Experimental Models of Patera Formation on Io

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ABSTRACT

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Jupiter's moon Io is the most volcanically active object in the known Solar System. Approximately 2% of its surface is covered by volcanic features called paterae. Theoretical models of paterae formation have been proposed, including the melt-through hypothesis. As no experimental models have been constructed for paterae on Io, we have constructed several scaled models of varying characteristics using material analogues of the Ionian crust. After applying subsurface heat, the resulting features are evaluated for similarity to Ionian paterae. One of our models produced a patera-like structure; this model comprised a relatively thick layer of powdery snow beneath wet sand. Its manner of formation lends support to the melt-through hypothesis.

Keywords: Io, Volcanism, Paterae, Planetary Science, Geomorphology

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Contents

Introduction

Why Study Io?

Io is the innermost large moon of Jupiter, discovered by Galileo in the year 1610. Behind Ganymede, Titan, and Callisto, it is the fourth largest natural satellite in the Solar System. Because of the orbit's position relative to Europa and Ganymede it experiences an orbital resonance with each of these two bodies: for every orbit of Europa, Io completes two orbits; for every orbit of Ganymede, Io completes four orbits. As a result of this, Io has an eccentric orbit. The eccentricity of Io's orbit, combined with its close proximity to Jupiter, results in the generation of large amounts of internal heat.

This prodigious internal heat makes Io the most volcanically active object in the Solar System and an important object of study; by learning about similar processes on Io, we can increase our understanding of volcanism and heat loss on Earth. The purpose of this report is to determine if we can reproduce the characteristics of a certain class of Ionian volcanoes, termed paterae, in an experimental model.

Paterae

Io's surface has over 400 volcanic depressions called paterae. These features have steep walls and relatively flat floors. A patera may range in size from 1 km to 200 km in diameter, the average diameter being about 40 km. Many paterae are associated with lava flows and lava lakes. The effects of tectonic activity are also visible, with at least 50 percent of paterae bounded by faults or mountains. While paterae share some similarities with volcanic calderas on Earth, it is unknown if they form in the same way.

The formation of paterae must depend, at least in part, on the nature of Io's crust. The surface of Io includes mafic lava flows, pyroclastic deposits, and sulfurous volatiles, specifically sulfur dioxide ($SO_{2)}$, sulfur monoxide (SO), and disulfur (S_2). All of these are deposited on the surface as the result of volcanic eruptions. As new eruptions take place, new layers of these materials will bury older material from previous eruptions. As such, Io's crust is believed to be made of silicates, mafic flows and intrusions, sulfur flows and sulfur dioxide frost, as well as pyroclastic deposits, which are all interlayered.

Melt-Through Hypothesis

According to the hypothesis of Keszthelyi et al. (2004), a magma chamber may collect at the base of a volatile rich zone of the crust. Heat from the magma may vaporize the overlaying volatiles, so that SO_2 seeps through the crust until it escapes the surface in a plume eruption. The loss of these volatiles to the atmosphere has an effect on the structural stability of the material above the magma chamber, eventually resulting in collapse. The magma chamber is then exposed at the floor of the newly formed patera.

This mechanism is unlike caldera formation on Earth, where magma chambers become partially emptied in an eruption. The empty space in the magma chamber, rather than the escape of crustal volatiles, leads to collapse and caldera formation.

Experimental Models

Caldera formation on Earth has been studied using experimental models. These models have been scaled to be appropriate for terrestrial conditions, incorporating materials such as sand, powdered clay, and dry ice. However, previously no experimental models have been applied to the conditions on Io. We hope to reproduce the characteristics of paterae in an experimental model. If achieved, it will provide evidence to either support or reject the melt-through hypothesis of patera formation.

Methodology

To experimentally explore patera formation, we have taken the following steps:

1) Design and construct an apparatus to contain our experiments
2) Create several different experimental models
3) Observe the resulting features
4) Compare with paterae on Io

Each of these steps is detailed in the sections that follow.

Experimental Apparatus Design and Construction

Acocella V. et al. (2001) and Kennedy B. et al. (2004) used experimental models to study caldera formation on Earth. Based on their approach, we have constructed an apparatus in which to contain our experiments. As seen in Figure 1, this apparatus is a metal box 61.5 cm long, 55.5 cm wide, and 51 cm deep. The size reduces edge-effects in our models. It is 50.0 cm deep to allow us to create models with a variety of different layers. The 3/8 inch steel provides structural strength to support the weight of our models while maintaining a high amount of thermal conductivity. The four steel legs of adjustable length allow the box to rest above a 10 in x 10 in electric hot plate, used to simulated a hot subsurface magma chamber. One side of the box is a movable wall that can be used to simulate tectonic compression or extension.

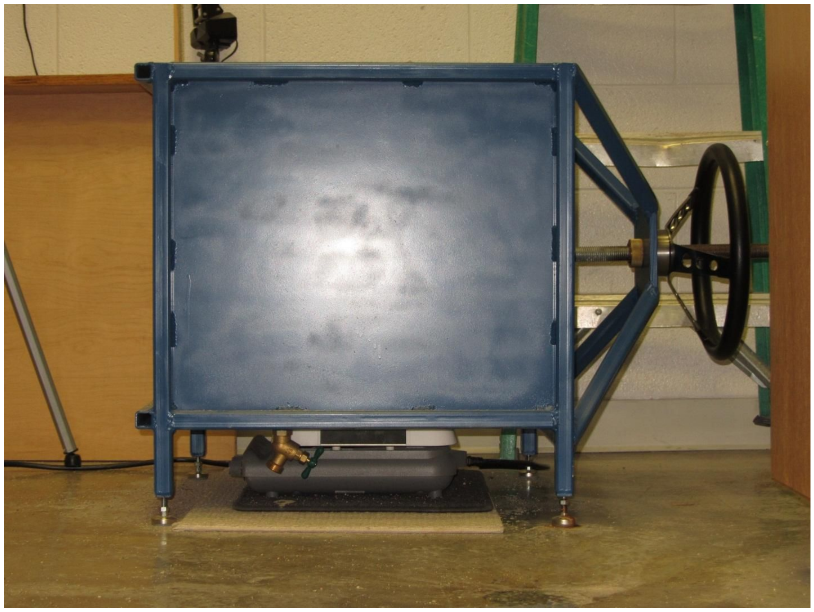

Figure 1: Experimental Apparatus, with hot plate and moveable wall

Creation of Experimental Models

For each experimental model, we interlayered varying thicknesses of sand and volatiles. For volatiles we used either dry ice or snow. The interlayering of sand and ice is meant to simulate the layers of dense, structurally strong silicates (represented with sand) and weak, less dense, sulfurous volatiles (represented with dry ice or snow) thought to form Io's crust. Because the exact structure of Io's crust is unknown, we have run several experiments, varying the number and thicknesses of layers each time. The following are examples of major endmember model setups; the outcomes of their runs are described later.

In Experiment 1, our model had one thin layer of dry ice. We filled the apparatus with 9 cm of sand, followed by 1 cm dry ice, and topped with 2 cm of dry sand. This configuration is seen in Figure 2.

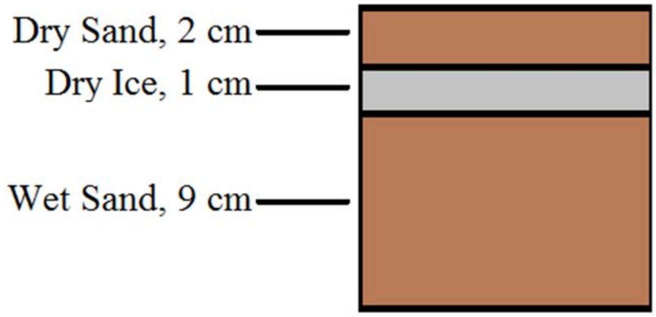

Figure 2: Experiment 1, model with one thin layer of dry ice

Experiment 2 used a model with two thin layers of dry ice. We filled the apparatus with 4.5 cm wet sand, 0.5 cm dry ice, 3 cm wet sand, 0.5 cm dry ice, and 1.5 cm wet sand. This is illustrated in Figure 3.

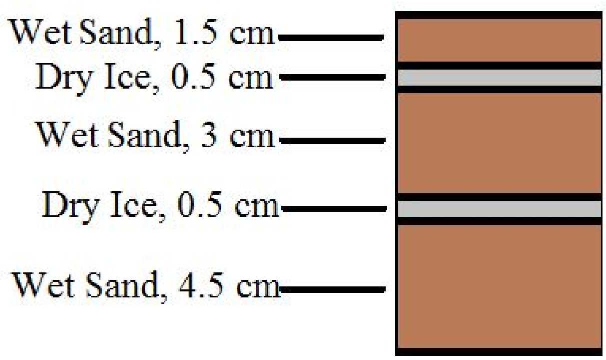

Figure 3: Experimental Model 2, model with two thin layers of dry ice

Experiment 3 used a model with one thick layer of snow. We filled the apparatus with 5 cm of wet sand, 10 cm of snow, and 7 cm of wet sand. This configuration is seen in Figure 4.

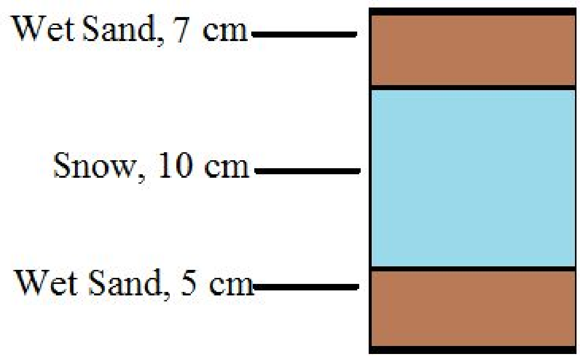

Figure 4: Experiment 3, model with one thick layer of snow

Method of Observation

Once our apparatus was filled with the desired sand and ice layers for a specific model, we began heating the model with the hot plate set to approximately 150° C. We acquired images at various stages of each experiment using a digital camera. Once the model reached a steady state, the experiment was concluded. We estimated that each experiment was active for 1 hour, with at least one photo taken every 10 minutes. At the end of the run time, we measured the dimensions of any features that formed as a result of the experiment.

Comparison with Galileo Data

We then evaluated the results of our experiments to determine which, if any, of the experiments produced patera-like structures. The photographs from each experiment were compared with data available from an online electronic database hosted by NASA. This database includes digital images of Io paterae from the Galileo mission. This allowed for a side-by-side comparison of the morphologies of actual paterae and our experimental results. Finally, we compared the dimensions of the features formed in our experiments with the range of existing patera.

Results

Each experiment produced surface features which were unique to the model used. In this section, we will describe our observation from each experiment, particularly the resultant surface features. We will then describe the results of our evaluation of their similarity to paterae on Io. Finally, the results are summarized in Table 2.

Experiment 1

In Experiment 1, a 1 cm thick layer of dry ice is buried beneath 2 cm of dry sand. Figure 4 shows a photograph from 30 minutes after the start of the experiment. In the center, a very shallow (~0.5 cm) depression formed. Frost is visible in and around the depression. This is believed to be a result of water vapor from the air condensing and freezing, due to the presence of dry ice.

Figure 5: A photograph taken 30 minutes into Experiment 1.

Frost began to form at 19 minutes. After 45 minutes, steam began to vent out from the northern region of the model. At this time, the frost began to slowly dissipate. At 1 hour and 20 minutes, all frost was gone, and the model attained a steady state. The resulting depression was neither deep nor steep-walled.

Experiment 2

In Experiment 2, two 0.5 cm thick layers of dry ice are buried beneath 1.5 cm of wet sand. Figure 6 shows the model 1 hour and 2 minutes after the start. We had difficulty obtaining a uniform thickness for these dry ice layers. Multiple small, pockmark-like depressions are visible. Most likely, these have formed above points where the dry ice was thicker than average. Frost and condensation are also visible.

Figure 6: A photograph taken 1 hour and 2 minutes into Experiment 2.

Experiment 3

Experiment 3 involved a 10 cm layer of snow buried beneath 7 cm of wet sand. This experiment produced a depression measuring 18 cm x 14 cm along the major axes. Approximately 40 minutes into the experiment, initial collapse occurred rapidly, (see Figure 7). As the experiment continued, fractures and the area of collapse grew progressively larger (see Figure 8). When the experiment ended, the maximum depth of the depression was 2 cm.

Figure 7: Initial collapse 40 minutes into Experiment 3.

Figure 8: The final image taken 50 minutes into Experiment 3.

Scaling

While interpreting the results of our experiments, we must consider the scaling relationships between our models and the surface of Io. As previously noted, the average diameter of paterae is about 40 km. As our experimental apparatus encompasses an area of 61.5 cm x 55.5 cm, we consider distances in our experimental models to be on a scale of approximately 1 cm : 1 km. Thus, we have the ratio of model length to actual length, $L^* = 1 \times 10^{-5}$. This and other scaling relationships are presented in Table 1.

Ratio	Approximate Value	Physical Properties
L^*	1×10^{-5}	Model length to Actual length
H^*	1×10^{-5}	Model height to Actual height
ρ^*	0.76	Density, Sand to Io's crust
g^*	5.4	Model gravity to Io gravity
σ^*	4.1×10^{-5}	Stress, where $\sigma^* = \rho^* g^* H^*$

Table 1: Scaling Relationships

The resulting stress ratio is comparable to that in experiments by Acocella V. et al. (2001) and Kennedy B. et al (2004), with stress ratios of 5×10^{-6} and 1.8 to 2.4×10^{-5}, respectively. Given this similarity, and the inherent difficulty of reproducing surface conditions of Io in an earth-based laboratory, we consider our materials to be reasonable analogues. Nonetheless, the difference in physical properties between our models and Io's surface may affect the accuracy of our results.

Similarity to Paterae on Io

We compared the features produced from our experiments with the definition of a patera (see Introduction: Patera), the dimensions of actual paterae, and images of actual paterae on Io. These images were produced with the Solid-State Imaging Camera of the Galileo Spacecraft.

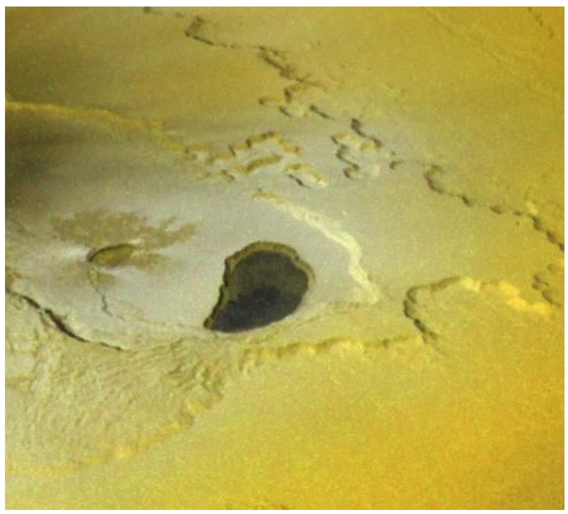

Figure 9: Tvashtar Patera, Galileo SSI, 2000.

One of the Tvashtar Paterae is seen in Figure 9. It is approximately 40 km x 25 km x 1km. Tupan Patera is seen in Figure 10. It is 79 km x 60 km x 0.9 km.

Morphologically, Experiment 3 most closely resembles a true patera; its dimensions are proportional to the accepted range, it exhibited steep walls and a relatively flat floor, and the main depression is surrounded by concentric fractures, analogous to faults and mountains on Io. Therefore, Experiment 3 is classified as patera-like.

Experiment 1 appears to be dimensionally proportional to true paterae, however, the extreme shallowness of the depression makes it difficult to characterize. For this reason, we classify it as possibly patera-like.

Experiment 2 created several small depressions, which were neither dimensionally proportional nor morphologically similar to actual paterae. For this reason, it is classified as not patera-like.

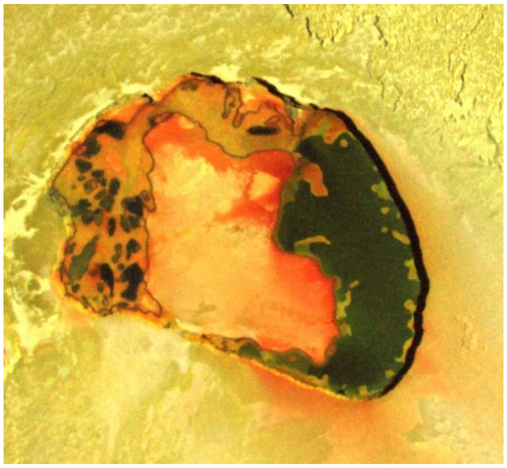

Figure 10:Tupan Patera, Galileo SSI, 2001

Name	Model	Feature Dimensions	Patera-like
Experiment 1	1 thin dry ice layer	20 cm x 20 cm x 0.5 cm	Possibly
Experiment 2	2 thin dry ice layers	3 cm x 1 cm x 1 cm	No
Experiment 3	1 thick snow layer	18 cm x 14 cm x 2 cm	Yes
Tvastar Patera	N/A	40 km x 25 km x 1 km	N/A
Tupan Patera	N/A	79 km x 60 km x 0.9 km	N/A

Table 2: Summary of Results

Discussion

Ultimately, we were able to successfully create a patera-like structure in a laboratory setting. The model to most faithfully do so was a thick layer of snow, used in Experiment 3. This model was significantly different from the other models used; it was the only thick layer model and the only snow model. The sporadic availability of snow limited the number of experiments we could perform with a snow model. Unfortunately, this means that we cannot say if a more patera-like structure occurred because of the thickness of the volatile layer, or because snow is a powdery $H_2 0$-based volatile whereas dry ice is a rigidly solid CO_2-based volatile.

The feature formed in Experiment 3 and its manner of formation, in which steam escaped through the top of the model resulting in a major collapse, lends support to the melt-through hypothesis. This suggests that paterae do not form in the same manner as calderas on Earth. If this is the case, then further investigation is needed to explain why volcanoes of this type are not seen on Earth.

We also note that the patera-like structure in Experiment 3 initially form with greater depth and very steep walls; some of this depth and steepness was lost after 10 minutes, prior to reaching a steady state. These changes may have occurred as a result of wet sand drying out and the changes in its physical properties as water throughout the model continued to vaporize.

In the future, we have planned more experiments in order to distinguish the influence of thickness and volatile type. We have also planned to introduce the movable wall to investigate the effects of tectonic extension.

In addition, we eagerly await further observations of Io's surface. Detailed images of Io have only been available since 1979, granting us only a few short decades' worth of high-resolution observations. And yet, in this geologically minute time span, there has been significant activity. We are confident that continued observations and experiments will increase our understanding of this fascinating member of our Solar System, and our understanding of our own planet's geophysical processes will increase in kind.

Bibliography

Lopes-Gautier R. et al. (1999) *Icarus, 140*, 243-264.

Radebaugh J. et al. (2001) *J. Geophys. Res. 106*, 33,005-33,020.

Keszthelyi L. et al. (2001) *J. Geophys. Res*. *106*, 33025-33052.

Zhang Q. et al. (2002) *Lunar Planet. Sci. Conf*., XXXIII, Abstract 1745.

Radebaugh J. et al. (2004) *Icarus, 169*, 65-79.

Lopes R. et al. (2004) *Icarus, 169*, 140-174.

Williams D.A. et al. (2002) *J. Geophys. Res. 107,* 5068.

Williams D.A. et al. (2004) *Icarus, 169*, 80-97.

Williams D.A. et al. (2006) *Icarus 186*, 204-217.

Acocella V. et al. (2001) *J. Volc. And Geoth. Res*. 111, 137-153.

Kennedy B. et al. (2004) *Geol. Soc. Am. Bull. 116,* 515-524.

Keszthelyi L. et al. (2004) *Icarus 169*, 271-286.