氏　　名　植村 千尋

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学 位 論 文 題 目　Study on the transition of anisotropy in polygonal crack patterns of paste and its application to Martian terrain

論 文 審 査 委 員　主　査　中原 明生
日本大学 理工学部 教授
岩田 隆浩
宇宙科学コース 准教授
稲富 裕光
宇宙科学コース 教授
安部 正真
宇宙科学コース 准教授
臼井 寛裕
JAXA 宇宙科学研究所 教授
狐崎 創
奈良女子大学研究院 自然科学系 教授

博士論文の要旨

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The gully focused on in this thesis is a groove-like feature found on the Martian slope that was most likely formed by flowing water. However, there were various theories of formation, and the debate has not been settled. Therefore, I focused on the shape of thermal contraction polygons seen in gullies and hypothesized that the gully formation process could be restricted. One of the effects that can control the contraction fracture phenomenon, a process similar to thermal contraction fracture, is the memory effect of the paste. This effect is a phenomenon in which the paste remembers the direction in which it is vibrates or flows during horizontal shaking due to plasticity, and cracks tend to propagate in the corresponding direction. When the solid volume fraction is high and the paste vibrates during shaking, cracks perpendicular to the shaking direction propagate (memory of vibration). On the other hand, when the solid volume fraction is low and the paste flows during shaking, cracks parallel to the flow direction propagate (memory of flow). Since this effect can be used to control the shape of crack fragments, I hypothesized that it could be applied to shape interpretation of Martian polygons. However, it was not clear by which parameter the memory effect transition occurs.

First, in order to quantitatively discuss the anisotropy of crack patterns, I devised an image analysis method using Shannon's information entropy. I quantified the randomness of cracks at each angle in a square image and used the fact that the entropy value is smaller when the cracks propagate along a particular direction to determine the anisotropic structure of crack pattern.

Next, experiments were conducted to confirm the relationship between the frequency and amplitude of oscillatory shear strain applied directly to the paste and the desiccation crack pattern in order to clarify the conditions under which the transition between memories of vibration and flow occurs. The jig of a rheometer, which measures the flow behavior of samples, was modified to apply oscillatory shear strain to the paste, which was then dried, and the desiccation crack patterns were observed. Previously, the experimental method has been to place the paste in a container, shaking the entire container horizontally, and then observe the crack pattern after drying. In this thesis, I established, for the first time, a method for conducting experiments by directly controlling the oscillatory shear applied to the paste. The crack patterns imaged were used to quantitatively determine the direction of the crack propagation using Shannon's information entropy. The results revealed that the memory of vibration appears when the amplitude of oscillatory shear strain is small at about 100%, and the memory of flow appears when the amplitude is large, exceeding 300~700%. I also found that frequency and the solid volume fraction of the paste have little effect on this transition. It was also clarified that multiple vibrations are required

for the memory of vibration to appear, whereas in the case of memory of flow, no vibrations are required and only a large shear deformation in one direction is needed. Consistent with the already proposed theory of memory of vibration, these results clearly demonstrated the conditions for transition, and it is considered that theoretical studies on the memory of flow and transition will be advanced. The clarification of the conditions for the occurrence of memories of vibration and flow has expanded the possibility of applying the memory effect to other fields, including interpretation of surface terrain of solid planets.

Next, I examined the effect of changing temperature on the memory effect and investigated the relationship with rheology by measurement. This was done because the temperature dependence of the rheology of pastes that are subject to attraction has not been systematically investigated on Mars, despite the fact that temperatures on Mars vary widely. Since it has been reported that clay minerals with an attractive force in water exist on Mars and that an attractive force between particles is necessary for the memory of flow, I target pastes with an attractive force system. Yield stress was derived from measurements by stress control, and viscosity was discussed as a ratio to elasticity by the Small Amplitude Oscillatory Shear (SAOS) measurements. The measurements revealed that the yield stress increased with temperature rise, and the rate of increase was higher than that of repulsive pastes. This is considered to be due to the fact that the attraction between particles becomes stronger as the temperature rise. The memory of the flow is expressed if a large deformation is given, which means that the stress required to give that deformation increases with temperature rise. This may affect the angle of repose for sediment flow on a Martian slope. The suggestion is that temperature could be one of the parameters to consider when discussing Martian terrain through memory effects.

Finally, based on the above results, a comparison was made between the ground-based desiccation fracture experiments and the analysis of Martian images. On planetary surfaces, sediment is not subjected to regular vibrations, and it is unlikely that anisotropy in fracture direction due to memory of vibration would occur. However, memory of flow only needs to be given shear in one direction and is likely to occur on planetary surfaces as well. Therefore, I conducted an experiment to see if the same trend is observed in the desiccation crack pattern formed after the paste flows on the slope. The results of the experiment showed that the memory of flow is also manifested when deformation is applied on the slope. The analysis of Martian images also revealed that it is consistent with the idea that the memory of flow was manifested by sediment flowing down the slope. Assuming that the gully was formed by water flow, the results of the experiments in this study suggest that the sediment was subjected to more than 600%~1400% strain during gully formation.

As a result of this thesis, the conditions for the transition between memories of vibration and flow and the conditions for the occurrence of each have been clarified. This has made it easier to consider the effects of the memory effect in interpretation of surface terrain of solid planets. It is suggested that there is no situation where the memory of vibration appears on Mars, but the memory of flow generated by one-directional shear, such as sediment flow, may appear. It is consistent to assume that the polygons with anisotropic crack direction seen on the gully were

formed by flowing sediment and that the anisotropy of the cracks appeared due to the memory effect of the paste after shrinkage fracture.

（別紙１ Separate Sheet 1）

Results of the doctoral thesis defense

博士論文審査結果

Name in Full
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Title
論文題目　　Study on the transition of anisotropy in polygonal crack patterns of paste and its application to Martian terrain

出願者は、固体惑星表層での流動的な物質を模擬した粘土ペースト（固体微粒子のサスペンション、以下ペースト）の物性を明らかにすることにより、固体惑星の地形の特徴を定量化して形成要因を絞り込むための手法を開発し、これを火星地形の形成メカニズムの推定に適用した。

ペーストが加振されたり流されたりした際に、外力の方向を塑性により記憶し、その後その方向に依存した平行亀裂が進展しやすくなる現象として、ペーストのメモリー効果が知られている。これは、熱収縮破壊と同様のプロセスである収縮破壊現象を制御できる効果である。ペースト中で乾燥亀裂の進展方向の遷移が起こることは知られていたが、その発生条件は不明であったため、火星地形の現在のパターンから過去の流動履歴を推測することは困難であった。本研究では、固体惑星表層画像から、地形パターンの異方性を定量的に解釈する情報エントロピーを用いた解析手法を開発し、亀裂パターンの定量的解釈を可能にした。また、ペーストのメモリー効果における亀裂伝播方向の遷移が起きる条件を実験的に明らかにし、惑星地形の形成にメモリー効果が寄与する可能性を示した。これにより、火星峡谷上のポリゴンの解釈に適用して、メモリー効果が実際に火星の地形の形成に関与している可能性を示して、固体惑星地形の解釈を可能とする新たな手法を確立させた。

本研究では、ペーストのメモリー効果における亀裂伝播方向の転移が発生する条件を明らかにするために、ペーストに直接与える振動剪断歪を制御する実験を行った。物質の流動挙動を測定する粘弾性測定装置であるレオメーターの治具を加工して、ペーストに振動剪断歪を与え、その後乾燥させて乾燥亀裂パターンを観察した。ペーストのメモリー効果は、塑性によってペーストが加振時に揺れや流れの方向を記憶し、それに応じた方向に亀裂が伝播しやすくなる現象（揺れの記憶、流れの記憶）を指す。実験で得られた乾燥亀裂パターンはシャノンの情報エントロピーを用いて亀裂方向が定量的に判別された。実験と解析の結果、振動剪断歪の振幅が 100%程度において揺れの記憶、100~500%を超える振幅では流れの記憶が表れること、転移には周波数やペーストの体積比率の影響が小さいことを明らかにした。また、揺れの記憶が現れるには複数回の振動の印加が必要であるのに対し、流れの記憶には振動は不要で一方向への大きな剪断変形が必要であることも明らかにした。これは既報告の揺れの記憶の理論とも整合的であり、本研究で示された転移条件から、流れの記憶や転移に関する理論研究への貢献が期待される。揺れの記憶・流れの記憶の発生条件の明確化により、固体惑星の表層地形をはじめ、他分野へのメモリー効果の応用可能性を拡張できる。

以上の結果を踏まえ、地上での乾燥破壊実験と火星画像との比較を行った。惑星表面では土砂が規則的な振動を与えられることは稀であり、揺れの記憶による亀裂方向の異方性が発生する可能性は低い。他方で流れの記憶は一方向の剪断により引き起こされるため、惑星表面においても発生する可能性が高い。そこで、斜面をペーストが流れた後に形成される乾燥亀裂パターンにおいて同様の傾向を示すことを確認する実験を行った。その結果、斜面上で変形を与えることによっても流れの記憶が表れることを示した。また、火星画像の解析から、斜面の土砂流により流れの記憶が現れたとの解釈が可能であることを示した。火星のガリー地形の水による形成を仮定すると、本研究の実験結果から、ガリー形成時に土砂は200%~1000%以上の歪を受けたと推定される。このように、物性物理の知見から火星表面地形の形成・進化を解明する手法を開発できたことは、火星における水の存在形態の研究に寄与するものである。

審査会においては、約１時間の公開講演・質疑応答、その後の審査委員全員との非公開質疑を通し、出願者が自らの発想で実験・データ解析・解釈を進め、かつ関連分野の専門家との議論を主体的に行って、本論文の執筆に至ったことが確認された。以上に鑑み、審査委員会は本論文が博士学位論文に相応しい優れたものであると全員一致で判断した。