Paterae on Io: Geologic Mapping of Tupan Patera and Experimental Models

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Paterae on Io: Geologic Mapping of Tupan Patera

and Experimental Models

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ABSTRACT

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Paterae cover approximately 2% of the surface of Io, Jupiter’s volcanically active moon. To understand the formation of these volcano-tectonic depressions we created a geologic map of a key region and compared this map with experimental models for Io paterae. Our mapping region is Tupan Patera, a patera that has experienced recent activity and is a detected hot spot. We identified four primary types of geologic materials: plains, patera floors, flows, and diffuse deposits.

We constructed an experimental model to test previous suggestions that paterae may form as volatiles in the silicate crust are vaporized by rising magma, creating instability, and subsequent collapse. The apparatus is a scaled model that uses sand (silicate crust analog), ice or snow (volatile analog), a hotplate (magma chamber analog), and a moveable paddle (to simulate extension). Our experimental collapse features exhibit many characteristics of paterae on Io, such as “islands,” terraces, straight margins, and steep scarps. Our model suggests that the role of volatiles in Io’s crust is a significant part of paterae formation.

Comparative studies between our map and model show it is possible Tupan is an emerging lava lake or one in a state of quiescence. Our studies have also culminated in the completion of a theoretical cross section for the geologic history of Tupan Patera. This cross section displays a sequence of events including the rise of magma as it preferentially volatilizes sulfurous layers in the crust, subsequent thinning, instability, and collapse, the likelihood of the patera floor sinking as a stoped block, and the more recent flow and diffuse deposits. This study gives some insight to the general formation of paterae on Io.

Keywords: Io, patera, model, experiment, map, Tupan
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# TABLE OF CONTENTS

ABSTRACT .................................................................................................................................... ii  
ACKNOWLEDGEMENTS ........................................................................................................... iii  
TABLE OF CONTENTS ............................................................................................................... iv  
LIST OF TABLES ......................................................................................................................... vi  
LIST OF FIGURES ....................................................................................................................... vi  
1. Introduction ............................................................................................................................. 1  
2. Background ............................................................................................................................ 3  
3. Geologic Map Methods .......................................................................................................... 7  
4. Map Units and Structures ...................................................................................................... 8  
   4.1 Patera Floor Materials ...................................................................................................... 8  
   4.2 Plains Materials .............................................................................................................. 13  
   4.3 Diffuse Deposits ............................................................................................................. 14  
   4.4 Lava Flow Materials ...................................................................................................... 15  
5. Unit Interpretation and Correlation .................................................................................... 16  
   5.1 Patera Floor Processes ................................................................................................... 17  
   5.2 Diffuse deposit processes .............................................................................................. 20  
   5.3 Lava flow processes ...................................................................................................... 20  
   5.4 Structural Features and Landforms .............................................................................. 22  
   5.5 Comparison with other regions ...................................................................................... 22  
6. Experimental Model ............................................................................................................ 22  
   6.1 Experimental Apparatus, Materials, and Scaling .......................................................... 23  
   6.2 Experimental Model Results ......................................................................................... 26  
   6.3 Model Set 1: (No Extension) ......................................................................................... 28
6.4 Model Set 2: (With Extension) ......................................................................................... 34

7. Map and Model Comparison/Discussion .............................................................................. 35

8. Geologic History .................................................................................................................. 40

9. Summary and Conclusions .................................................................................................... 44

REFERENCES ............................................................................................................................. 48
LIST OF TABLES

Table 1: Material units identified in the Tupan region of Io.......................................................... 9
Table 2: Scaled parameters for analog modeling of paterae on Io. .................................................. 27
Table 3: Description of experimental results selected from selected experiments. ......................... 29

LIST OF FIGURES

Fig. 1 Galileo SSI (Solid State Imager) image of Tupan Patera..................................................... 2
Fig. 2 Galileo Image of the Prometheus region of Io ................................................................. 4
Fig. 3 Galileo NIMS (Near Infrared Mapping Spectrometer) image.............................................. 5
Fig. 4 Type areas of geologic units in the Tupan area................................................................... 11
Fig. 5: Geologic map of the Tupan region of Io ........................................................................... 12
Fig. 6: Diagram of apparatus (a), photograph of apparatus (b), and author for scale (c). ............. 25
Fig. 7: This graph depicts the relationship between the final scarp height of model craters and the thickness of the layer of ice used. .................................................................................. 30
Fig. 8: This histogram displays the frequency of various experimental crater diameters. The average diameter for experimental craters was found to be 26 cm......................................................... 32
Fig. 9: A series of photographic sequences that show surface deformation over time. These experiments were static (the paddle was not moved). ........................................................................ 33
Fig. 10: A series of photographic sequences that show surface deformation with time. These experiments simulated patera formation during extension..................................................... 36
Fig. 11: Example of an experimental crater that formed by differential collapse of cohesive materials, resulting in an island ................................................................. 38
Fig. 12: Several of our craters formed in a manner similar to a terrestrial trapdoor caldera........ 39
Fig. 13: Many of our craters exhibited straight margins................................................................. 41
Fig. 14: Cross section of Tupan Patera showing its sequential development................................ 44
1. Introduction

Io, the innermost of the four Galilean satellites of Jupiter, has the youngest known surface in our solar system (McEwen et al., 2000a). The geological youth of the surface can be attributed to the high amount of volcanic activity, detected by remote observations from Earth and the Voyager, Galileo, Cassini and New Horizons spacecraft (McEwen et al., 1998a). More than 400 of Io's volcanic features are paterae, volcano-tectonic depressions that amount to ~2% of Io's surface (Lopes-Gautier et al., 1999; Radebaugh et al., 2001; Keszthelyi et al., 2001; Zhang et al., 2002). Paterae on Io are characterized as having steep walls, flat floors, and arcuate margins (Radebaugh et al. 2001), and many contain current eruptions, evidenced by associated thermal emission (Rathbun et al. 2002, 2004; Marchis et al. 2005; Davies et al. 2011; Veeder et al. 2011, 2012). One technique to understanding Io’s paterae is to utilize geologic mapping to determine the distribution of volcanic materials and to identify the stratigraphic relationships (Williams et al., 2002; 2004; 2005; 2007). In addition, various models have been suggested to explain the formation and evolution of these features, which seems to require a strong tectonic component (Radebaugh et al., 2001) and the depletion of crustal volatiles (Keszthelyi et al., 2004). Although various formation hypotheses have been proposed, no known experimental models have been made to constrain the formation and evolution of paterae specific to Io’s conditions.

The objective of this study is to investigate the geologic processes that formed the Tupan region of Io, a large, active patera and surrounding plains in the southern tropical anti-jovian hemisphere (Fig.1). This was accomplished through creation of a geologic map, which allows us to understand the types of material units and structures present and to identify the types and ordering of geologic processes. We examined the morphology of Tupan Patera and investigated the possibility that paterae may form from instability of the crust due to the depletion of volatile-
Fig. 1 Galileo SSI (Solid State Imager) image of Tupan Patera obtained during the orbit I32 flyby in October of 2001. Black is interpreted to be recently solidified silicate lava, yellow is predominantly long chain sulfur ($S_8$), and red is short chain sulfur ($S_2$ or $S_3$), the presence of which indicates recent volcanic activity, as explained in the text. There is a slightly elevated plateau (or “island”) of cold crustal material within the bounding scarp. Patera walls are 1 km deep, as indicated by shadow measurements. Tupan Patera is about 80 km across. Resolution is 135 m/pixel, north is up, and illumination is from the upper right. Image is PIA 02599 and is courtesy of NASA.
rich layers within the crust (Radebaugh, 2001, 2005; Keszthelyi et al., 2004). To examine this hypothesis, we created an experimental model to simulate patera formation, with the inclusion of volatiles and thermal input. Our mapping and experimental model allowed us to interpret and further constrain the process of formation of Tupan Patera and other paterae on Io.

2. Background

The Tupan region (~18.73°S, 141.13°W) is located in Io’s anti-jovian hemisphere, south of the equator. The region, named for the Brazilian thunder god, consists of Tupan Patera (Fig. 1), a large (79 km across at its widest portion and approximately 900 m deep) volcanic depression and the plains that surround it (Doute et al., 2004; Lopes et al., 2004; Turtle et al., 2004). Prominent red diffuse deposits that surround and fill portions of the patera can be seen even in distant Galileo observations (Figure 2; Lopes et al., 2001). These deposits are interpreted to be high-temperature, short-chain sulfur (S$_3$ and S$_4$), and are possibly a result of the condensation of S$_2$ rich volcanic gases (Spencer et al., 1997; Spencer et al., 2000). This is based on the observation of S$_2$ in Pele’s plume on Io, and also that shortly after the photolysis of S$_2$, there is a production of red S$_3$ and S$_4$ molecules by polymerization (Spencer et al., 2000). This indicates that Tupan Patera is recently active, as such deposits tend to fade to long-chain (S$_8$) yellow materials over a maximum of several weeks (Geissler et al. 2004), which adds to the value of mapping this region (McEwen et al., 1998a; Turtle et al., 2001; Geissler et al., 2004). In addition, Tupan Patera has features that are typical of many paterae on Io, such as a curved margin that transitions to a straight portion which may indicate either ongoing tectonism, preexisting fractures, or the failure of a brittle crust during patera formation (O’Reilly and Davies, 1981; Radebaugh, 2001, 2005; Keszthelyi et al., 2004). A bright, central plateau or
Fig. 2 Galileo Image of the Prometheus region of Io at a resolution of about 25 km/pixel. This image was taken during the I24 flyby in July of 1999. Tupan Patera can be seen in the lower right of the image. The image is about 1,300 km across. Image is PIA 02543 courtesy of NASA.
Fig. 3 Galileo NIMS (Near Infrared Mapping Spectrometer) image obtained during the I32 flyby in October 2001. The infrared image (3b) uses false color to indicate the thermal intensity at a wavelength of 4.7 microns. Reds and yellows indicate hotter regions; blues are colder. Note that dark regions of Tupan Patera (3a) are hotter and the island in the center is cool (Lopes et al., 2004).
“island”, which contrasts with the surrounding, dark patera floor, is a feature also seen in other paterae. It may be a region that is relatively cooler than the surrounding patera floor and composed of plains materials. Tupan Patera also has some unique features that may be indicative of its high level of current activity, including a complex system of intermingled patches of various colors, which have been interpreted as sulfurous volatiles and lava flows, on the patera floor.

The image used for mapping was obtained on October 12, 2001 during the I32 orbit at a resolution of 135 m/pixel (Fig. 1). North is to the top of the image and the Sun illuminates the surface from the upper right. Aside from global-scale images (e.g. Fig. 2), this is the only visible image obtained of Tupan Patera. A near-infrared image was obtained on October 16, 2001 (Fig. 3b) and in a color map using these data reds and yellows indicate hotter regions; blues are colder. Note that hotter areas correspond with darker regions in the visible image, whereas cooler areas are generally brighter.

Because we have no in situ information on rock ages or lithologies, we use albedo, color, textural, and geomorphological information to define geologic units. Therefore, our map is technically a geomorphological map, similar to other planetary geologic maps (Wilhelms, 1990). The ultimate goal is to define material units and structures and place them within their stratigraphic context. This enables an interpretation of the geologic evolution of the area.

Various analog models have been built to simulate terrestrial volcanism (Anderson, 1936; Lipman, 1984; Marti et al., 1994; Acocella et al., 2000, 2001, 2007, 2008; Kennedy et al., 2004; Lavallee et al., 2004) but no known models have been built to simulate Io volcanism. Consequently, we built a simple experimental model to constrain the formation of paterae on Io.
The degree to which our experimental results can be applied to conditions on Io is limited, to a certain extent, by our current knowledge as obtained solely by remote sensing. Therefore, there may be imperfections in scaling parameters such as viscosities, strain rates, and cohesion. We attempted to account for the range of these values that may occur on Io. Consequently, our experiments are not meant to simulate a specific patera; instead our goal is to understand the influence of various mechanisms that might account for the wide range of patera morphologies.

3. Geologic Map Methods

The geologic map of the Tupan region was produced using the Galileo SSI orbit 132 mosaic (spatial resolution 135 m/pixel) (Fig. 1). The methodology and geologic mapping approach of Williams et al. (2002; 2004; 2005; 2007) after Wilhelms (1972, 1990) was utilized for this study, including similar constraints and interpretations employed in those projects. Other mapping studies of Io have also been successfully undertaken (Schaber 1980, 1982, 1989; Bunte et al., 2008, 2010; Leone et al., 2009).

Constraints on planetary mapping on Io include the lack of full-coverage, high-resolution images, a wide range of phase angles across available images, and lack of multiple images. In the case of Tupan Patera, the chief limitation is the lack of multiple images. There is currently only one image that is a candidate for a geologic mapping project, and fortunately it was obtained with relatively good lighting and resolution. This limitation results in an inability to observe changes over time to the patera, and requires us to produce a map for this region at a given point in time, October, 2001.
4. Map Units and Structures

Following the convention used in previous Io mapping projects (Williams et al., 2002, 2004, 2005, 2007, 2008), we define four major types of geologic units for the Tupan region: patera floor materials, plains materials, lava flow materials, and diffuse materials. Subunits with detailed descriptions and interpretations can be found in Table 1. Figure 4 shows type localities for our map units and subunits. Previous studies have shown that on Io, surface color is closely related to composition (Geissler et al., 1999, 2001; Spencer et al., 2000; Williams et al., 2005). Therefore, we use color to classify the various surface material units in the Tupan region. One characteristic that helps us to stratigraphically date the events within each of the units is the temporal trend of dark materials to brighten, and bright materials to darken with the passage of time (Williams et al., 2002). Figure 5 shows our map of the material units, subunits, and structural features found in the Tupan region. We discuss in more detail the various units and subunits as they can be identified in the Tupan region.

4.1 Patera Floor Materials

The geologic units found on the patera floor have a range of colors and albedos. It is important to note that patera floor units are not defined as such by their color, albedo, or composition but simply by their being located within the patera rim; and therefore, many patera floor units and subunits resemble units found outside of paterae. One such example is members of the Flow Materials unit, which are defined as occurring outside of the bounding scarp of paterae, even though the materials might be similar in composition or origin to some patera floor units. Though there are similarities between patera floor units and flow units, these have traditionally been mapped separately from each other (Schaber, 1980; 1982; Williams et al., 2002, 2004, 2005). Similarly, we have chosen to map flow units and patera floor units separately.
Table 1: Material units identified in the Tupan region of Io.

<table>
<thead>
<tr>
<th>Material Units</th>
<th>Unit Symbol</th>
<th>Description</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red diffuse deposits</td>
<td>(d&lt;sub&gt;r&lt;/sub&gt;)</td>
<td>Bright red unit that mantles the underlying materials. Primarily occurs as an asymmetrical deposit SE of Tupan Patera. This unit has decreasing optical depth with increasing distance from the patera.</td>
<td>The red diffuse deposit unit is likely composed of short chain sulfur (S&lt;sub&gt;2&lt;/sub&gt;-S&lt;sub&gt;4&lt;/sub&gt;) (Spencer et al. 2000) and is a pyroclastic fall deposit. This unit thinly mantles the underlying unit and decreases in optical depth with increasing distance from Tupan Patera. The patera is interpreted to be the source of these deposits.</td>
</tr>
<tr>
<td>Red flow material</td>
<td>(f&lt;sub&gt;r&lt;/sub&gt;)</td>
<td>Bright red unit that has sharp contacts with the surrounding bright plains unit. Locally it is gradational with the red diffuse deposits. Margins of this unit are lobate. Units appear to extend into topographic lows. In this region it is only found on the island of Tupan Patera.</td>
<td>The red flow materials are likely compositionally similar to the red diffuse deposits. The red flow units, however, may have formed where the flux of short chain sulfur particles were great enough to allow the particles to flow after falling to the ground. They may also have some other source that produces liquid flows of short chain sulfur.</td>
</tr>
<tr>
<td>Bright flow material</td>
<td>(f&lt;sub&gt;b&lt;/sub&gt;)</td>
<td>This unit has a high albedo surface that appears bright yellow. Contacts with the surrounding plains are sharp. Limited to a ring around the western part of the patera. Lengths of individual outcrops are greater than widths and margins are lobate. Units appear to extend into topographic lows. Albedo variations and cross-cutting relations can be used to define age relationships and even separate younger from older units. See f&lt;sub&gt;b&lt;/sub&gt;&lt;sub&gt;2&lt;/sub&gt; and f&lt;sub&gt;b&lt;/sub&gt;&lt;sub&gt;1&lt;/sub&gt; on the map.</td>
<td>Bright flow materials are interpreted to be lava flows composed of either sulfur or sulfur dioxide (Williams et al., 2002, 2005, 2007) Brighter flows have been more recently emplaced. This difference in albedo results in the labeling of the two flows, f&lt;sub&gt;b&lt;/sub&gt;&lt;sub&gt;1&lt;/sub&gt; being less bright was emplaced first and is older than f&lt;sub&gt;b&lt;/sub&gt;&lt;sub&gt;2&lt;/sub&gt;.</td>
</tr>
<tr>
<td>Green patera floor material</td>
<td>(pf&lt;sub&gt;r&lt;/sub&gt;)</td>
<td>Green to dark-green unit with a smooth surface. Has distinct contact with surrounding units. In this region it is generally found around the patera rim. Typically seen where red patera floor unit meets the dark patera floor unit.</td>
<td>The green patera floor unit possibly forms as the sulfurous red patera floor unit (pf&lt;sub&gt;r&lt;/sub&gt;) comes in contact with the silicate dark patera floor unit. On Io, when sulfurous and silicate materials react it results in a green color (Geissler et al., 1999; Phillips, 2000). The green patera floor unit commonly appears around the rim of the red patera floor flows where they are in contact with the dark patera floor.</td>
</tr>
<tr>
<td>Red patera floor material</td>
<td>(pf&lt;sub&gt;b&lt;/sub&gt;)</td>
<td>Dark-red unit with a smooth surface. Has distinct contact with surrounding units. In this region it is generally found around the patera rim and in contact with the green patera floor unit.</td>
<td>The red patera floor unit is probably similar in composition to the red diffuse deposit unit and is likely short chain sulfur. It is interpreted to be material in the crater wall that melted and flowed onto the patera floor.</td>
</tr>
<tr>
<td>Material Type</td>
<td>Description</td>
<td>Explanation</td>
<td></td>
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<td>-----------------------------------</td>
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</tr>
<tr>
<td>Bright patera floor material</td>
<td>Bright yellow-orange unit that has distinct contact with surrounding units. Occurs within the patera rim and has a somewhat smooth surface. The bright patera floor is mottled by patches of dark patera floor.</td>
<td>One explanation for this unit is that bright sulfur flows spilled onto the patera floor and patches were subsequently boiled off, thus exposing the dark patera floor beneath. Another explanation is that this unit consists of a preexisting block of collapsed crustal materials that is being melted through by magma. (Keszthelyi et al., 2004).</td>
<td></td>
</tr>
<tr>
<td>Dark patera floor material</td>
<td>This unit consists of black surfaces that lie within the patera. There is a distinct contact with other patera floor units. The unit appears smooth and dark and, in places, is mantled by overlying bright material (pf&lt;sub&gt;b&lt;/sub&gt;). This creates the complex intermingling of dark and bright patera floor units on the west side of Tupan Patera.</td>
<td>Dark patera floor materials are interpreted to be silicate lava flows. In the case of Tupan Patera, these silicate lava flows are coated in places with sulfurous materials which creates patera floor units of various colors. The dark patera floor unit may be more recently emplaced and warmer than adjacent units. Isolated dark patches may indicate areas where the hotter silicate lava boiled off overlying deposits.</td>
<td></td>
</tr>
<tr>
<td>Yellow bright plains material</td>
<td>Layered and textured surface with colors in shades of yellow. Albedo varies and the surface is hummocky; apparently consisting of a multitude of volcanic flows. Locally, mantled by overlying diffuse deposits or flows. This can be seen in areas where the yellow bright plains material is closer to the patera.</td>
<td>The yellow bright plains unit is interpreted to consist of a silicate crust that is covered with sulfur-rich materials (Keszthelyi et al., 2004). We have also mapped the central island within Tupan Patera to be yellow bright plains that have become unstable, due to the melting of volatiles in the crust, and collapsed within the crater rim.</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4 Type areas of geologic units in the Tupan area; arrows point to specific surfaces. Yellow bright plains material \((p_{by})\), dark patera floor material \((p_{fd})\), bright patera floor material \((p_{fb})\), red patera floor material \((p_{fr})\), green patera floor material \((p_{fg})\), bright flow material \((f_b)\), red flow material \((f_r)\), red diffuse deposits \((d_r)\). See Table 1 for description. Illumination is from the upper right.
Fig. 5: Geologic map of the Tupan region of Io, including correlation of map units. The map is based on NASA image PIA 02599 (Fig. 1).
The patera floor materials range from dark black, red, and green to bright yellow-orange. These color differences have been interpreted to indicate the compositions of the various materials (Geissler et al. 1999; Phillips et al. 2000; Lopes et al., 2001; Spencer et al., 2000; Williams et al., 2002, 2004, 2007). The dark black patera floor units are interpreted to be relatively fresh silicates, because they become covered over time by sulfur and sulfur dioxide frosts emitted as vapors by volcanoes (McEwen et al., 1998a; Lopes et al., 2001; Geissler et al. 2004). The red patera floor unit is likely composed of short-chain sulfur ($S_3$, $S_4$) that is either diffuse plume deposits mantling relatively cooler sulfur flows on the floor of the patera or is sulfur volatiles originally contained within the patera wall that were heated and flowed onto the patera floor (Keszthelyi et al., 2004). Patera floor materials have been seen to change from red to green, possibly as a result of chemical reactions of sulfurous deposits with warm, silicate materials (Geissler et al., 1999). For example, red materials on the floor of Pillan Patera changed over time to a greenish color (Phillips, 2000; Keszthelyi et al., 2001). Finally, the yellow and orange-tinted regions on the patera floor may be mixtures of long-chain sulfur ($S_8$) and possibly $SO_2$, with greenish-yellow patches being attributed to contamination by silicates (Williams et al. 2002; Bart et al., 2004; Keszthelyi et al., 2004).

4.2 Plains Materials

In the Tupan region, the plains materials are mottled yellow-gray color and are mapped by Williams et al. (2011) as a bright plains subunit of plains materials. The plains unit is thought to be composed of silicates mantled by sulfur- and $SO_2$-rich materials (Bart et al., 2004;
Keszthelyi et al., 2004) based on the detection of these materials by NIMS (Spencer et al., 2000; Douté et al., 2002). It is generally mottled in appearance, possibly the result of chemical decomposition of sulfur-rich surface materials, modified volcanic deposits, mass movement, and/or \( \text{SO}_2 \) sapping (McEwen et al., 2000b; Schenk et al., 2001; Moore et al., 2001; Williams et al., 2002).

Within Tupan, there is a bright island, similar to that found in other paterae, such as Loki (Howell et al., 2014) and Camaxtli (Williams et al., 2002). We have included the island with the plains unit, because of their similar colors (compositions), textures, and inferred ages. The central island here is heavily mantled by red diffuse deposits. The island is cooler than surrounding patera floor materials (Fig. 3) and appears to be elevated above the rest of the patera floor. Evidence of this can be seen by the presence of the black line following the western patera scarp that also marks almost the entire edge of the island. This “deposit” may indicate that lava levels in the patera were at one point higher and subsequently fell, leaving the black deposit on the walls of all elevated features. Also, several lava-like flows seem to emanate from the eastern margin of the island, indicating it is elevated above the rest of the patera floor. However, the lack of any recognizable shadow associated with the island suggests that it is not as high as the bounding scarp of the patera itself.

4.3 Diffuse Deposits

In the area of Tupan Patera, we have identified only one subunit of diffuse deposits: red. Red diffuse deposits have a pyroclastic origin and are thought to be composed of short-chain sulfur polymers \( (\text{S}_3, \text{S}_4) \) (McEwen et al., 1998a; Spencer et al., 2000) that are relatively short-
lived, as they tend to fade upon cooling or chemical alteration (McEwen et al., 1998a; Turtle et al., 2001; Geissler et al., 2004). The red diffuse deposits can generally be found southeast of Tupan Patera and are also found on the patera island. These deposits show decreasing optical depth with increasing distance from Tupan Patera, indicating they likely emanated from a vent or vents within the patera. The volcanic activity at Tupan Patera causes the release of gases that precipitate to form solid aerosols and liquid droplets that then fall and mantle the underlying topography to form diffuse deposits, similar to what is seen at other volcanically active areas of Io (Williams et al., 2011).

4.4 Lava Flow Materials

In our map of Tupan Patera we recognize two subunits of lava flow materials not included in patera floor materials: bright flows and red flows. Lava flow units typically have lengths greater than widths, appear to flow toward topographic lows, and have a lobate and elongated morphology (Williams et al. 2002, 2004, 2005, 2007; Bunte et al. 2008, 2010). The bright flows unit overlies the yellow bright plains unit in this region. The composition of bright flows is considered to be sulfur-dominated (Lopes et al., 2001). The variations in albedo within the bright flows subunit are interpreted to indicate the relative age of flows: The higher the albedo, the younger the flow, as bright flows tend to dull over time. This interpretation has resulted in our definition of two separate bright flow subunits: \( f_{b1} \) and \( f_{b2} \). The unit \( f_{b2} \), being brighter, is interpreted as being younger and more recently emplaced than the unit \( f_{b1} \). The red flow unit \( f_r \) can be found predominantly on the island of Tupan Patera. This flow unit has not been defined in other Io mapping projects. The high resolution of the image used for our map,
coupled with the high level of volcanic activity of Tupan, make this unit present here and easily discernible. The margins of this unit are alternately straight and lobate and the materials appear to follow structural trends and extend into topographic lows. This unit likely has a similar composition as the red diffuse deposits but at a higher concentration. The red flow unit occurs in areas where perhaps the concentration of the red diffuse deposits became great enough to allow the materials to flow.

5. Unit Interpretation and Correlation

Io’s active surface renders it free of impact craters and makes it difficult to correlate the ages of different units. Therefore, stratigraphic correlation techniques, such as superposition and cross-cutting relationships, must be used to relatively date the various geologic units and determine a relative sequence of events for the Tupan region of Io. Maps of other regions of Io demonstrate this method of correlation works well in areas with active eruptions and other volcanic activity (Williams et al., 2007). Within and around Tupan Patera, recent volcanic activity enables the interpretation of the sequence of events using lava flows and diffuse deposits (Fig. 5). We also utilize our understanding of how materials change in appearance over time by fading, brightening, darkening, or changing color. Each of these processes has been observed in various locations on Io and this knowledge was employed as we created a correlation of the geologic materials within and around Tupan Patera. Because of the lack of multiple images over time, no correlations could be made between older and more recent phases of volcanism.
5.1 Patera Floor Processes

Tupan Patera exhibits a complex intermingling of both dark and bright patera floor units within its western margin, with several possible interpretations for these associations. First, the light materials could result from the concentration of plume deposits, which accumulated in an incomplete fashion across the patera floor. Second, collapses along the rim of the patera or the thermal liberation of interlayered crustal volatiles could yield light materials that flowed over the top of the dark patera floor materials. Some of these materials could have even flowed from outside the bounding scarp of the patera (Keszthelyi et al. 2004). After deposition, relatively warmer areas on the patera floor may have heated and boiled off patches of the bright patera floor materials, thus exposing the dark lava beneath. A third possible scenario is that the bright patera floor materials could be a portion of the plains materials that collapsed upon formation of the patera. This portion of the crust could have become heated from below, and as the volatiles contained within were baked out, it may have become dense, resulting in sinking of the crustal material and creating a stoped block. Subsequently, underlying magmas may have melted through in spots on this block, resulting in the mottled appearance visible in the western portion of the patera. We favor the third explanation because the morphological evidence for this interpretation is strong, but the actual scenario may involve some aspects of the first two explanations as well. The stoped block could have accumulated plume deposits or bright flows when it was generally cooler, and now a resurgence of lava through fractures in the block have resulted in magma melting through the surface deposits.

The dark patera floor appears as a solid expanse of dark material on the eastern side of the patera. These are likely areas of relatively recent lava flows, where temperatures are high enough to boil off overlying volatile deposits. This is consistent with both NIMS and ground-
based observations of the location of highest heat flow within Tupan (Veeder et al. 2011) (Fig. 5).

The red and green patera floor units appear to have emanated from the patera scarp and island. Many of these flow-like units have red materials at the center and have margins of, or are enclosed by, green materials. These could be flows that were either initially red or were yellow or bright that were then covered by red diffuse deposits. Then, short-chain sulfur reacted with the dark, silicate patera floor to form the green materials. This green color has been observed in other locations of Io, and has been postulated as resulting from a reaction of sulfurous materials with silicate materials (Geissler et al., 1999; Phillips, 2000; Keszthelyi et al., 2001). It is also possible the green materials are a spectral blend of red and black materials, as these are found at the margins of the lobate forms, where the red materials are probably thinner.

Along the western portion of the patera scarp and island there is a thin black line, regular in thickness at 100 m or so and continuous around many portions of the patera, morphologically similar to a high water line or contour line. This may have been emplaced when lava filled Tupan as a lava lake, and was at a higher level and then subsequently dropped, leaving behind a black “bathtub ring” deposit. Such deposits are typical in lava lakes, where lake levels rise and fall, for example at Kilauea Iki (Carr and Greeley, 1980). Alternatively, even if there was no lake, or if lake levels remained stable over time, lavas could be plastered along the patera sides, where vents enter the floor and activity is most intense (Lopes et al., 2004). However, given the continuous nature, uniformity in width and contour-line-like morphology of the deposit around the patera, we favor the first explanation.
Because of the smooth, dark patera floor and the thin, dark contour line feature, we have explored the possibility that Tupan Patera is a lava lake (Lopes et al. 2004; Davies and Ennis 2011). This would require the volcanic depression to contain liquid lava and also be directly connected to a magma source, which is believed to be the case for Loki (Rathbun et al., 2002, 2004; Lopes et al., 2004; Howell and Lopes, 2007; Howell et al., 2014) and Pele (Lopes et al., 2004; Rathbun et al., 2004; Radebaugh et al. 2004). Lava lakes exhibit such features as a dark floor contained within a crater, and fountaining and cracks where the cooled crust breaks apart, often against patera walls. They may also have periodicity in thermal output and incandescent exposures of lava. Tupan has a dark floor within a depression, and there is a high level of volcanic activity, indicated by the red sulfur deposits. The thin black line that follows the western patera and island rims suggests the rising and lowering of lava in a lake or pond. All of these observations are consistent with the interpretation that this patera, if it is not currently a lava lake, may once have been a lava lake. However, resolution, and lack of nighttime observations, precluded any chance of seeing evidence for cracking or foundering of a cooled crust or incandescent lava. The location of the NIMS pixels with highest thermal emission are found around the rim of the patera, similar to other lava lakes; The presence of a lava lake at Tupan is still somewhat uncertain, but Tupan lacks any significant thermal periodicity as seen in other lava lakes (Davies and Ennis, 2011).

The southern margin of Tupan is linear, which suggests possible structural control on the formation and evolution of the patera (Radebaugh et al. 2001). These hypothetical structures may also have influenced magma ascent and emplacement. The island observed within the bounding scarp comes in contact with the patera on the southern margin. It is possible that as volatiles in the crust were heated, overlying materials collapsed preferentially, leaving behind high-standing
materials that formed the island. The island may have experienced something similar to a terrestrial trapdoor caldera collapse (Lipman et al. 1984), having the appearance of being hinged or connected to the surrounding terrain at the southern margin. Other evidence of this can be seen by observing a lack of the thin black deposit along the southern margin, indicating materials are relatively higher in elevation in that location based on the assumption the deposit is a horizontal marker.

5.2 Diffuse deposit processes

The red, diffuse deposits in the Tupan region are interpreted to be pyroclastic deposits expelled from the magma chamber. They were mapped as one unit, because although the red diffuse deposits can have varying degrees of concentration, they are compositionally the same and were more than likely emplaced in the same manner.

It is also worth noting that the red diffuse deposits in the Tupan region seem to be elongated from NW to SE on most parts of the map. Occasionally the rarefied atmosphere can attain some directionality in flow, or perhaps these pyroclastic materials were launched as projectiles in one direction from the patera vent.

5.3 Lava flow processes

The bright flow units that appear in the Tupan region to the west and southwest of the patera have been interpreted to be sulfur-rich in composition, likely of long-chain sulfur, or S₈ (Williams et al. 2001, 2002, 2005, 2007). There are two distinct bright flow units that are
interpreted to be different in age, as determined by differences in albedo. Flows that appear brighter are interpreted to be younger whereas older are darker due to the tendency of materials with a high albedo to darken over time. These flows are either primary or secondary in origin. If they are primary, then the magma chamber, which is the vent’s source, may have at one time supplied the patera with sulfur-rich flows, and then undergone a change in which it now primarily supplies Tupan Patera with the silicate lavas that can be seen within the patera. If they are secondary, then they formed when heat from silicate magma melted the surrounding, sulfur-rich, country rock (Williams et al. 2011). Of the two explanations the latter is the most likely for the Tupan region of Io. An example of secondary volcanism can be found by observing the older, darker ($f_{b1}$) of the two bright flow units. Part of this flow appears to have spilled over the edge of the patera scarp and fallen to rest on the southernmost portion of the island. Further support for the secondary interpretation lies in the very localized sources of the bright flows, none of which are within the patera. They appear to be fracture controlled and lie close to the rim of the patera. If the source of these flows was a magma chamber, they should originate from within the patera, or appear to have flowed from the center of the patera prior to its collapse.

The red flow unit that appears in the Tupan region is interpreted to have originated as flows because it has clear straight or undulatory margins, as opposed to the more diffuse nature of the boundaries of the red diffuse deposits. However, it is possible the red flow unit has a similar composition and method of emplacement to red diffuse deposits. Where red flow units occur it is likely in a location where red diffuse deposits reached a high enough concentration to flow, perhaps similar to terrestrial ash flows, spatter or mud flows, where flow occurs when concentrations reach high enough values.
5.4 Structural Features and Landforms

In the Tupan region, the only structural features found are scarps, the largest of which are found around the patera rim and island. During formation of the patera, as volatiles were heated and liberated, there would have been instability that would have led to faulting, eventually resulting in collapse of the brittle and cohesive crust to produce steep scarps. There are also several scarps on the plains, in a heavily mottled area to the northeast of the patera, that could have originated from tectonic activity and/or sapping (Bunte et al., 2010). There is no noticeable dome, cone, or shield related to the patera within the mapped region.

5.5 Comparison with other regions

The geologic history and progression of volcanic and tectonic activity found in the region around Tupan Patera is similar to that found in other regions of Io (Williams et al., 2001, 2002, 2004, 2005, 2007; Bunte et al., 2008, 2010; Leone et al., 2009). The geologic history of the region and stratigraphic relationships between each unit appear to be comparable to global trends.

6. Experimental Model

To help constrain the evolution of paterae on Io, we have constructed and run an experimental analog model. Such analog experiments have been performed to simulate the formation of terrestrial calderas (Acocella, 2000, 2007, 2008; Kennedy et al., 2004; Lipman, 1994). While there have been numerical and theoretical models made for paterae on Io (Keszthelyi et al., 2004; Radebaugh et al., 2004; Radebaugh 2005; Matson et al., 2006) there are
no published results from any physical analog models created to constrain patera formation on Io. In our attempts to understand the evolution of paterae on Io, we have taken the unique conditions on Io into account: 1) a crust composed of dense, high-melting-temperature silicates interlayered with less dense, mafic pyroclastic layers and volatiles and other types of deposits (Keszthelyi et al., 2004), 2) large volumes of dense, high-temperature melts (McEwen et al., 1998a), 3) the absence of obvious outflow deposits that would have accompanied collapse and the eruptive emptying of a magma chamber, and 4) the role of tectonism on patera formation (Radebaugh et al., 2001). The objective of the analog experiments is comparison with the geologic map of Tupan Patera and images of other paterae on Io to aid in understanding how these volcano-tectonic depressions form.

6.1 Experimental Apparatus, Materials, and Scaling

The experimental apparatus consists of a steel cube that is open at the top (Fig. 6), measuring 0.5 m on each edge and with legs to suspend it above the floor. The apparatus includes a vertical metal paddle that can be moved laterally inward and outward, by turning a wheel, to simulate extension or compression. A hot plate rests under the box, measuring 0.25 m on an edge, and was used to simulate heat from an underlying magma chamber. A camera suspended above the apparatus was used to obtain images, time lapse or video of the progress of the experiment. Materials used to simulate Io’s crust include layers of wet, poorly sorted sand, snow or water ice in pellet form (with each pellet being approximately 0.5 cm in diameter). When interlayered, these materials represent layered sheets of silicates and sulfurous volatiles thought to be present in Io’s crust. Wet sand was chosen as it is more cohesive than dry sand and
would more correctly model steep-sided collapses that occur in Io’s cold and brittle crust (O’Reilly and Davies, 1981). Water ice and snow were chosen to represent volatile materials as they are easily melted and vaporized at reasonable temperatures and easy to procure. One of the failings of using water ice is that once it melts it tends to drain to the bottom and then out of the apparatus. On Io, volatiles likely escape through sublimation and subsequently deposit on the surface (Keszthelyi et al., 2004). Future experimentation should use dry ice as it would prove to be a better analog in that respect; however, water ice proved to be a useful substitute in our experiments.

Analog experiments should attempt to closely resemble natural examples in terms of geometry, kinematics, and dynamics (Sanford et al., 1959; Ramberg et al., 1970; Acocella et al., 2000, 2001; Kennedy et al., 2004). This translates into the need for various elements of the apparatus to be scaled correctly. In terms of length and depth we assumed that 1 cm within the apparatus is equivalent to 1 km on Io which results in a depth ratio of $H^* = 10^{-5}$. We determined a temperature ratio of our experiments of $T^* = \text{temperature of the hot plate/temperature of magma chamber on Io}$. The hot plate reached a temperature of about 750 K and an assumed temperature for a magma chamber on Io is 1850 K (McEwen et al., 1998b), leading to a temperature ratio of approximately 0.4. Patera formation on Io may take $10^2$-$10^5$ years and our experiments ran for approximately 1800-3900 seconds resulting in a time ratio of about $5.8 \times 10^{-7}$ to $1.3 \times 10^{-9}$. We used 2,500 kg/m$^3$ as an average density for Io’s crust (Leone and Wilson, 2001). We determined a density ratio for our experiments of $\rho^* = \text{density of model crust/density of Io’s crust}$. We used the value 1905 kg/m$^3$ for the density of wet sand (crust analog) and the value 750 kg/m$^3$ for snow or ice pellets (volatile analog). The density ratio ranges from 1.5 to 1.7.
Fig. 6: Diagram of apparatus (a), photograph of apparatus (b), and author for scale (c).
depending on the amount of ice used in the experiment. The gravity ratio \((g^*)\) in our model is about 5.5, using a value of 1.796 m/s\(^2\) for Io’s surface gravity. Sand cohesion can be scaled to rock strength by using the stress ratio \((\sigma^*)\), which is a product of the density ratio \((\rho^*)\), the gravity ratio \((g^*)\), and the depth ratio \((H^*)\): \(\sigma^* = \rho^* g^* H^* = 1.6 \times 5.5 \times 10^{-5} \approx 8.8 \times 10^{-5}\). We assumed a value of approximately \(10^6\) Pa for the tensile strength of volcanic rocks so the model should have a tensile strength (cohesion) of about 88 Pa. Poorly sorted, damp sand can be said to have a cohesion of about 0-100 Pa (Kennedy et al., 2004), and therefore our selected materials are appropriately scaled to the cohesion of volcanic rock. Also of note, stress ratios in the experiments of Acocella et al. (2000) were about an order of magnitude smaller \((5 \times 10^{-6})\), but our experiments lie between this value and that of Kennedy et al. (2004), which ranged from about 1.8 to \(2.4 \times 10^{-5}\). Therefore, our values fall within the bounds of reasonable limits for the execution of scaled experiments. See Table 2 for a summary of the scaled parameters.

These experiments are not meant to simulate a specific patera on Io but to examine the influence of various mechanisms that might account for the wide range of patera morphologies. From the many experiments undertaken, a few significant experiments and results are described in the following sections and in Table 3.

6.2 Experimental Model Results

The experiments were divided into two sets: those that involved collapse in a uniform stress regime and those that used the paddle to simulate contemporaneous, external tectonic forces in the horizontal direction. Subsets of these experiments involved varying ice layer thickness: 5 cm, 7.5 cm, and 10 cm. For each of the experiments the apparatus was filled with 10
Table 2: Scaled parameters for analog modeling of paterae on Io. The stress ratio was calculated using the scaled parameters for density, gravity, and length.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Value on Io</th>
<th>Value in Experimental Analog</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Length</td>
<td>1 km</td>
<td>1 cm</td>
<td>10&lt;sup&gt;5&lt;/sup&gt;</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Density of crust</td>
<td>2500 kg/m&lt;sup&gt;3&lt;/sup&gt; (total density)</td>
<td>1905 kg/m&lt;sup&gt;3&lt;/sup&gt; (sand)</td>
<td>1.5 to 1.7</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;v&lt;/sub&gt;</td>
<td>Density of volatiles</td>
<td>750 kg/m&lt;sup&gt;3&lt;/sup&gt; (ice)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>Gravity</td>
<td>1.796 m/s&lt;sup&gt;2&lt;/sup&gt;</td>
<td>9.8 m/s&lt;sup&gt;2&lt;/sup&gt;</td>
<td>5.5</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>1850 K</td>
<td>750 K</td>
<td>0.4</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>10^2 to 10^5 years</td>
<td>1800-3900 s</td>
<td>5.8 x 10^-7 to 1.3 x 10^-9</td>
</tr>
<tr>
<td>σ</td>
<td>Stress</td>
<td>44.9 x 10&lt;sup&gt;6&lt;/sup&gt; Pa</td>
<td>141.4-158.4 Pa</td>
<td>1.8 to 2.4 x 10^-5</td>
</tr>
</tbody>
</table>
cm of wet sand, followed by a given thickness of ice or snow, and finally with another 5 cm of wet sand. This resulted in the total thickness of the sand/ice pack to be 0.2-0.25 meters. For simplicity, we chose to use a smaller thickness of sand in the upper layer because this made deformation more readily observable. In our experiments we have only used one layer of ice, although studies suggest that Io’s crust is most likely silicates interlayered with volatile materials (Keszthelyi et al., 2004).

For each experiment the hotplate was allowed to preheat approximately 10 minutes before the experiment began. We chose to preheat the apparatus before the layers were added because we wanted to observe the effects of our magma chamber analog (hot plate) on our ice layer thickness and not the effects of the ambient room temperature. Preheating allowed the hot plate to reach the maximum temperature desired by the time the layers of sand and ice were put in place. Once the hotplate was operating and the apparatus was filled with materials, the subsequent events involving deformation and, in some cases the collapse of a steep sided crater after about an hour of elapsed time, were observed and captured on camera. In the following sections the characteristics of each set of experiments are described in detail. A summary of these experiments can be found in Table 3. Figure 7 is a graph of scarp height of the experimental craters and the thickness of the ice layer. This ratio was not found to be one to one; the scarp was always lower than the thickness of the ice layer.

6.3 Model Set 1: (No Extension)

The first set of experiments simulated patera formation in a static environment with no directed stress. Similar materials were used in all model runs, but we varied the volatile layer thicknesses. Observable surface deformation in every run began with concentric fracturing
Table 3: Description of experimental results selected from selected experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Volatile thickness$^2$ (cm)</th>
<th>Paddle$^3$</th>
<th>Time$^4$ (s)</th>
<th>Crater Dimensions$^2$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>5</td>
<td>No</td>
<td>1980</td>
<td>36x30x5</td>
</tr>
<tr>
<td>33</td>
<td>5</td>
<td>No</td>
<td>2400</td>
<td>23x18</td>
</tr>
<tr>
<td>17</td>
<td>7.5</td>
<td>No</td>
<td>1860</td>
<td>10x3x3</td>
</tr>
<tr>
<td>19</td>
<td>7.5</td>
<td>No</td>
<td>1800</td>
<td>23x14x0.5</td>
</tr>
<tr>
<td>37</td>
<td>7.5</td>
<td>No</td>
<td>3060</td>
<td>15x15x4</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>No</td>
<td>2400</td>
<td>18x14x7</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>No</td>
<td>2820</td>
<td>24x22</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>No</td>
<td>2460</td>
<td>31x29x1</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
<td>No</td>
<td>1920</td>
<td>5x2</td>
</tr>
<tr>
<td>21</td>
<td>10</td>
<td>No</td>
<td>3300</td>
<td>17x13x1</td>
</tr>
<tr>
<td>23</td>
<td>5</td>
<td>Yes</td>
<td>3180</td>
<td>10x7</td>
</tr>
<tr>
<td>26</td>
<td>5</td>
<td>Yes</td>
<td>2700</td>
<td>30x2x5</td>
</tr>
<tr>
<td>14</td>
<td>7.5</td>
<td>Yes</td>
<td>2520</td>
<td>3x1x5</td>
</tr>
<tr>
<td>30</td>
<td>7.5</td>
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<td>50x5x7</td>
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<tr>
<td>27</td>
<td>7.5</td>
<td>Yes</td>
<td>2400</td>
<td>7x4x6</td>
</tr>
<tr>
<td>31</td>
<td>7.5</td>
<td>Yes</td>
<td>3060</td>
<td>26x18x4</td>
</tr>
<tr>
<td>28</td>
<td>10</td>
<td>Yes</td>
<td>2820</td>
<td>30x29x3</td>
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<tr>
<td>29</td>
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<td>Yes</td>
<td>2820</td>
<td>31x21x3</td>
</tr>
<tr>
<td>32</td>
<td>10</td>
<td>Yes</td>
<td>2340</td>
<td>32x20</td>
</tr>
<tr>
<td>34</td>
<td>10</td>
<td>Yes</td>
<td>3540</td>
<td>11x9</td>
</tr>
<tr>
<td>36</td>
<td>10</td>
<td>Yes</td>
<td>2820</td>
<td>20x14</td>
</tr>
</tbody>
</table>

1 Experiment numerically refers to a given model run.  
2 Volatile thickness refers to the amount of ice used.  
3 Deformation refers to whether or not the paddle was used to simulate tectonism.  
4 Time refers to the time taken for a collapse to occur.  
5 Maximum crater dimensions refer to the measurement of the two long axes when the experimental crater was at its largest size and third dimension represents scarp height.
Fig. 7: This graph depicts the relationship between the final scarp height of model craters and the thickness of the layer of ice used. The scarp height was measured for each experimental crater and then averaged with other craters in the same ice thickness class (5, 7.5 or 10 cm). The graph shows the ratio of scarp height and ice thickness is not one to one; the scarp height is always less than the thickness of the ice layer.

\[ y = 0.376x + 0.7767 \]

\[ R^2 = 0.9074 \]
followed by sagging, with the absence of a scarp, in the area above the hotplate. This was followed in approximately half of the experiments by collapse and crater formation as the layer of ice either melted or vaporized enough to create instability. The collapse and creation of a crater bounded by a scarp was generally short-lived and sudden. After the collapse steam could be seen emanating from within the crater. Also, ice could be seen, exposed within the walls of the crater. These craters were generally steep-sided and had depths approximately one-seventh their widths with an average long axis of 26 compared with a hotplate diameter of 50 cm (Fig. 8). About 25% of the experimental craters had central plateaus or islands on their floors, indicating differential collapse, with the greatest depth occurring along the crater margin. In some cases, collapse was asymmetric and the crater floor remained attached at the margin like a hinge, similar to terrestrial trapdoor calderas and what we observe at the southern margin of Tupan patera.

Craters were generally circular with some straight and some arcuate margins. After a crater developed, it grew in size as ice in the walls continued to melt and the overlying sand became unstable and collapsed. These collapses were usually in the form of blocks of sand that came to rest on the crater floor but in areas were the sand had dried sufficiently the collapse would occur as a grain flow. When the collapses were in the form of blocks of sand this usually resulted in the formation of terraces around the margin of the experimental crater.

This set of experiments was run using 5 cm, 7.5 cm, and 10 cm of ice. The thicker the layer of ice, the more likely there would be collapse and crater formation. The crater scarp height increased with increasing thickness of ice (Fig. 7). Figure 9 displays images of craters that formed under the experimental conditions of set one. A summary of these experiments and the crater dimensions can be found in Table 3.
Fig. 8: This histogram displays the frequency of various experimental crater diameters. The average diameter for experimental craters was found to be 26 cm.
Fig. 9: A series of photographic sequences that show surface deformation over time. These experiments were static (the paddle was not moved). The left column displays results from an experiment that included a 5 cm thick layer of ice. This crater collapsed to form islands on the floor of the crater. The middle column displays results from an experiment that used 7.5 cm of ice. This crater collapsed in a manner similar to terrestrial trapdoor calderas as the crater floor is merged with the uncollapsed surface on the left side. The right column displays the results from an experiment that used 10 cm of ice. Note that with increased amount of ice the crater scarp becomes more defined and steep, and the crater itself is larger. The white circle denotes the approximate location and size of the hotplate beneath the apparatus.
6.4 Model Set 2: (With Extension)

The second set of experiments simulated patera formation with the use of the paddle to create an environment of active extension. In these experiments the apparatus underwent 3 cm of extension, experiencing 3.4% strain over the course of the experiment. The experiments started by initiating extension by means of the wheel and paddle. Throughout ongoing extension, surface deformation began with linear fractures that formed perpendicular to the direction of extensional motion. This was followed by concentric fracturing and then sagging in the area over the hotplate. Fractures were much more deep and pronounced than in the set that did not use the paddle to create regional stresses. In most experiments there was collapse and crater formation. In these experiments, the craters appeared to collapse cohesively along preexisting fractures formed recently by the extension. This often resulted in the formation of a straight segment that extended along one side of the crater, which became more pronounced as paddle motion continued. Craters also exhibited features similar to those that did not experience tectonic simulation, such as islands, trapdoor morphologies, terraces, and blocks of sand collapsing along crater margins. Craters within this set of experiments were often smaller than those in the set with no tectonic simulation, and collapse occurred much earlier (Table 3).

This set of experiments was run using 5 cm, 7.5 cm, and 10 cm of ice. Similar to the experiments that underwent no regional stresses, the greater the amount of ice, the more likely collapse and subsequent crater formation were to occur. Similarly, scarp height typically increased with increasing thickness of ice (Fig. 7). Although the ratio of ice thickness to scarp height was not found to be one to one, there was a measurable increase in average scarp height in experiments that used a greater amount of ice. This is probably because as a greater amount of ice became melted, the overlying layer of sand experienced more displacement, thus creating a
steep scarp. Figure 10 displays images of craters that formed under the experimental conditions of set two. A summary of these experiments and the crater dimensions can be found in Table 3.

7. Map and Model Comparison/Discussion

The craters and surrounding regions in our analog experiments exhibit a variety of features observed in paterae on Io (Radebaugh et al., 2001; Williams et al., 2002, 2004, 2007; Keszthelyi et al., 2004). These features include steep-sided collapse features, craters that range from rounded to elongate, central islands (Fig. 11), trapdoor collapses (Fig. 12), terraces, straight and arcuate segments (Fig. 13), linear and concentric fracturing, and mass wasting along the bounding scarp. Many of these features are seen at Tupan Patera, specifically.

One obvious similarity between Tupan Patera and the craters in our experiments is the presence of an island (Fig. 11). It appears that wet sand retained its coherence, enabling an island to form. Perhaps as volatiles are heated and then liberated, the crust becomes weakened in certain locations and gradually collapses in a cohesive manner, and in some cases produces an island. The presence of islands may be due, in part, to structural or compositional anisotropies in the crust. The heated fluids and volatiles in the model, and by analogy the magma at paterae, may be directed towards areas with more volatiles or faulting, which could leave an island remaining near the center. Further, it may be possible that islands are areas where there are relatively less volatiles or a higher concentration of silicates. Sulfur frosts on Io are not necessarily deposited uniformly and, therefore might become incorporated into the crust with unequal distributions. Islands may remain as areas that experienced less displacement during patera formation due to a higher concentration of silicates vs. sulfur volatiles. Another factor that may contribute to the presence of islands is that lava lake activity tends to be greater along the
Fig. 10: A series of photographic sequences that show surface deformation with time. These experiments simulated patera formation during extension. A movable paddle on the right was extended to the right. The left, middle, and right columns display the results from experiments that used 5, 7.5, and 10 cm of ice respectively. Notice that these experiments have linear fractures in addition to the concentric fractures seen in the static experiments. In the set of experiments that used 10 cm of ice, the crater collapsed along preexisting fractures that formed as a result of paddle movement creating the straight margin seen on the right side of the crater. The white circle depicts the approximate location and size of the hotplate beneath the apparatus.
margins, which would result in relatively less activity near the center. This might leave any collapsed material in the center relatively unchanged in comparison to the margins having experienced less venting of volatile layers within the island. Finally, differential collapse could result in the creation of an island.

Our map of Tupan Patera suggests that the central island may have been aided by trapdoor collapse. The island appears to be loosely attached to Io’s crust at a point on the southern end, where lava flows that originate outside of the bounding scarp extend onto the island. In some of our experimental results (Fig. 12), a trapdoor morphology could be seen, strengthening this interpretation for Tupan Patera.

Tupan exhibits a straight segment along its southern margin. Several of our experimental craters formed straight segments (Fig 13). In the case of the experiments with no tectonic simulation this probably formed as a result of the failure of the cohesive layer of wet sand. In the case of the experiments with tectonic simulation these straight segments formed first as extension produced linear fractures, along which the growing instabilities in the crust could propagate, leading to collapse. Tupan Patera, along with other paterae such as Tvashtar Patera D, Thomagata, Prometheus, Loki and many others exhibit a straight segment on one of their margins. It is estimated that approximately 50% of paterae exhibit this feature (Radebaugh et al., 2001) and our map of Tupan Patera and experimental models support the hypothesis that these straight margins may form due to tectonic components (Jaeger et al., 2003; Radebaugh et al., 2004).

Several paterae on Io have in proximity what may be considered to be a sapping scarp. Such a scarp can be seen northeast of Tupan, though this feature runs outside the boundary of the
Fig. 11: Example of an experimental crater that formed by differential collapse of cohesive materials, resulting in an island seen resting on the crater floor. Approximately 25% of our experimental craters exhibited islands on their floors.
Fig. 12: Several of our craters formed in a manner similar to a terrestrial trapdoor caldera with the floor of the crater connected to the surface by a hinge. The above two images depict this with arrows pointing to the area that acted as a hinge. The bottom crater also exhibits an island on its floor. The island within Tupan Patera may have formed in a similar manner, with the hinge being located on its southern margin.
high-resolution image and we cannot see its full extent. Another example can be seen in the Tvashtar Paterae, which are surrounded by a complex, elevated plateau. In our experimental apparatus we observed an exterior fracture system outside of the bounding scarp of the experimental craters (Fig. 9 and 10). This fracture system resulted in a gradual decrease in elevation with increasing proximity to the crater and may be similar to what we observe around some paterae on Io.

Finally, our comparative studies between our map and model have contributed to the cross section animation of Tupan Patera (Fig. 14). Also it is worth noting that our experimental model is simple in nature, yet it has reproduced many morphological features seen in a variety of paterae. While we understand that the actual conditions on Io are much more complex, we have concluded that the role of a crust that is interlayered with silicates and volatiles is of great significance in patera formation.

8. Geologic History

The geologic history of the Tupan region, as informed by the geologic map and the experimental models, began with the formation of the plains materials through emplacement as multiple overlapping lava flows interspersed with volatiles, mainly sulfur and $SO_2$, deposited from regional plume eruptions. This unit was then degraded by $SO_2$ sapping, mass wasting, and contact with warm silicates or sulfur flows. This degradation is likely ongoing and has taken place continuously over the formation of the region.

The formation of Tupan Patera occurred when rising magma formed a high-level, laterally extensive, subsurface magma chamber that then heated overlying volatile layers within
Fig. 13: Many of our craters exhibited straight margins. Both of the paterae (a and b) formed during experiments where the paddle was used. In both cases fractures formed initially and then collapse of the crater occurred along the fractures. In the above two images the arrows point to the straight margins, notice the preexisting fractures that can be seen extending beyond the straight margins.
the plains materials, creating instability and faulting (Fig. 14a). The plains materials overlying the magma chamber collapsed cohesively, creating a depression, or incipient patera. Continued, gradual collapse, and perhaps subsurface lateral extension of the magma chamber, further enlarged the patera. The faults around the rim of the patera may have directed magma ascension, causing lava to erupt preferentially around the rim of the patera. As magmatism continued, most remaining volatiles within the collapsed patera floor were thermally removed, through sublimation or liquification. Parts of the patera floor, particularly near the rim of the patera, now denser than the underlying magma chamber because of removal of volatiles, would then founder and sink further (Fig. 14b). The western and eastern portions of the floor of Tupan may be regions that have further sunk, or in other words, stiped blocks. One the east, lavas erupted onto this stiped block, forming overlapping flows or a lava lake. Black patches in the western floor region may be areas where magma ascension is being facilitated and melting through the block, creating a mottled appearance, and indicating this portion of the patera is less mature than on the east, where magma has successfully risen and filled in the floor (Fig. 14c). In the center of the patera, an island was stranded, sinking below the level of the surrounding plains, but not as far as the portions of the patera near the margins. The island, in its location at the patera center, was more protected from the excessive heat and magmatism that occurred along the fractures at the patera margins.

The bright flow materials were likely the next unit to develop. Two visible flow events occurred, the older one now having a lower albedo and less defined contact with the plains unit and the younger one now having a higher albedo and sharper contact. These bright flows may have formed as country rock was melted in fissures within the patera wall (Fig. 14d).
The lava in the patera floor may have filled the patera to varying levels over time, as indicated by the thin black deposit found along most of the patera walls that indicates a high lava line. The rim of the patera was likely widened as volatile layers in the scarp were melted, creating instability and collapse, as evidenced by slump blocks along the northern margin and the arcuate nature of the rim morphology, and is consistent with the morphology of other paterae. This process may also be partially responsible for some of the bright patera floor materials. The red and green patera floor units likely resulted from heating of volatiles within the crust, causing them to melt and flow across the floor. The red patera floor units may have initially been yellow in color and then may have been coated by red diffuse deposits. Alternatively, the red patera floor units could have initially been red in color as they flowed onto the patera floor. The contact of the sulfurous red patera floor with the silicate-dominant dark patera floor then resulted in the green patera floor materials, either in a chemical or spectral mixture (Fig. 14e).

The red flows and diffuse deposits appear to cover most features and are thus the most recently emplaced. Here at Tupan, the red materials are deposited in relatively thick concentrations compared to other regions of Io. This indicates that the red diffuse materials around Tupan Patera may form as the result of episodic plume activity that has been ongoing since the initial collapse and formation of the patera. The red flow materials most likely formed as the red diffuse deposits precipitated onto the surface and reached concentrations that allowed the materials to flow (Fig. 14f). Some of the red flow materials appear to have been truncated at the margin of the central island, indicating they may have been deposited prior to the collapse of the floor to the north. This is difficult to imagine if the red deposits disappear over the course of weeks, but it best explains the morphology in that region.
We compared this geologic history, based on conclusions drawn from our mapping, to our experimental model in order to develop a cross section animation of Tupan Patera (Fig. 14). This cross section is meant to serve as a theoretical explanation for the formation of Tupan Patera.

9. Summary and Conclusions

We have created a geologic map of the Tupan region of Io using a Galileo image to understand the evolution of paterae on Io. Our map indicates that Tupan is a complex volcano, with a history involving lava flows or a lava lake, and with regions of varying levels of current magmatic and volcanic activity. The presence of red diffuse deposits around the margins of the patera suggests that Tupan was recently active at the time the image was taken. Individual lava flows in the region, generally yellow in color, are likely a result of localized melting of the country rock by the heat within the patera and appear, from variation in albedo, to be different ages. The island of the patera is possibly the result of the failure of a brittle crust as sulfur volatiles were melted or vaporized by magma rising along structural and compositional anisotropies in the crust which leads to a differential collapse with collapse concentrated on the margins of the patera. Evidence for this interpretation is that the island appears to be elevated and is similar in color and morphology to the plains unit, and may also be connected to the surrounding plains on its southern margin, similar to a trapdoor caldera.

The creation of a map of Tupan Patera is a complement to other regional maps and global maps of Io and other mapping projects that are underway or yet to come. Together these maps will allow for further understanding and interpretations to be made in regards to the geologic processes occurring on Io, both on local and global scales. Our model experiments are the first
Fig. 14: Cross section of Tupan Patera showing its sequential development. Colors correlate with those found in the geologic map (Fig. 5). This cross section has been vertically exaggerated in order to show both large and small-scale features of paterae volcanism.

a. Magma begins to rise from a subsurface magma chamber heats the overlying layered crust and is directed into sills and dikes by anisotropies in the crust.

b. Layers of sulfurous volatiles are melted or vaporized by magmatic heat thinning the crust over the magma chamber and initiating collapse. Faulting begins to accommodate removal of volatiles. Portions of the patera floor may increase in density in areas where more volatiles are removed from it than other parts of the patera floor and sink as a stoped block into the magma, as seen on the eastern side of the crater. Sulfur vents as diffuse vapor.

c. Silicate lava flows erupt onto the thinned crust in the eastern patera (forming dark patera floor materials). Lava continues to melt through any remaining crustal materials that exhibit themselves as bright patera floor. On the western side of the crater a portion of the crust begins to break off. The island remains in the center, elevated. This is perhaps due to it being an area with relatively fewer volatiles or perhaps volcanism is focused around the edges of the patera due to structural features such as faulting. As the crust on the west side of the patera begins to break off and sink, the lava begins to melt through it and create several lava lakes.

d. The stoped block continues to sink and areas where lava lakes formed begin to develop a cooled crust. This may be an explanation for the mottled appearance on the western side of the patera. Bright flows form as country rock is melted in fissures within the patera wall. Red patera floor materials appear as flows emanating from the island and patera walls.

e. The red patera floor interacts with the silicate crust of the dark patera floor and begins to form a rim of green patera floor materials. Sulfur within the magma becomes volatilized by heat and released pyroclastically.

f. The volatiles condense at the surface and form red diffuse deposits and, in areas with high enough concentration, red flows.
(known) scaled analog models to be performed in terms of Io volcanism and we hope future studies will be carried out to further this work. The geologic history we constructed for Tupan Patera may prove useful in the context of other paterae on Io as well.

We have attempted to further constrain patera formation by comparing our geologic map to experimental models. Our analog paterae exhibit several features that can be observed in actual paterae on Io. These features include: straight margins, terraces, trapdoor collapses, landslides, and islands. Our model supports current theories that paterae form as magma heats layers of volatiles in Io’s crust which results in instability and subsequent collapse of the overlying materials. The interpretation of the island as a less collapsed portion of the upper crust is consistent with our geologic map findings.

A series of cross sections for the evolution of Tupan Patera incorporates all of the findings from our geologic map and experimental models. Future work on constraining patera formation would benefit from further experimentation, especially with the addition of dry ice, a simulated high-level magma chamber, and the use of multiple layers of ice and sand to more accurately simulate the materials and environments that lead to patera formation. Future comparative studies will further develop our understanding of paterae volcanism and how Io releases its internal heat.
REFERENCES


