Spatial distribution of ice blocks on Enceladus and implications for their origin and emplacement

Hilary R. Martens a,⇑, Andrew P. Ingersoll a, Shawn P. Ewald a, Paul Helfenstein b, Bernd Giese c

a Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA
b Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14853, USA
c German Aerospace Center, Institute of Planetary Research, Berlin, Germany

Article history:
Received 3 July 2014
Revised 15 September 2014
Accepted 17 September 2014
Available online 11 October 2014

Keywords:
Enceladus
Satellites, surfaces
Geological processes
Ices

Abstract
We have mapped the locations of over 100,000 ice blocks across the south polar region of Saturn’s moon Enceladus, thus generating the first quantitative estimates of ice-block number density distribution in relation to major geological features. Ice blocks were manually identified and mapped from twenty of the highest resolution (4–25 m per pixel) Cassini Imaging Science Subsystem (ISS) narrow-angle images using ArcGIS software. The 10–100 m-diameter positive-relief features are marginally visible at the resolution of the images, making ice-block identifications difficult but not impossible. Our preliminary results reveal that ice blocks in the southern hemisphere are systematically most concentrated within the geologically active South Polar Terrain (SPT) and exhibit peak concentrations within 20 km of the tiger-stripe fractures as well as close to the south pole. We find that ice blocks are concentrated just as heavily between tiger-stripe fractures as on the directly adjacent margins; although significant local fluctuations in ice-block number density do occur, we observe no clear pattern with respect to the tiger stripes or jet sources. We examine possible roles of several mechanisms for ice-block origin, emplacement, and evolution: impact cratering, ejection from fissures during cryovolcanic eruptions, tectonic disruption of lithospheric ice, mass wasting, seismic disturbance, and vapor condensation around icy fumeroles. We conclude that impact cratering as well as mass wasting, perhaps triggered by seismic events, cannot account for a majority of ice-block features within the inner SPT. The pervasiveness of fracturing at many size scales, the ubiquity of ice blocks in the inner SPT, as well as the occurrence of linear block arrangements that parallel through-cutting crack networks along the flanks of tiger stripes indicate that tectonic deformation is an important source of blocky-ice features in the SPT. Ejection during catastrophic cryovolcanic eruptions and condensation around surface vents, however, cannot be ruled out. Further, sublimation processes likely erode and disaggregate ice blocks from solid exposures of ice, especially near the warm tiger-stripe fractures. The relative paucity of blocks beyond the bounds of the SPT, particularly on stratigraphically old cratered terrains, may be explained in part by mantling of the surface by fine particulate ice grains that accumulate over time.

© 2014 Elsevier Inc. All rights reserved.

1. Introduction

Enceladus, an icy satellite of Saturn approximately 500 km in diameter, orbits at a distance of 3.94 Saturn radii (R_S) and currently exhibits both cryovolcanic and tectonic activity across its geologically youthful South Polar Terrain (SPT) (Porco et al., 2006; Spencer et al., 2006; Spencer and Nimmo, 2013). Hot thermal anomalies and active geysers emanate from four large parallel fractures, nicknamed the “tiger stripes,” which extend over 100 km in length and cut the SPT along strike directions of ~30–45° west of the sub-Saturn meridian (Porco et al., 2006; Spencer et al., 2006; Abramov and Spencer, 2009; Spitale and Porco, 2007).

Enceladus’s surface morphology differs markedly from region to region as well as from the other saturnian satellites (Porco et al., 2006; Spencer and Nimmo, 2013). Cratering statistics for various terrains on Enceladus suggest a range of discrete ages, perhaps indicating discrete episodes of geologic activity throughout Enceladus’s history (Porco et al., 2006). The northern hemisphere of Enceladus as well as mid-latitude zones on the Saturn-facing and anti-Saturn sides are characterized primarily by heavily cratered terrain with ages in the range of 1–4 Ga or older (Kirchoff and Schenk, 2009).
Mid-latitudes on the leading and trailing hemispheres exhibit substantial tectonic deformation, with ages c. 10 Ma – 2 Ga (Kirchoff and Schenk, 2009). The SPT, in contrast, is effectively devoid of craters and may be as young as 0.5 Ma or younger (Porco et al., 2006). Porco et al. (2006) first reported on the observation of discrete positive-relief features, inferred to be “ice boulders,” scattered across Enceladus’s south polar region in high-resolution images captured by Cassini’s Imaging Science Subsystem (ISS). The highest-definition Cassini images suggested that extensive fields of ice boulders might be largely restricted to the SPT, an active tectonic region that is bounded by a prominent circumpolar scarp at ~55°S latitude. Since the term boulder traditionally refers to a rock rather than an ice formation, we favor the term “ice block” to prevent any confusion, but we are referring to the same morphological feature. Moreover, we note that the term “ice block” should be interpreted broadly here to mean either an isolated unit in loose contact with the ground or an exposure of blocky ice rooted to an outcrop (Fig. S1), since we are unable to differentiate between the two with certainty at the resolution of the images.

Based on the absence of craters and high number density of ice blocks in the SPT, Porco et al. (2006) postulated that the ice blocks are not crater ejecta, but rather the result of tectonic or seismic processes. Furthermore, Landry et al. (2014) found that the size-frequency distribution of ice blocks observed in six ISS images of the SPT is reminiscent of boulder fields on Earth and Mars that are also unrelated to cratering processes. Here we present the first detailed spatial analysis of the ice-block features.

Rock boulders on planetary bodies such as the Moon, asteroids, and the martian satellites are quite common in our Solar System. Most non-terrestrial boulders are likely produced during impact events (Lee et al., 1996, 1986; Chapman et al., 2002; Bart and Melosh, 2010; Dombard et al., 2010; Veverka et al., 2001). Rock boulders, however, may additionally result from catastrophic disruptions of a body during formation, as proposed for Asteroid 25143 Itokawa (Saito et al., 2006; Fujiwara et al., 2006; Michikami et al., 2008), or periglacial activity, as on Mars (McEwen et al., 2007).

The active tectonic and cryovolcanic environment at Enceladus, however, differs significantly from the relatively dormant asteroids and rocky satellites of the inner Solar System. Thus, the mechanism(s) creating the blocky-ice features on Enceladus could potentially have important implications for the dynamics of the geologically active SPT. Yet, apart from an awareness of their existence, little is known about the ice blocks on Enceladus.

Our goal here was to characterize the spatial distribution of the ice-block features by mapping their locations in high-resolution images across Enceladus’s southern hemisphere. We also introduce several hypotheses for the origin and emplacement of the ice-block features, examining each mechanism in turn and in light of our observational results.

### 2. Methodology

To map the distribution of ice-block number density in relation to major geological features across Enceladus’s southern hemisphere, we acquired Cassini ISS images of Enceladus’s surface from the publicly accessible Planetary Data System (PDS) archives, sponsored and maintained by NASA’s Science Mission Directorate. Since the size range of the ice blocks (~10–100 m in diameter) renders the small features nearly or completely imperceptible at the resolution of most Cassini ISS images, we restricted our study to include only images of the highest resolution (4–25 m per pixel) and greatest quality (i.e., limited smearing and good illumination). We thus obtained a catalog of twenty ISS narrow-angle images, suitable for ice-block mapping. The label numbers, acquisition dates, approximate resolutions, and geographic coordinates of the twenty images are listed in Table 1.

Using the Integrated Software for Imagers and Spectrometers (ISIS) version 3.0 package, we converted raw PDS image files into ISIS cube format, attached spacecraft timing and positioning information (SPICE kernels) to each cube file, and performed basic radiometric corrections. We made minor modifications to the camera pointing using the ISIS function qte to improve alignment between the images in our catalog as well as relative to wide-angle images of the south polar region. We then mapped each updated cube file into a polar stereographic projection and imported the images into ArcGIS for analysis.

Select regions from nine of the twenty images in our catalog are shown in Figs. 1–3. Note that the small-scale positive-relief features, which we identify as ice blocks, are generally ubiquitous in most of the images (Figs. 1, 2A, C and 3C). Moreover, ice blocks are present on ridges as well as in areas of lower topographic relief (Figs. 1, 2A, C and 3C). Two of the images (Fig. 2B and D), which are furthest from the south pole and tiger-stripe fractures, are relatively devoid of ice blocks. The map view locations of the images are shown in Fig. 3A for context.

Since some of the images show a few widely spaced ice blocks scattered across an otherwise smooth terrain (e.g., Fig. 1D), we speculate that the positive-relief features in these examples might represent discrete blocks rather than exposed outcrops of rough and hummocky terrain (see Fig. S1). In contrast, other images show an apparent alignment of ice-block features along fracture networks adjacent to the tiger stripes, which might instead indicate exposed pinnacles jutting out from partially buried rough and hummocky terrain (Fig. 11).

Fig. 3 illustrates the steps we took to map the ice-block features and compute number densities. Within ArcGIS, we partition each image into several non-overlapping regions, which we henceforth refer to as “mapping sectors” (Fig. 3D). To avoid including shaded regions in our density computations, we define the boundary of each mapping sector such that illuminated areas are outlined tightly. The mapping sectors have a mean area of approximately 7 km², with a standard deviation of 8 km². Whereas smaller regions enhance our spatial resolution of the number-density distribution, larger regions reduce noise in the counting statistics. Thus, we endeavored to remain reasonably consistent with the sizes of our

### Table 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Acquisition date (yyyy-ddd)</th>
<th>Resolution (m/pixel)</th>
<th>Latitude, longitude (°, 'W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1500063766</td>
<td>2005-195</td>
<td>3.7</td>
<td>73, 353</td>
</tr>
<tr>
<td>N1597182368</td>
<td>2008-224</td>
<td>8.0</td>
<td>77, 86</td>
</tr>
<tr>
<td>N1597182401</td>
<td>2008-224</td>
<td>11.5</td>
<td>78, 79</td>
</tr>
<tr>
<td>N1597182434</td>
<td>2008-224</td>
<td>15.0</td>
<td>78, 73</td>
</tr>
<tr>
<td>N1597182467</td>
<td>2008-224</td>
<td>18.4</td>
<td>80, 57</td>
</tr>
<tr>
<td>N1597182500</td>
<td>2008-224</td>
<td>21.8</td>
<td>82, 23</td>
</tr>
<tr>
<td>N1597182533</td>
<td>2008-224</td>
<td>25.3</td>
<td>82, 32</td>
</tr>
<tr>
<td>N1604166937</td>
<td>2008-305</td>
<td>8.7</td>
<td>86, 319</td>
</tr>
<tr>
<td>N1604166970</td>
<td>2008-305</td>
<td>12.1</td>
<td>87, 301</td>
</tr>
<tr>
<td>N1604167003</td>
<td>2008-305</td>
<td>15.6</td>
<td>89, 108</td>
</tr>
<tr>
<td>N1604167059</td>
<td>2008-305</td>
<td>21.4</td>
<td>80, 263</td>
</tr>
<tr>
<td>N1604167092</td>
<td>2008-305</td>
<td>24.9</td>
<td>68, 267</td>
</tr>
<tr>
<td>N1637462909</td>
<td>2009-325</td>
<td>16.4</td>
<td>78, 30</td>
</tr>
<tr>
<td>N1637462964</td>
<td>2009-325</td>
<td>14.4</td>
<td>77, 31</td>
</tr>
<tr>
<td>N1637463028</td>
<td>2009-325</td>
<td>12.3</td>
<td>77, 33</td>
</tr>
<tr>
<td>N1637463631</td>
<td>2009-325</td>
<td>12.2</td>
<td>52, 32</td>
</tr>
<tr>
<td>N1637463515</td>
<td>2009-325</td>
<td>17.5</td>
<td>63, 32</td>
</tr>
<tr>
<td>N1637463615</td>
<td>2009-325</td>
<td>21.6</td>
<td>68, 34</td>
</tr>
<tr>
<td>N1660432760</td>
<td>2010-225</td>
<td>16.6</td>
<td>79, 63</td>
</tr>
<tr>
<td>N1660432914</td>
<td>2010-225</td>
<td>19.9</td>
<td>77, 81</td>
</tr>
</tbody>
</table>
mapping sectors at several square kilometers, but nevertheless are limited by the spatial geometry of the illuminated areas. With the mapping sectors defined, we then identified and recorded the locations of all individual ice-block features within each mapping sector (Fig. 3E). Number densities are subsequently computed by dividing the total number of ice-block counts within a mapping sector by the area of the sector.

Ice-block counting is a subjective process, akin to crater counting (Kirchoff and Schenk, 2009), particularly since the ice blocks are only just visible at the resolution of the images; hence, to...
remain consistent throughout the analysis, a single one of us (HRM) hand-picked all of the ice blocks identified in this study. To guide our visual selection of ice blocks, we used the Sun location (or Saturn location, when the Sun was below the horizon) to identify appropriate shadows adjacent to clusters of at least 3–4 bright pixels. Where shadows were not well defined, we made a best effort to visually assess isolated clusters of bright pixels, based on surrounding terrain and similarity to other well defined ice blocks.

To account for disparities in ice-block visibility due to the range of spatial resolutions in our image catalog, we calibrate our number densities empirically. Using twelve pairs of overlapping images, we examined the relationship between average ice-block number density and image resolution. Fig. 4 shows ratios of ice-block number density versus ratios of image resolution in a log–log plot for each overlapping image pair. The data exhibit a linear relationship in log–log space given by:

$$\log_{10}\left(\frac{D_1}{D_2}\right) = x\log_{10}\left(\frac{v_1}{v_2}\right) + \beta;$$

where $D_1$ is the ice-block number density of the first image in an overlapping pair, $D_2$ is the ice-block number density of the second image, $v_1$ is the resolution of the first image, $v_2$ is the resolution of the second image, and $x$ and $\beta$ are empirically derived parameters from the linear regression analysis. The least-squares fit produces a slope, $x$, of $-2.18 \pm 0.46$ and a coefficient of determination ($R^2$) equal to 0.93. Uncertainties in the slope were determined by estimating maximum and minimum slopes about the mean based on 1-sigma standard deviations at the end points (dashed lines in Fig. 4).

Fig. 3. Methodology used to map the ice-block features within ArcGIS. (A) Polar stereographic projection of Enceladus’s South Polar Terrain (SPT). The location of our example image (panel B) is shown as a red star. Yellow and white dots identify the locations of the images shown in Figs. 1 and 2, with labels indicating the specific panels. The dashed white circle on the map denotes 60°S latitude. The sub-Saturn meridian is at top of page. (B) Image N1597182388, which we use to demonstrate our methodology. The red box indicates the magnified region examined in panels C, D, and E. (C) Magnified version of the selected region from the full image (red box in panel B). The orange arrow denotes the direction of sun illumination. (D) Illuminated areas have been outlined (green lines) to form the individual “mapping sectors.” Only one complete mapping sector is visible, with the tip of a second mapping sector appearing towards the bottom of the image. (E) Within each mapping sector, we identify and mark individual ice blocks, depicted by the pink dots. The number of ice-block counts (pink dots) within each mapping sector (green bounded region) yields our number density estimate for each mapping sector. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Relationship between mean ice-block number density ratios and image resolution ratios for twelve overlapping image pairs used in our study. The data exhibit a linear trend in log–log space, with a slope of $-2.18$ and an intercept close to zero. As an example, the data point corresponding to a log$_{10}$ mean ice-block number density ratio of $-1$ is derived from images N1597182533 (25.3 m/pixel) and N1604166937 (8.7 m/pixel), which partially overlap. In this case, the mean ice-block number density for the lower resolution image, within the region of overlap, is $-27$ blocks per square km and the mean ice-block number density for the higher resolution image is $-300$ blocks per square km. The solid black line represents the best fit to the data from linear regression analysis. The dashed lines represent maximum and minimum slopes computed between the fitted values at the endpoints $\pm 1$ standard deviations. The fit is used to calibrate number densities in a relative sense, whereby number densities observed for our lower resolution images are corrected to reflect what we would expect to observe at higher resolutions.
Overlapping images of the same resolution should theoretically produce identical number densities; hence, the intercept term, $b$, should be zero in the ideal case. From the fit, we obtain a value of $b = 0.02$, which is very close to zero and therefore encouraging.

If the ice blocks ranged from 10–100 m in diameter, then image resolutions of 5 m/pixel would be sufficient to resolve all ice blocks. Smaller ice blocks likely exist, but we cannot resolve them with our current image database. Hence, it must be stressed that our empirical formula calibrates lower-resolution images relative to higher-resolution images in our catalog, specifically over the range of ~5–25 m/pixel.

Thus, we can calibrate the densities for each mapping sector, relative to a reference resolution determined by the highest-resolution images in our catalog, using the formula:

$$\log_{10} \left( \frac{D_0}{D_C} \right) = -2.18 \log_{10}(\frac{X_i}{5.0}) + 0.02, \quad (2)$$

where $X_i$ is the resolution of the image containing the current mapping sector, $D_0$ is the original number density derived for the mapping sector, and $D_C$ is the calibrated ice-block number density for the mapping sector. Note that the choice of the reference value for the resolution (here 5 m/pixel) will affect the absolute number densities computed.

We then examine the spatial distribution of the calibrated ice-block number densities in relation to major geological features, such as the tiger stripes and dominant plume source regions (i.e. jets) (Spitale and Porco, 2007), by finding the minimum geodesic distance on Enceladus’s surface between the midpoint of each mapping sector and the feature of interest.

### 3. Results

Fig. 5 shows each mapping sector in a polar stereographic projection, colored by its corresponding calibrated number density, from all twenty images used in our study. Warm colors, indicating higher concentrations of ice-block features, are clustered in the vicinity of the tiger-stripe fractures, with maximum number densities observed near the south pole. Ice-block concentrations decrease rapidly away from the polar region, reducing to an average of <20 ice blocks per square km outside the bounds of the SPT at ~55°S latitude (Fig. 2D), corroborating initial observations that the ice blocks are concentrated predominantly within the SPT region (Porco et al., 2006; Landry et al., 2014).

Furthermore, we also note a relative paucity of ice-block features beyond the along-strike limits of the tiger-stripe fractures as well as at the outer edges of the SPT, where the nearest tiger stripe is at least 20 km away (Fig. 5; also, Fig. 2B). In general, the highest concentrations of ice blocks exist within 15° latitude of the south pole, a region we dub the “inner SPT.” The distinct spatial correlation between the ice blocks and the tiger-stripe fractures implies a connection between the presence of the ice blocks and the exceptional geological activity occurring in Enceladus’s south polar region.

Systematic spatial variations in ice-block number density within the bounds of the inner SPT are also observed. For example, ice-block concentrations around Damascus, the easternmost tiger-stripe fracture, are systematically lower than around Cairo and Baghdad, the two central tiger-stripe fractures. Moreover, concentrations also vary along the strike direction of individual tiger-stripe fractures, such as along Baghdad (second fracture from east) where concentrations in excess of 1000 blocks per square km at the south pole gradually reduce to ~500 blocks per square km near the boundary of the inner SPT. No obvious patterns in ice-block concentration, however, exist in the regions between the tiger-stripe fractures.

Magnified views of ice-block concentrations near the tiger-stripe fractures are shown in Fig. 6, illuminating the local spatial variability in ice-block number density across the inner SPT. The high number-density sectors astride the south pole are striking...
and warrant further investigation. Additional high-resolution images targeted at the south pole would help to confirm our observations of elevated ice-block number density in that area, since our current values are derived from a single image (Fig. 2C). Again, it is apparent that ice-block concentrations around the Cairo and Baghdad fractures (Fig. 6A) are significantly higher than concentrations near to the Damascus fracture (Fig. 6B). The discrepancy in concentration on opposite sides of the inner SPT could suggest a preference for ice blocks to be located westward of the tiger-stripe fractures (Figs. 5 and 6B). We have mapped a total of ~15% of the inner SPT, for which high-resolution images are available. Increasing the spatial coverage of high-resolution images across the SPT would contribute greatly to our understanding of ice-block spatial variability.

Fig. 7 shows the distribution of ice-block number densities in relation to major geological features: (A) the tiger-stripe fractures (solid red lines in Fig. 5), (B) the tiger stripes in addition to other major fractures (dashed red lines in Fig. 5), (C) the south pole,
and (D) the plume source regions identified by Spitale and Porco (2007) (gray dots in Fig. 5). Since the tiger stripes and other major fractures extend many km in length, we finely discretize each fracture into a large number of points, compute the geodesic distance from the center of a mapping sector to each point along a fracture, and then select the minimum value. Thus, we obtain a single, minimum geodesic distance measurement for each mapping sector in relation to the tiger stripes as well as the other major fractures. For the plume sources (Fig. 7D), we compute geodesic distances for each mapping sector relative to the geographic coordinates provided by Spitale and Porco (2007). In all distance measurements, we assumed a spherical geometry with a radius of 250 km.

Ice-block number densities, derived for each mapping sector, are depicted as blue dots in Fig. 7. From the scatter in the individual mapping-sector values, we compute mean number densities from a moving average (green diamonds in Fig. 7) as well as 1 standard deviations from the mean values as estimates of uncertainty (gray shaded regions in Fig. 7). The scatter in the individual mapping-sector values reflects uncertainties in the counting statistics, image resolution and clarity (i.e. ice block visibility), and calibration method, as well as actual spatial variations in ice-block concentration (e.g., Figs. 2C and 6).

The high concentration of individual number-density values clustered near to the tiger-stripe fractures and plume source regions (blue dots in Fig. 7) results from the design of the high-resolution imaging campaigns, which target the SPT and the tiger stripes. In other words, a greater number of mapping sectors fall within the bounds of the inner SPT than beyond 15° latitude of the south pole. Based on the scatter in the individual mapping-sector values, we infer a wide range of ice-block number densities across the inner SPT, and only low number densities beyond the tiger-stripe region.

In relation to the tiger-stripe fractures, the ice blocks reach peak mean concentrations at an average distance of approximately 10 km, yet remain overall elevated and steady between 0 and 20 km distance, within our uncertainty limits (Fig. 7A). Since the parallel tiger-stripe fractures are separated by ~30–40 km, the ice blocks are effectively ubiquitous in this region on the whole. Short-scale spatial fluctuations in ice-block number densities between the fractures do occur, but no conclusive pattern emerges with respect to the active fracture margins or jet sources (see also Fig. 8). At ~20 km distance from the tiger-stripe fractures, ice-block number density declines sharply (Fig. 7A). The relatively low concentrations of ice blocks observed beyond 20 km distance come from images at the outer edges of the SPT that lack a neighboring tiger stripe. The few data points at ~80 km distance from the tiger stripes fall outside the bounds of the SPT and indicate a near absence of ice-block features in that region (see also Fig. 2D).

In Fig. 8, we examine ice-block concentration along a plane that spans the region between the Cairo and Baghdad tiger-stripe fractures. Although ice-block number density fluctuates across the plane, no obvious correlation exists between concentration and local distance to tiger-stripe fractures. In other words, we do not systematically observe higher concentrations of ice blocks immediately adjacent to the tiger stripes versus 10–20 km distance away, or vice versa, within our level of uncertainty.

Including additional large fractures in the analysis also does not have a statistically significant effect on the results (Fig. 7B), lending support to the conclusion that ice-block features are not necessarily clustered exclusively along the flanks of major fractures. We note, however, that we have not accounted for the plethora of smaller fractures that cut the SPT; thus, fracturing might still play a role in the presence of the ice-block features.
Additionally, mean ice-block concentrations remain steady up to ~20–30 km distance from the active SPT plume sources identified by Spitale and Porco (2007), before dropping off rapidly (Fig. 7D). As with the tiger stripes and other fractures, no clear pattern emerges between ice-block concentration and the currently active plume sources, other than a broad regional association. Since the fractures and jet sources are clustered near to the south pole and overlap one another within the inner SPT, however, it is difficult to discern the extent to which the various trends might superimpose.

The highest absolute number-densities are observed very close to the south pole, as discussed previously (Fig. 7C). Ice-block concentrations drop from an average of nearly 1500 blocks per square km at the south pole to around 1000 blocks per square km at 10 km distance. A second drop in ice-block number density occurs at ~50 km from the south pole, which corresponds to the boundary of the inner SPT.

In summary, the ice-block features are dramatically most concentrated within the inner SPT region (Figs. 5–7) and the highest number densities occur at the south pole (Figs. 6B and 7C). Ice-cratered terrains to the west and curvilinear patterns of ridges and troughs to the east. In this view, ice blocks that are tens of meters in size are made visible by shadows that they cast. The blocks are not randomly distributed, but rather appear to be most densely concentrated along the crests of ridges. From Fig. 9A, it is clear that significant collections of ice blocks do exist well beyond the SPT region. While the viewing and illumination geometry of the image may cause blocks at lower elevations to be unresolvable, one consistent interpretation of the scene is that the valleys, and any significant amount of blocks that they may hold, are mantled by a thick layer of granular debris or detritus that has accumulated from downslope movement of fine grains over time.

Fig. 9C shows a high-resolution (~4 m/pixel) view of the inside of Ali-Baba crater (55°N, 20°W), located in one of the most heavily-cratered regions of Enceladus. Few ice blocks can be confidently identified in the image. However, outcrops of blocky ice may be present along the cliff walls of prominent parallel fractures, which separate the mesas or terraces that cascade down the slope of the central crater dome. As we discuss later, the absence of ice-block features may be explained by mantling of the surface by fine particulate ice grains that accumulate over time, a phenomenon that may be widespread on the most heavily cratered regions of Enceladus.

In summary, the ice-block features are dramatically most concentrated within the inner SPT region (Figs. 5–7) and the highest number densities occur at the south pole (Figs. 6B and 7C).
blocks are also observed in the outer SPT (55–75°S latitude), but at much lower concentrations (Figs. 5 and 7). Although sparsely mapped, our results indicate that regions beyond the SPT are effectively devoid of ice blocks (Figs. 5 and 7), except perhaps in highly tectonized or cratered terrains (Fig. 9). We note that, in some areas, variations in ice-block number density over short spatial scales can be substantial, with high number-density regions juxtaposed next to smooth terrain (Figs. 2C, 5 and 6). Overall, however, no clear pattern emerges with respect to the tiger stripes and jet sources (Figs. 7 and 8); the tiger-stripe margins, on average, do not contain higher concentrations of ice-block features than between the fractures, and vice versa. Within the inner SPT, the ice-block features seem to occur in substantial and approximately equal numbers atop ridges, on the sides of slopes, as well as in areas of lower topographic relief (Figs. 1, 2A, C, 3C and 11). In some locations, the ice blocks appear to be separate units placed at random (Fig. 1D), whereas in other regions they may be outward-projecting exposures of partially buried rough and hummocky terrain (Fig. 11).

4. Discussion

It is likely that no single geological mechanism can fully account for the presence and distribution of all ice-block features on the surface of Enceladus. Rather, a variety of mechanisms have almost certainly exerted varying influence over the placement and appearance of the ice blocks. Consideration needs to be given not only to modes of emplacement of the blocks, but also to how their appearance and detection can be affected by the local geological environment. The role of each mechanism can change in significance with location and geological setting on Enceladus. Here, we consider the roles of several mechanisms for ice-block formation and emplacement in light of our observational results and geomorphological evidence. The mechanisms include: impact cratering, ejection from fissures during cryovolcanic eruptions, tectonic disruption of lithospheric ice, mass wasting, seismic disturbance, and vapor condensation around icy fumeroles. We also briefly examine processes that might modify the appearance of the ice-block features over time.

4.1. Impact cratering

The ballistic emplacement of ejecta fragments during impact cratering events is a major source of widely scattered small (typically <200 m-diameter) rocky fragments and blocks on airless silicate bodies such as Mercury, the Moon, asteroids, and the martian satellites. These debris fields, attributed to large impacts (Lee et al., 1996, 1986; Chapman et al., 2002), are superficially similar in appearance to the ice blocks observed on Enceladus. Examinations of high-resolution images of Enceladus’s surface, however, show that the SPT is practically devoid of impact craters (Figs. 1 and 2), implying that impact cratering cannot be the primary source of the observed ice blocks (Porco et al., 2006). Moreover, the close association of the ice blocks with the tiger stripes and adjacent fractured terrain also argues against a significant role for impact ejecta in the SPT geological setting (Fig. 7). We therefore reject impact cratering as a primary source of the ice-block features within the SPT. This conclusion is independently supported by a concurrent study of Landry et al. (2014) who examined size–frequency distributions of SPT ice blocks. They found that the best-fit distribution model poorly matched boulder statistics expected from crater ejecta, such as on asteroid Eros. Rather, model fits more closely resembled distributions of terrestrial and martian boulder fields.

4.2. Ejection from fissures during cryovolcanic eruptions

Our second hypothesis involves ejection of ice blocks through suitably wide surface vents during large cryovolcanic explosions, perhaps as new fissures open up. To test the validity of our hypothesis, we can roughly calculate the plume velocities that would be required to entrain ice blocks in the geyser-like jets.
We estimate the saturation vapor pressure of the jets, \( p_v \), as a function of temperature using the ideal-gas version of the Clau-
sius–Clapeyron relationship:

\[
p_v(T) = p_0 \exp \left[ \frac{L}{R} \left( \frac{1}{T_0} - \frac{1}{T} \right) \right].
\]  

where \( p_0 = 611 \text{ Pa} \), \( T_0 = 273.15 \text{ K} \), \( L = 2.83 \times 10^8 \text{ J kg}^{-1} \) is the latent heat of sublimation for water ice (assumed constant), and \( R = 461 \text{ J K}^{-1} \text{ kg}^{-1} \) is the specific gas constant. The density of the vapor, \( \rho_v \), may now be computed from the ideal gas law:

\[
\rho_v = \frac{p_v}{RT}
\]  

Thus, the drag force, \( F_d \), on an ice block entrained in the flow may be written as:

\[
F_d = \frac{1}{2} \rho_v v^2 CD Ab,
\]  

where \( v \) is the velocity of the ice block with respect to the plume, \( Ab \) is the cross-sectional area of the ice block (assumed spherical), and \( CD \) is the drag coefficient. We adopt a drag coefficient of 0.5, which is typical for a spherical object in turbulent flow (Kuete and Chow, 1986).

Equating the drag force with the force due to gravity at Enceladus’s surface, we derive the minimum plume velocity, \( v_{\text{min}} \), required to suspend an ice block in the flow:

\[
v_{\text{min}} = \sqrt{\frac{2m g_s}{\rho_s CD Ab}}
\]  

where \( g_s = 0.11 \text{ m s}^{-2} \) is the gravitational acceleration at the surface of Enceladus and \( m_s \) is the mass of the ice block. Ice blocks are assumed to be spherical and homogeneous, with uniform densities of 920 kg m\(^{-3}\). For realistic plume temperatures, Eqs. (3) and (4) accurately represent plume vapor density, which increases monotonically as a function of increasing temperature. Thus, higher plume temperatures translate into higher vapor densities and, therefore, lower minimum velocities.

We may now compare our computed minimum plume veloc-
ities, required to suspend ice blocks 10–100 m in diameter, with realistic plume velocities in order to determine if ejection from the tiger-stripe fractures during large cryovolcanic eruptions is a viable mechanism for ice-block emplacement. The thermal velocity, \( v_{\text{th}} = \sqrt{\frac{2L}{\rho_s g_s}} \), represents a lower limit on jet speed. The maximum speed of a jet emanating from a nozzle into vacuum is (Landau and Lifshitz, 1959):

\[
v_{\text{na}} = \sqrt{2C_s T}.
\]  

where \( C_s = 1850 \text{ J kg}^{-1} \text{ K}^{-1} \) is the specific heat of water vapor.

Fig. 10 shows the thermal and nozzle velocities, across a temperature range of 230–310 K, superimposed on model curves for the minimum plume velocities required to suspend ice blocks of various diameters. Our simple force balance calculation suggests that plume velocities of order 1 km s\(^{-1}\) or higher are sufficient to suspend and perhaps eject the observed ice blocks via entrainment in the flow. Empirically, recent estimates indicate that collimated jets supplying the gas plume may indeed reach speeds of up to 1 km s\(^{-1}\) or higher (Hansen et al., 2011), lending support to the fea-
sibility of the ejection hypothesis.

Assuming maximum nozzle velocities, plume temperatures in excess of 266 K and 296 K are sufficient to suspend ice blocks with diameters of 10 m and 100 m, respectively (Fig. 10). For sub-vertical vent geometries and jet velocities exceeding the minimum speed required for ice-block suspension in the flow, ice blocks may be ejected outward and blanket the surrounding terrain. Fur-
thermore, if the ice blocks were porous, the reduced ice-block mass would diminish the plume temperatures required to eject them.

The current cryovolcanic activity at Enceladus suggests a possible reservoir of boiling water near to the surface, requiring localized temperatures of at least 273 K or higher (Porco et al., 2006). Although ammonia–water mixtures could reduce the tempera-
tures required to sustain the liquid reservoir, only small amounts of ammonia have been observed in the plume (Waite et al., 2009). Small amounts of N\(_2\) have also been detected, though, perhaps a result of thermal decomposition of ammonia in a very hot (500–800 K) interior (Matson et al., 2007). Moreover, observed solid plume particles are salt-rich, strongly suggesting a direct con-
tact between liquid water in a subsurface ocean and Enceladus’s rocky core (Postberg et al., 2011). Thus, the plume temperatures discussed in connection with Fig. 10 are at least consistent with the observations.

Enceladus’s heat output may also have been higher in the past (Porco et al., 2006). Several lines of evidence point toward episodic tectonic and cryovolcanic activity at Enceladus (O’Neill and Nimmo, 2010; Spencer and Nimmo, 2013), particularly since the current heat output is insufficient to initiate melting but perhaps enough to sustain it (Porco et al., 2006; Spencer and Nimmo, 2013) and the current heat output far exceeds the estimated steady state heat production (Meyer and Wisdom, 2007). Strong varia-
tions in plume activity with orbital phase have also been observed, suggesting that surface fractures open and close from apoapse to periapse (Hedman et al., 2013).

On the other hand, generating cracks wide enough to allow for the passage of ice blocks 10–100 m or larger in diameter is a diffi-
cult task that would require exceptionally high stresses and strain rates (Crawford and Stevenson, 1988). Using a simple scaling rela-
tionship (Crawford and Stevenson, 1988; Ingersoll and Pankne (2010) derived crack widths along the tiger stripes of order 10 cm, which is far smaller than the size of the ice-block features. Moreover, models developed by Abramov and Spencer (2009) indicate that the narrow (<1 m) fractures provide the best model fits to Cassini’s Composite Infrared Spectrometer (CIRS) spectra of the SPT in light of the plume observations: although fractures of order 100 m width provide equally good fits to the CIRS spectra, the corre-
sponding reduction in temperature of the fractures results in...
plume supply rates inconsistent with observation, assuming vapor pressure equilibrium and thermal escape speeds (see also Goguen et al. (2013)). Thus, ejection of the ice blocks by entrainment in the jets seems unlikely under the current conditions, but perhaps plausible during a more active period in Enceladus’s history.

Furthermore, our observations indicate that, on average, ice-block features are ubiquitously spread across the inner SPT with no statistically significant preference for clustering on the flanks of the tiger stripes, jet sources, or other large fractures (Figs. 7 and 8). Thus, for the ejection hypothesis to be valid, it would need to explain the fairly even distribution of blocks between fractures. Jets emerging at various angles and speeds could constitute one possibility. Another possibility, since the inner SPT is heavily fractured, could involve a spatial shifting of jet sources over time. At the very least, the ejection hypothesis is consistent with the overwhelming presence of ice blocks within the inner SPT, where the cryovolcanic activity is concentrated (Figs. 5 and 7).

Due to the sheer number of ice-block features in the SPT, as well as limitations related to image resolution, we have made no attempt in this study to track the size distribution of the ice blocks in relation to the tiger-stripe fractures and jet sources. Future investigations on this front, however, could shed important light on the ejection hypothesis, since larger blocks would tend to land closer to the ejection points.

4.3. Tectonic disruption of lithospheric ice

Fractures of many size scales are ubiquitous on Enceladus and the importance of tectonism in their formation is well established. On Earth, tectonically-induced fracture and erosion are major block-forming agents (cf. Molnar et al., 2007). On Enceladus, tectonic disintegration of surface ice was initially suggested by Porco et al. (2006) as a mechanism for the origin of the ice blocks, which were first observed during a close flyby of Enceladus’s SPT in July 2005 (Table 1, N1500063766).

Tectonic mapping of the active SPT region from more recent imaging data revealed the presence of pervasive compressional, extensional, and shear features (Porco et al., 2006; Spencer et al., 2009; Helfenstein, 2010). As displayed in Fig. 11, our highest-resolution images show that the surface of Enceladus is extensively sliced by quasi-parallel networks of fine-scale fractures that have typical spacing on the order of hundreds of meters.

In many locations, we are unable to discern from the images the extent to which the ice blocks are separate isolated units, in loose contact with the ground, or whether they are solid outcrops of partially buried hummock ice that are anchored to the lithosphere beneath a thin particulate covering. In geological settings where spatial separation of the ice-block features is observed across otherwise smooth terrain (e.g., Fig. 1D), discrete, freestanding blocks are plausible. However, in other settings, such as in the segment of Baghdad Sulcus shown in Fig. 11, linear arrangements of ice-block features parallel a locally pervasive network of cracks that cross-cut the tiger stripe. Fig. 9 also shows block-like features assembled in quasi-linear arrays. In these settings, the blocks appear to be protrusions of hummocky, disrupted surface ice poking through a thin particulate detritus deposit or scree apron.

Moreover, our number-density observations indicate that concentrations of ice blocks are elevated throughout the heavily fractured and ropy terrain of the inner SPT (Figs. 1, 7 and 8), with no special preference for the jet sources or thermally enhanced tiger-stripe margins. Thus, the spatial distribution of the ice-block features across the inner SPT is consistent with a tectonic origin for the blocks.

Diurnal tidal flexing of Enceladus follows a cycle of 1.37 days, yielding maximum shear stresses on the order of 100 kPa derived from published modeling calculations (cf. Nimmo et al., 2007, 2014; Smith-Konter and Pappalardo, 2008; Hurford et al., 2009, 2012; Porco et al., 2014). In comparison, lithospheric ice at typical temperatures on Enceladus has a brittle yield strength on the order of a few tens of kPa (cf. Nimmo et al., 2007; Hurford et al., 2009), and possibly less due to cyclic fatigue introduced by constant flexing of the lithosphere and the concomitant release of seismic energy from shear motion along existing faults. The ubiquity and high spatial-density of cracks seen in ISS images at many size scales (Patthoff and Kattenhorn, 2011) (see also Fig. 11) clearly indicates the extensiveness and importance of lithospheric fracturing across Enceladus’s SPT.

Therefore, we conclude that tectonic disruption of lithospheric ice probably plays an important role in producing hummocky ice formations within the SPT. We do, however, note that ice blocks are effectively absent from at least a few heavily fractured regions beyond the inner SPT (Fig. 2B, D); thus, we infer that the thermal, tectonic and geological conditions within the inner SPT are uniquely capable of producing and/or preserving the observed high concentrations of ice-block features in that area.

4.4. Mass wasting

Mass wasting occurs when debris becomes dislodged from a high topographic relief structure, such as a ridge or hilltop, and moves downslope under the force of gravity. Mass wasting can affect the appearance and placement of icy blocks in two primary ways: (1) downward collapse of large blocks from topographically elevated exposures and/or (2) by settling and downslope movement of fine particulates. The former process would preferentially deposit large blocks at the base of valleys. The latter process may leave rigid block outcrops partially exposed at high elevation while obscuring block-scale relief downslope.
Since the ice blocks are tens of meters in size, the second mechanism seems unlikely to significantly alter the appearance of the ice-block fields in the geologically youthful SPT and cannot explain their origin. Furthermore, although deep valleys are often obscured by shadow, we do not observe a dearth of ice blocks in regions of lower topographic relief (e.g., Figs. 1 and 11), implying that fine particulate matter has not buried them. Similarly, we do not observe disproportionately high concentrations of ice blocks in low topographic relief settings either. Rather, we observe substantial numbers of ice-block features scattered atop ridges (e.g., Fig. 3), which seems to discredit the first mechanism.

Although mass wasting undoubtedly occurs in the tectonically and cryovolcanically active regions of Enceladus, we conclude that mass wasting cannot play a dominant role in producing the substantial number of ice blocks observed across the inner SPT.

4.5. Seismic disturbance

Seismic events, related to tectonism, can significantly affect the placement and morphological appearance of ice blocks in a variety of important ways. Firstly, large seismic events can act as a triggering mechanism for slumps and landslides that disrupt the integrity of the ice lithosphere as well as entrain and redistribute ice blocks during mass wasting events. Nevertheless, ice blocks are widespread atop ridges, on sides of slopes, and in valleys within the SPT, as discussed previously (e.g., Figs. 1, 2, 3 and 11); hence, mass wasting in response seismic events cannot be a dominant mechanism for ice-block emplacement in that region.

Secondly, seismic shaking can act as an agent for mobilizing, settling, and downslope wasting of fine particles. The selective downslope motion of the fine particles could expose blocky outcrops of ice that are more firmly anchored on ridge-crests and which might otherwise be buried from sight, as well as obscure ice blocks downslope. Mobilization of fine particles, however, does not appear to play a commanding role in the inner SPT since ice-block features exhibit no clear preference for regions of higher topographic relief.

Thirdly, violent or repeating episodes of seismic shaking may alter the morphological appearance of ice blocks over time by eroding them into smaller components, as postulated for rock boulders on asteroid Eros (Dombard et al., 2010). It is difficult to discern from the images the extent to which seismic shaking may have eroded ice-block features, but the pervasiveness of ice blocks across the inner SPT indicates that seismic shaking has not been substantial enough to erode them entirely. Seismic shaking might also locally shift individual ice blocks to different locations.

We infer that seismic energy alone cannot account for the majority of ice-block features observed in the SPT in terms of a source mechanism, but seismicity likely produces some blocks during mass wasting events and may also alter the morphological appearance of blocks over time. Alternatively, Landry et al. (2014) proposed that ice blocks entrained in finer-grained debris on Enceladus may rise to the surface from the “Brazil nut effect,” or granular convection: a mechanism by which agitation of the particle mixture, perhaps due to seismic shaking, produces settling and circulation patterns similar to fluid convection (Knight et al., 1993).

4.6. Vapor condensation around icy fumaroles

Our highest-resolution images fail to show morphological details that clearly identify any eruptive vent. The most confident vent identification to date was derived from Cassini’s Visible and Infrared Mapping Spectrometer (VIMS) measurements collected during a single low-altitude pass over Bagdad Sulcus, indicating highly localized thermal emissions emanating from a fissure ~9 m wide (Goguen et al., 2013). Since ice blocks exist over similar size scales, it is worth considering whether the ice-block features might arise from local accumulations of water–ice and condensed volatiles around miniature vents or icy fumaroles.

Parasitic fluid and gas conduits branching away from the large tiger-stripe fractures or from subsurface reservoirs of liquid water and exsolved gases might feed the vents. If the subsurface of Enceladus contains an extensive network of narrow fractures and conduits, then small vents or icy fumaroles may potentially appear in significant numbers across the surface, analogous to geyser and fumerole fields on Earth. In addition to condensation of vapor, liquid water may flash freeze at the surface, creating an icy spatter cone around the vent.

CIRS observations constrain the endogenic power generated by the SPT to be in the range of 15.8 ± 3.1 GW (Howett et al., 2011), which far exceeds the estimated heat output generated by radioactive decay in the silicate core (Porco et al., 2006). The source of Enceladus’s thermal power remains somewhat elusive, but the prevailing theory involves episodic heating through time-varying tidal forcing (Spencer and Nimmo, 2013). We suggest that latent heat released due to condensation of volatiles and liquid water around thousands of small (m- or cm-scale) vents, scattered across the SPT but concentrated near the large tiger-stripe fractures, could also contribute to the observed thermal emissions. Support for this hypothesis may be derived from the CIRS spectra, which suggest significant thermal emissions emanating from the tiger-stripe margins rather than the fractures alone (Spencer et al., 2011, 2006; Abramov and Spencer, 2009; Howett et al., 2011) as well as observations by Cassini’s Ultraviolet Imaging Spectrograph (UVIS) of a diffuse background of plume vapor along the length of the tiger stripes (Hansen et al., 2011).

Tidal deformation, generated primarily by Enceladus’s orbital eccentricity and close proximity to Saturn, correlates with and likely controls the mass flux of the plumes (Hurford et al., 2007; Hedman et al., 2013). Tensile forces generated by the tides might also facilitate the propagation of volatiles through subsurface cracks feeding the small vents. Linear elastic forces that serve to pinch off the cracks at the base could potentially entrain liquid water as well (Crawford and Stevenson, 1988).

To investigate the feasibility of the fumerole hypothesis, we roughly estimate the power generated by latent heat release during assemblage of the vent cones. Given the percentage of surface area that we have mapped within 15° of the south pole (where the vast majority of ice blocks reside) along with the corresponding number of ice-block features located (~10⁶), we approximate the total number of possible vents in the SPT to be of order 10⁶. We have not used the calibrated number densities in our extrapolation, since the absolute numbers are sensitive to the value of the reference resolution; hence, our estimate is considered a minimum for the total number of ice-block features in the SPT.

For 10⁶ vent cones, with a base radius and height typical for ice-block features of 20 m, the total mass would be approximately: 920 kg m⁻³ × 8000 m² × 10 m × 7.4 × 10¹⁰ kg, assuming the blocks are made of solid ice. The energy released during ice-block formation by condensation of liquid water and vapor is computed by multiplying the total mass by the latent heat release: (7.4 × 10¹⁰ kg) × (2.5 × 10⁶ J kg⁻¹) = 1.8 × 10²⁷ J. The 16 GW of endogenic power emission inferred from the CIRS spectra equates to 5 × 10²⁷ J of energy release per year. Thus, if the 16 GW of radiated energy is supplied exclusively by vapor from below condensing at the surface, it would take of order 40 years to create the vent cones, which is much less than the estimated age of the SPT and is therefore plausible.

One significant drawback of the icy-fumerole hypothesis is that the positive-relief features are observed ubiquitously across the SPT, including between the tiger-stripe fractures, where negligible
thermal emissions have been detected (Howett et al., 2011). The theory does, however, explain the relatively high concentrations of ice blocks confined to the inner SPT. We speculate that tectonic motion between the tiger stripes could mobilize vent cones away from the tiger-stripe source region over time, rendering them inactive, or that the ropy terrain in between the tiger stripes (e.g. Fig. 1C) might represent former sites of elevated thermal activity. Thus, icy fumeroles cannot be ruled out as a viable mechanism for producing the ice-block features observed across the SPT.

4.7. Morphological evolution of ice-block features

Since the SPT is a geologically dynamic environment, it is also worth considering mechanisms that might modify the appearance of ice blocks over time. We have already discussed the role that seismic shaking and mass wasting could play in eroding, revealing, or obscuring ice-block features. Another important mechanism involves sublimation of ice, which could disaggregate and erode ice blocks along the ubiquitous small cracks and seams that dissect heavily fractured exposures of solid ice (Porco et al., 2006).

On other icy satellites where sublimation produces dramatic erosion of topographic features, such as on the galilean satellites Callisto and Ganymede (Prockter et al., 1998; Moore et al., 1999) and on the saturnian satellite Iapetus (Spencer and Denk, 2010), solar insolation and the accumulation of dark sublimation lag deposits, which progressively accumulate and further enhance the absorption of radiant energy and heat, drive the sublimation process. Near the south pole of Enceladus, however, the anomalously high surface temperatures, presumably derived from tidal heating, likely drive sublimation more so than solar insolation.

Recent high-resolution data from the Cassini VIMS instrument have detected temperatures as high as 197 ± 20 K at a highly localized site (~9 m in diameter) along Baghdad Sulcus, posited to be an active geyser orifice (Goguen et al., 2013). Slightly lower-resolution (10-km scale) CIRS data, collected during SPT flybys in 2005 and 2006, were consistent with temperatures up to 223 K near the tiger-stripe fractures (Abramov and Spencer, 2009). CIRS data collected during a subsequent SPT flyby in 2010 at km-scale resolution revealed temperatures as high as 177–185 K at the location of Damascus Sulcus, reducing to ~130 K at the flanks (Spencer et al., 2011). Goguen et al. (2013) modeled the sublimation of ice over the temperature range 170–240 K and found that, on timescales of years to decades, sublimation can remove meter-scale thick layers of ice. Thus, in some limited areas of the SPT with concentrated thermal emissions, sublimation can effectively and efficiently ablate and widen the orifices through which geysers erupt.

Beyond the highly localized sites of active geysers and over much broader areas of the SPT, surface temperatures are somewhat lower but still elevated relative to elsewhere on Enceladus; therefore, sublimation erosion might still operate as an agent for disaggregating ice blocks from exposures of fractured ice, albeit over longer time periods. Spencer et al. (2006) determined that typical surface temperatures on Enceladus range from 33 K to 145 K, with a mean of 75 K; the highest temperatures were observed near the south pole.

Using a model for solid-ice sublimation, reportedly accurate from 273.15 K down to at least 110 K (Andreas, 2007; Murphy and Koop, 2005; Pruppacher and Klett, 1997), we determine that temperatures below ~102 K, which characterize most of Enceladus, cannot sublimate a 1 cm-thick layer of ice over the age of Enceladus. Hence, the paucity of ice blocks beyond the boundaries of the SPT may be partly due to colder temperatures and attendant low sublimation rates that allow particulate cover to accumulate. Higher temperatures are sustained only in the south polar regions. Between 102 K and the maximum temperatures observed in the SPT of ~200 K (Abramov and Spencer, 2009; Goguen et al., 2013), the sublimation rate increases by over ten orders of magnitude. At temperatures near 121 K, a 1 cm-thick layer of solid ice sublimes within the 0.5 Ma age of the SPT. At 145 K, a 1 cm-thick layer of ice sublimes in less than 130 years.

Thus we propose that, in combination with ubiquitous fracturing and seismic shaking, sublimation erosion plays a unique role in sculpting local arrangements of ice blocks from highly fractured slabs of ice across the SPT. In this scenario, sublimation erodes and widens pre-existing fractures and joints in exposed solid ice. As particulate residue and small clumps of ice drop off the sublimating ice, perhaps aided by seismic shaking, they accumulate in fluffy debris skirts at the base of the segmented ice slabs. Each slab would likely still be fused at the base to an underlying foundation of solid ice, but as it continues to erode, it evolves into a blocky knob or pinnacle. As in the example of Fig. 11, we suggest that the exposed icy knobs appear as freestanding ice blocks due to the obscuring presence of particulate debris around their bases (Fig. 51).

Even though sublimation may not play a significant role in the morphological evolution of ice blocks beyond the SPT, the downslope movement of fine particulates might be important since the terrains are much older. For example, in the northern fractured terrain of Fig. 9A, downslope retreat of fine particles appears to have uncovered blocks along ridge crests and also obscured block-scale relief at lower elevations. A better example is shown in Fig. 9C, where fractures appear to trap the progressive downslope movement of particulate debris from the central crater dome of Ali-Baba in sluice fashion. Most of the terraced terrain appears to be mantled by a smooth particulate layer. Nearest the top side of the image, higher up-slope of the central crater dome, fine particulates appear to have wasted downslope and engulfed a parallel system of cracks surrounding it (Helfenstein et al., 2013).

Additional mechanisms, such as re-accreting plume material, can also obscure the presence of ice blocks over time. It is well established that vapor and ice particles that erupt from the active SPT often re-accrete onto the surface. The two most significant mechanisms are (1) decoupling of larger particles from the erupting jet streams and subsequent ballistic emplacement near the jet sources (c.f. Ingersoll and Ewald, 2011) and (2) re-capture and accretion of E-ring particles back onto the surface of Enceladus (Verbiscer et al., 2007; Kempf et al., 2010; Schenk et al., 2011). The first mechanism is a local phenomenon of special import to the morphological evolution of blocks around tiger stripes, best evidenced by the Cassini VIMS discovery that grain sizes in the vicinity of the tiger-stripe fractures are approximately twice as large as the global average (Brown et al., 2006). In particular, the adjacent ridges and their outward flanks along the Baghdad Sulcus valley may be partially covered with ice-grain fallout from active jets (Fig. 11).

On a more global scale, albedo and color patterns on Enceladus are consistent with the predicted surface distribution of re-accreted E-ring ice (Schenk et al., 2011; Kempf et al., 2010). The paucity of blocks in ancient cratered regions (c.f. Fig. 9C) could be due not only to normal regolith-gardening processes, but also to the accumulation of E-ring debris. In this interpretation, blocks that might arise from impact cratering and tectonism are buried under an obscuring layer of fine ice grains.

5. Summary and conclusions

We have measured how the spatial density of ice-block features in the southern hemisphere of Enceladus varies in relation to important South Polar Terrain (SPT) geological features. Our most important results are: (1) the ice blocks are systematically most

...
concentrated within the geologically active SPT and predominantly within 15° latitude of the south pole, which we distinguish as the inner SPT. (2) Number densities appear to be highest at the south pole, exhibiting concentrations up to ~1500 ± 450 blocks per square km, (3) Variations in ice-block number density over short spatial scales can be substantial, with high number density regions juxtaposed next to smooth terrain in some areas, and (4) Apart from a broad regional association, average ice-block number densities exhibit no distinct pattern with respect to the tiger-flank fractures or jet sources. We considered these results in the context of photogeological evidence from our highest-resolution images and in relation to different possible mechanisms for the emplacement of blocky-ice features and their subsequent, geological-setting-dependent evolution.

We discover that ice-block fields are not exclusive to the SPT but, in at least one northern hemisphere example, the blocks appear to concentrate at the crests of ridges in a tectonically resurfaced region on the leading-side of Enceladus. We speculate that a majority of ice blocks beyond the SPT arise from impact events, tectonism, and/or mass wasting. Re-accreting plume and E-ring material likely modifies the appearance of the blocks over time. The geological environment within the SPT, however, is unique: heavily fractured and ropy terrain, elevated surface temperatures, and intense cryovolcanic activity. Our results clearly show a spatial correspondence between the highest concentrations of ice-block features and the geologically dynamic inner SPT, implying a connection and potentially distinctive origin for the blocks present in that region.

We conclude that impact cratering is not a significant source of ice blocks in the SPT, but may be elsewhere on Enceladus. We also dismiss seismic disturbance and mass wasting as dominant mechanisms for ice-block origin and emplacement within the inner SPT, though the processes undoubtedly occur and will affect the morphological appearance of the ice-block fields over time. Sublimation processes also act as agents for erosion and disaggregation of ice blocks. We cannot rule out ejection and ballistic emplacement of ice blocks by jet eruptions; however, as a mechanism for emplacing the largest blocks, catastrophic cryovolcanic eruptions and suitably wide surface fractures would be required. The perversiveness of fracturing at many size scales, the general ubiquity of ice blocks across the inner SPT, and the occurrence of linear block arrangements that parallel through-cutting crack networks indicate that tectonic disruption of lithospheric ice constitutes an important source of blocky-ice features in the SPT. We speculate that fumerolic condensation of ice around parasitic vents may also produce some ice blocks.

Acknowledgments

We thank Alex Hayes and Antoine Lucas for valuable guidance in image processing using ISIS and mapping using ArcGIS. Alex Hayes graciously provided additional utility code for reading and processing ISIS files within Matlab. We are also grateful for the insightful and helpful comments raised by two anonymous reviewers. This manuscript is based upon work supported by the National Science Foundation Graduate Research Fellowship to H.R. Martens under Grant No. DGE-1144469. P. Helfenstein gratefully acknowledges support from NASA CDAP Grant NNX12AG82G.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.icarus.2014.09.035.

References

Brown, R.H. et al., 2006. Composition and physical properties of Enceladus’ surface. Science 311 (5766), 1425–1428.
Fujiiwa, A. et al., 2006. The rubble-pile Asteroid Itokawa as observed by Hayabusa. Science 312 (5778), 1330–1334.