introducing it into Eqs (3), we get the three stress components

$$\sigma_r = \sigma_\theta = 0, \tau_{r\theta} = \frac{m}{2\pi h r^2} \qquad (a \le r \le b) \tag{5}$$

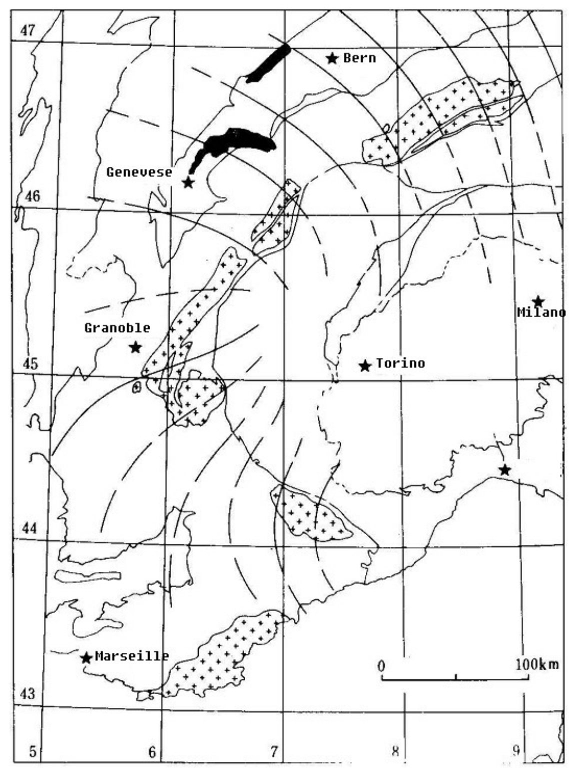

Fig.4 Trajectories of compression axes in the western Alpine arc drawn from the focal mechanism [10]

This result indicates that the element at every point in the disc subject a pure shear stress state. From this result and that both the orientation of the greatest and least principal stresses, making an angle of 45 degrees with the pure shear stress plane, we can draw the trajectories of principal stresses in Fig. 5.

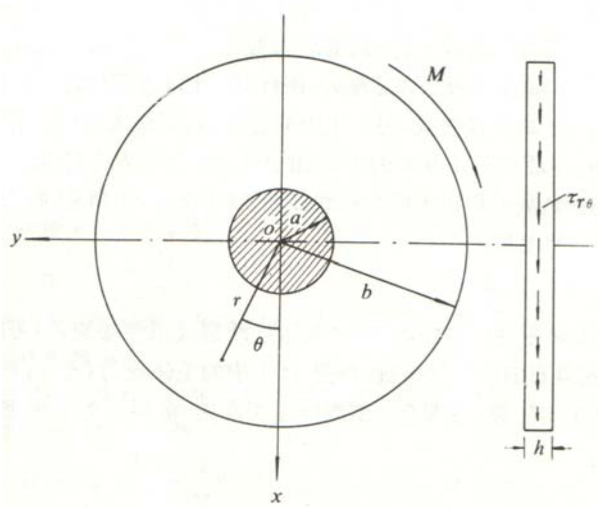

Fig.5 Mechanical model for the formation of vortex fracture system

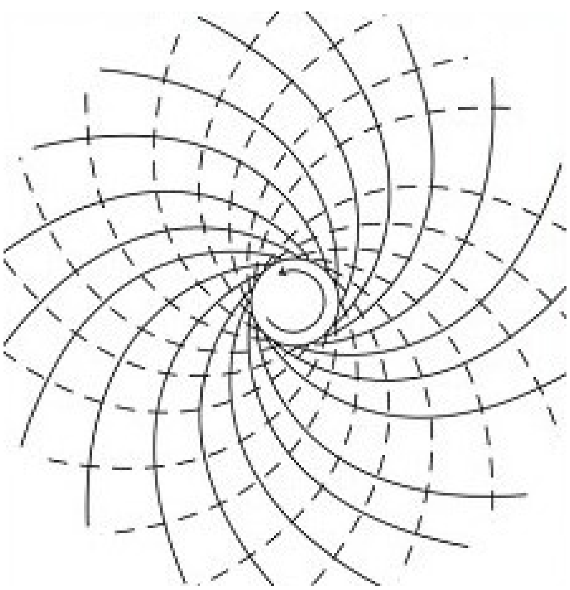

Fig. 6 Trajectories of principal stresses resulted from the analytical solution. The solid lines represent the trajectories of greatest principal stresses, which correspond to the spiral troughs in the northern polar ice cap. The dashed lines represent the trajectories of the least principal stresses.

Physical modeling of vortex structure: Fig.7 shows one of the physical modeling results. It is the crack pattern developed in the brittle-coating sprayed on the surface of the model subjected to a relative opposite rotation between the inner circular side and the outer circular side of the disc in Fig.5. We can make a comparison between the brittle-coating crack pattern and the trajectories of the greatest principal stresses. We can also make a comparison between the crack pattern in Fig.7 and the arrangement of the spiral troughs in the northern polar ice cap (Fig.1). The resemblance among them is undoubted. Another physical modeling result is shown in Fig.8. It is resulted from a clay model subjected to differential rotation between the inner core and the outer part of the clay disc. We can observe two sets of fractures in the model. One set are following the trajectories of the greatest principal stresses. The other set are the shear fractures making an angle of a to the greatest principal stress according to the Coulomb Criterion of Failure. From many experiments, we observed that only one set of the shear fractures developed instead of two conjugate shear fractures.

$$a = p/4 - f/2$$

where f is the internal friction angle of material.

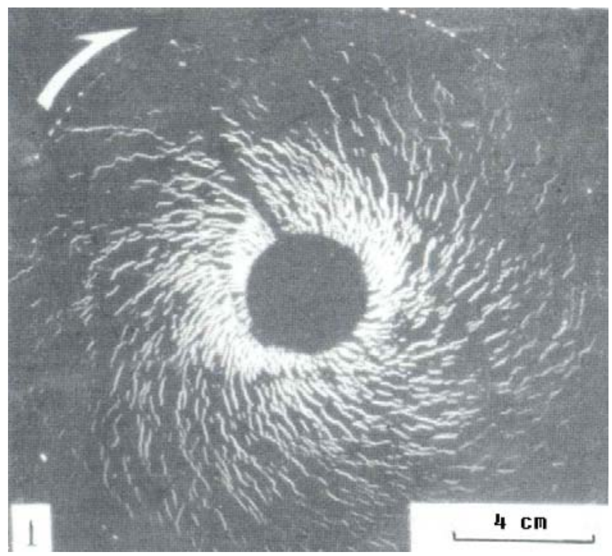

Fig.7 Vortex fracture system resulted from brittle-coating experiment

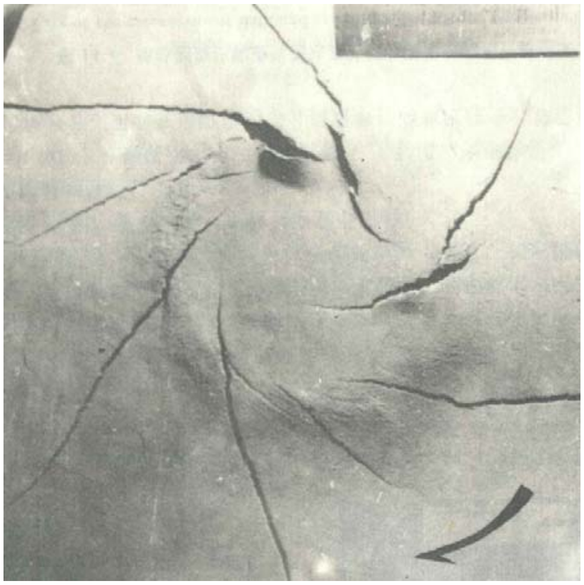

Fig.8 Vortex fracture system in clay model. Note that there are two sets of fractures. One set are tension fractures. Another set near the core are shear fractures. Source from [9]

Implication and discussion: The above model results suggest that the vortex or spiral trough system in the north polar ice cap can be formed from the difference of rotation between the inner circular side and the outer circular side of the ice cap. The model is also suitable to the formation of the spiral troughs in southern polar ice cap by changing the rotational sense. The question is what causes the differential rotation between the inner arc and the outer arc of the ice cap? In our opinion, it is resulted from an accelerating rotation of the present Mars. The first evidence is that the northern troughs spiral out anticlockwise whereas the southern troughs spiral out clockwise. Both of them could be results by the accelerating rotation of the Mars. The second evidence is that the age of the troughs are believed be very young. Another support comes from the opinions of Kostrikov and Garagash. They believe that the ice cap should be two parts in some condition, that is a inner part with elasticity (strongly sticking to the polar rock mass) and an outer part with plasticity and with bed thaw (without bed friction) of the ice cap. In summary, we interpret that the spiral troughs in the polar ice caps are resulted from vortex fracture systems. The formation of the vortex fracture systems is because of the differential rotation between the inner part and the outer part of the ice caps resulted from the current accelerating rotation of the Mars.

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