PLANETARY SCIENCE

Tectonic overturn on Enceladus

The south pole of Saturn's icy moon Enceladus is anomalously warm, geologically youthful and cryovolcanically active. Episodic convective overturn explains how the moon's modest sources of internal heat can be channelled into intense geological activity.

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The energy budget of Enceladus, Saturn's second nearest major satellite, holds a number of perplexing enigmas. This ice moon of only about 500 km in diameter orbits Saturn in the frozen outer reaches of the Solar System, yet it is volcanically and tectonically active, with giant geysers of water vapour and ice erupting into space through fissures in its surface. This intense geological activity is focused only at the body's south pole, whereas other regions of the surface have been either tectonically inactive for eons or little affected by tectonic resurfacing at all. But whether the physical mechanisms that at present resurface the south polar region are the same as those that resurfaced other parts of Enceladus long ago is not known. Writing in *Nature Geoscience*, O'Neill and Nimmo[1] explain Enceladus's regionally focused volcanic and tectonic activity, as well as its peculiar geological history, by simulating convective overturn in a regime that alternates between long periods in which the icy crust is immobile and short ones when it can regionally deform and partially overturn in response to a subsurface convection cell.

Global geological patterns on Enceladus (Fig. 1) provide important clues to the nature of the body's past and present internal processes. A distinct geological province of uniquely active cryovolcanism and recent tectonic deformation[2] lies poleward of about 55° S. This province is isolated from the rest of Enceladus by a prominent south-facing circumpolar scarp that encloses a discontinuous system of features indicative of compression, such as icy mountain chains, within its periphery. Central to the south polar region is a family of five parallel rifts, informally called the 'tiger stripes', that are most probably extensional features. From these rifts, jets of water vapour and ice particles are discharged into space.

In contrast, the oldest surface on Enceladus is an expanse of ancient heavily cratered terrain that forms a continuous band stretching from the Saturn-facing side of Enceladus over the north pole and down the opposite side of the moon to the margin of the South Polar Terrain province. The two hemispheres that are divided by this heavily cratered band point, respectively, in the direction of orbital motion and leeward of it. Both hemispheres have quasi-circular provinces of tectonically disrupted terrains of different geological age. These tectonically deformed provinces are intermediate in age between the young south polar region and the older ancient cratered terrain[2], are similar in scale to the South Polar Terrain province and show evidence of elevated regional heat flux in the past[3,4]. They may record past epochs of geological activity that are similar to the activity observed today at the south pole[5].

The regional pattern of extensional rifts at the centre of the South Polar Terrain province, the compressional features that

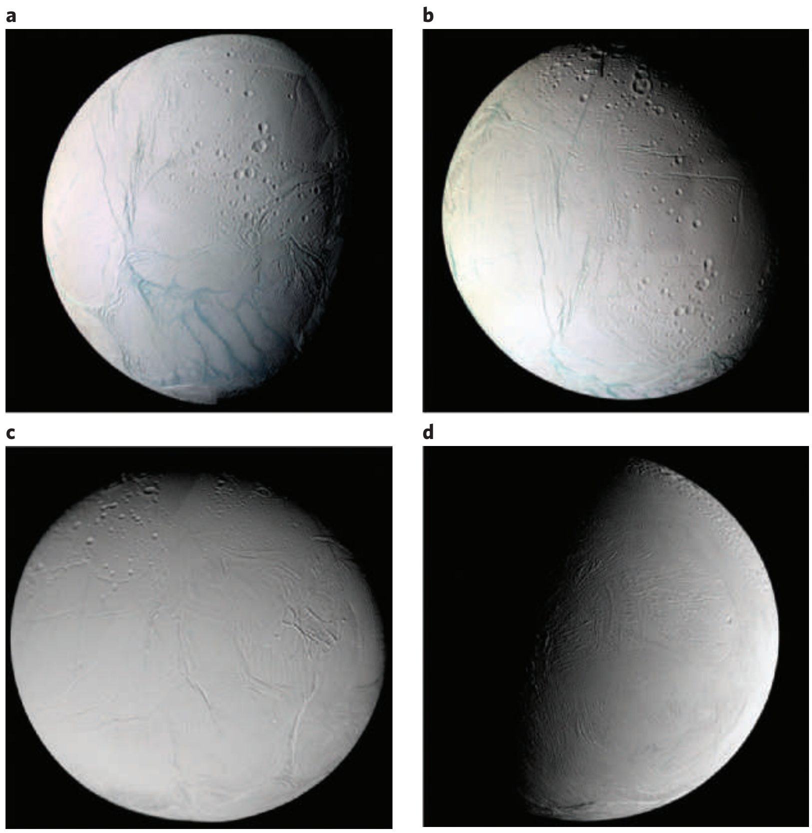

Figure 1 | Global distribution and variety of terrains on Enceladus, obtained with the Cassini oribter's Imaging Science Subsystem (ISS). According to the model by O'Neill and Nimmo[1], the youngest terrain on Enceladus (lower half of part **a**) is an expression of ongoing tectonic overturn that includes convection of the moon's ice surface and regionally enhanced heat loss, as evidenced by geysers that emanate from the 2-km-wide rifts called 'tiger stripes' (shown in a greenish hue) and extend over about 130 km. The oldest terrain (top half of **a** and right side of **b**) is heavily cratered. The leading (**c**) and trailing (**d**) sides of Enceladus show tectonically disturbed terrains of intermediate age that could have been resurfaced during previous episodes of active overturning. Images courtesy of NASA (http://photojournal.jpl.nasa.gov/).

bound it and the anomalously high heat flux over the central south polar region[6] suggest that a convecting mantle plume underlies the south pole and drives its geological activity. Whether the visible south polar ice covers a subsurface sea[7] or slowly convecting warm ice is unknown. The rotational perturbation to Enceladus's moment of inertia from either of these would probably have caused the anomaly to migrate to the pole[8]. Tidal heating, which may be enhanced at the south pole owing to local thinning of the icy shell over a regionally warm interior, is probably the main source of energy that feeds the geological activity[9,10]. However, current models substantially underestimate the south polar heat loss observed by the Cassini orbiter.

O'Neill and Nimmo[1] provide a new theoretical framework to explain how Enceladus's available sources of internal energy can be channelled efficiently to drive its active geology. Their key innovation is a logical, self-regulating mechanism by which Enceladus can accumulate local reservoirs of thermal energy over long intervals of 100 to 1,000 million years and then release the energy in a relatively short period of about 10 million years with intense regionally focused heat loss accompanied by attendant tectonic overturn and cryovolcanism. During convective transport, warm buoyant material at the centre of a convection cell rises while cold dense material sinks at the edges to be recycled.

In the proposed model, over the long period of energy accumulation with a static lid, the cold brittle shell of ice at the surface of Enceladus is relatively thick and strong, and sits immovably over the warm convecting mantle plume (or alternatively, the strength of convection is relatively weak). Over time, however, the upwelling of warm mantle material progressively thins the overlying ice shell until finally it becomes thin and weak, relative to convective forces. As a consequence, it fractures, tectonically deforms and mechanically integrates with the convective motion of the underlying cell. This period marks the mobile-lid interval that we are observing on Enceladus at present. The enhanced heat loss that accompanies the transition from static-lid to mobile-lid convection eventually depletes the thermal reservoir so that the outer shell refreezes to a thickness where the moon returns to its static-lid regime.

Although preliminary, the model proposed by O'Neill and Nimmo[1] is an important breakthrough. It is the only conceptual framework so far that can simultaneously reconcile the internal energy budget of Enceladus with the observed anomalous heat loss at the south pole, the regional nature and size scale of south polar tectonism, and the presence, scale and older geological age distribution of other tectonically deformed provinces. ❐

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HYDROLOGY

All mixed up?

Large rivers are fuelled by waters originating from distinct regions. These different water masses each carry their own chemical fingerprint, but they are thought to blend into one when they reach the main river owing to turbulent mixing.

The rate of turbulent mixing — and thus the degree to which river waters mix — is important for determining the fate of different water masses and the spread of pollutants, but is difficult to measure and hence uncertain. Equally uncertain is the influence of riverbed morphology on mixing.

Now Julien Bouchez, of the Institut de Physique du Globe de Paris, France, and colleagues show that water in the Solimões River, the largest tributary of the Amazon River, is poorly mixed (*Earth Planet. Sci. Lett.* doi:10.1016/j.epsl.2009.11.054; 2009). They examined the sodium concentration and strontium isotopic composition of river water in a cross-section of the Solimões River. Lateral heterogeneities revealed the presence of two distinct water masses originating from two different sources.


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One of the water masses contained high levels of the radiogenic strontium isotope and low levels of sodium, and probably originated from a lowland source. They suggest that the Purus River, which discharges into the Solimões River around 100 km upstream of the sampling site, is the source of this radiogenic water. The other water mass was defined by lower levels of radiogenic strontium and higher concentrations of sodium, and probably reflected the Solimões mainstream, which originates in the Andes.

Using the sodium concentration data they estimated the efficiency of turbulent mixing in the Solimões River; despite the presence of distinct water masses, efficiency was high compared with other rivers. They attribute this to the presence of islands and sand dunes on the riverbed, which are thought to increase the efficiency of lateral mixing.

The above results, together with previous studies, demonstrate that chemical heterogeneities can extend up to tens of kilometres downstream from confluences in large rivers; the distance could be even greater in the presence of smooth riverbeds, which are common in engineered channels.

If these findings are representative of other large rivers, estuaries around the world could contain the chemical signatures of several tributaries.

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