PLANETARY SCIENCE

Plate tectonics on ice

Jupiter's icy moon Europa is criss-crossed by extensional features. A tectonic reconstruction suggests that Europa's extension is balanced by subduction — if so, Earth may not be the only planetary body with a plate tectonic system.

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Plate tectonics has been thought to be unique to our world. The Earth rids itself of internal heat through a convecting mantle and concentrates surface deformation along boundaries between rigid plates, which move away from, towards or alongside each other. Subduction zones, convergent boundaries where one tectonic plate slides under another and is recycled into the Earth's mantle, are unique to plate tectonic systems. Although Mercury, Venus and Mars show clear signs of tectonic activity, such as systems of thrust faults and rift valleys, none of these rocky planets have been convincingly shown to have a system of moving tectonic plates, either today or in the past. Writing in *Nature Geoscience*, Kattenhorn and Prockter[1] present tantalizing evidence of plate tectonics operating on another Solar System body, Jupiter's icy moon Europa.

Slightly smaller than Earth's Moon, Europa has a silicate mantle that is surrounded by a global ocean thought to contain several times more water than all of Earth's oceans[2], enclosed by a water ice shell. The icy moon has a young surface criss-crossed by pervasive fractures and ridges that probably record less than 2% of the moon's geologic history, given the scarcity of preserved craters[3]. The abundance of tectonic features, together with the young age of the surface, suggests that the moon might be experiencing ongoing tectonic activity. Such tectonism is predicted by models of surface stresses caused by both short-term tidal flexing as Europa moves closer to and farther from Jupiter with every orbit, and a longer-term change in the moon's shape as the ice shell slips around the tidally locked interior[4].

Perhaps the most puzzling aspects of Europa's surface are the widespread extensional features. These include bands of deformed ice that are often symmetric about a central axis. Based on tectonic reconstructions, these areas have been interpreted as zones of extension where new icy material is being added to the ice shell over time[5]. Since it is unlikely that Europa has been growing in size, there must be convergent structures that are accommodating extension of the icy crust. However, few candidate features have been identified and Europa lacks the high topography indicative of zones of compression on Earth, such as the Andes or Himalaya mountain ranges.

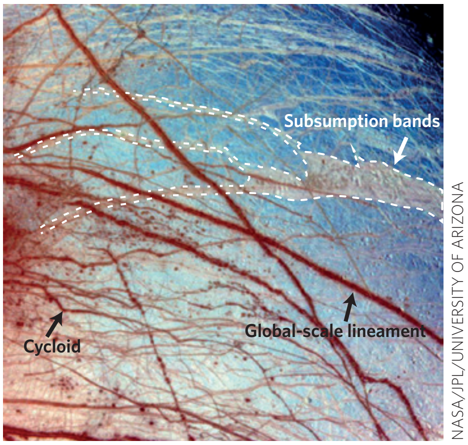

Figure 1 | Tectonic features on Europa, shown in false colour. Kattenhorn and Prockter[1] suggest that the compressional counterpart of tensional features, such as the lineaments and cycloids seen in this location, are subduction-like boundaries called subsumption bands.

Kattenhorn and Prockter[1] meticulously reconstructed a portion of Europa's surface in the northern trailing hemisphere (Fig. 1) using high-resolution images from NASA's Galileo spacecraft, which was in orbit around Jupiter from 1995 until 2003. In the reconstruction, they translated and rotated rigid pieces of the icy crust to match up structural features that had been separated by tectonic activity. Once all the segments of fractures, ridges and bands had been put back together, they noticed that a wide zone in the reconstruction is missing from Europa's present-day surface. They suggest that this slab of surface ice was subducted and absorbed — or subsumed — into the underlying, warmer layer of the ice shell. Similarly, tectonic reconstructions of the Earth's surface reveal missing slabs of oceanic crust that are widely accepted to have been subducted at convergent plate boundaries. However, because of the difference in buoyancy between the cold terrestrial crust and the warm mantle, a subducted slab on Earth is not subsumed as proposed for Europa.

According to the interpretation of Kattenhorn and Prockter, the missing material is destroyed along a so-called subsumption band that is analogous to a subduction zone. The subsumption bands are connected to features interpreted as transform boundaries — where two rigid plates slide horizontally past each other — as well as a range of structures indicating compressional, extensional, or shear motion or some combination thereof.

The evidence for plate tectonics on Europa is based on more than the tectonic reconstruction. On Earth, volcanism is concentrated along subduction zones, such as the Ring of Fire framing the Pacific Ocean. On Europa, Kattenhorn and Prockter identify what might be cryolavas on the overriding plate. Their location adjacent to the subsumption band suggests they are analogous to volcanic constructs near subduction zones on Earth.

Although there are many similarities between subduction zones on Earth and the proposed subsumption bands on Europa, what we know about subduction on Earth poses a potential problem for a similar process occurring on Europa. Subduction on Earth involves a cold slab of oceanic lithosphere plunging into warmer asthenosphere material beneath an overriding plate composed of oceanic or continental lithosphere. Where two continental plates meet at a convergent boundary, subduction is impeded because continental crust is less dense and thus too buoyant to sink.

The scenario proposed by Kattenhorn and Prockter involves a rigid outer portion of Europa's water ice shell subducting into warmer and softer ice below. But water ice is more buoyant in its cold, solid phase than it would be in the warmer, slushy subsurface of Europa. It is therefore unclear how subduction can physically occur on Europa. Kattenhorn and Prockter suggest a mechanism where the push supplied by extension at ridges is the driving force, instead of the plate being pulled by the subducting slab, which is thought to be the dominant driving force for plate tectonics on Earth. However, the stresses and rates of extension required for this mechanism to overwhelm buoyancy forces have not yet been quantified nor shown to be reasonable for Europa.

Furthermore, volcanism on Earth is generated because a subducting slab of oceanic crust is water-rich, which lowers the melting temperature of overriding rock. On Europa, the subducting slab of ice would be similarly heated by friction, but any meltwater would be denser than ice and expected to sink, rather than rise to the surface as cryovolcanism. Perhaps pressure squeezes pockets of meltwater up to the surface, but the plausibility of this mechanism has also yet to be assessed.

Of the hundreds of geologic features mapped in the study region, only about 30 crosscut the subsumption bands, indicating that these zones are perhaps less than five million years old. Whether a subduction-like process is responsible or not for the missing surface ice, the region has experienced extensive recent convergence. Subsumption bands may represent a diagnostic geomorphologic signature left behind at convergent zones on Europa.

Additional subduction zones would be required for the destruction of surface area through subsumption to balance the creation of the new ice at dilational bands, which are estimated to represent about 10–40% of the total surface area of Europa[6]. However, much of Europa's surface is not imaged at a resolution high enough for the tectonic reconstruction approach employed by Kattenhorn and Prockter. A potential future mission from NASA, the Europa Clipper, would acquire the data needed to identify subduction zones and constrain their surface and subsurface structure.

Kattenhorn and Prockter[1] suggest that subduction, and hence a plate tectonic system, is operating on Europa. Thus, icy Europa may be more tectonically similar to rocky Earth than any other planetary body we know of. Perhaps Europa and Earth are even more uniquely similar: It is tempting to note the correlation between the existence of both life and plate tectonics on Earth and wonder if the latter might not be a requirement of the former. ❐

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References

1. Kattenhorn, S. A. & Prockter, L. M. *Nature Geosci.* **7,** 762–767 (2014).
2. Pappalardo, R. T. *et al. J. Geophys. Res.* **104,** 24015–24055 (2012).
3. Bierhaus, E. B., Zahnle, K. & Chapman, C. R. in *Europa* (eds Pappalardo, R. T., McKinnon, W. B. & Khurana, K. K.) 161–180 (Univ. Ariz. Press, 2009).
4. Kattenhorn, S. A. & Hurford, T. in *Europa* (eds Pappalardo, R. T., McKinnon, W. B. & Khurana, K. K.) 199–236 (Univ. Arizona Press, 2009).
5. Patterson, G. W., Head, J. W. & Pappalardo, R. T. *J. Struct. Geol.* **28,** 2237–2258 (2006).
6. Figueredo, P. *Cryovolcanic and Tectonic Resurfacing Mechanisms on Europa and Ganymede* PhD thesis, Univ. Arizona (2002).

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BIOGEOCHEMISTRY

Microbial flexibility

As an essential building block of amino acids, proteins and DNA, nitrogen is key to life on Earth. Nitrogen is also the main constituent of our atmosphere, but the main form it takes, N_2, is unusable by almost all living organisms but a few select microbes. Instead, most living creatures, from bacteria to primates, rely on nitrogen that has been bound in oxides, as ammonia or in organic compounds. Many microbes actually make a living by cycling nitrogen from one fixed state to another: they gain energy using various nitrogen species as electron donors and receptors.

One part of the nitrogen cycle is nitrification, in which bacteria and archaea oxidize ammonia, and nitrite-oxidizing bacteria convert nitrite to nitrate. One of the most widespread genera of these nitrite-oxidizing bacteria is *Nitrospira*, with species occurring in oxic oceans, soils, hot springs and even wastewater treatment plants. However, *Nitrospira* appears to alternatively be able to perform anaerobic respiration, with H_2 as an electron donor and nitrite as an electron acceptor. Culture experiments and genetic sequencing now suggest that *Nitrospira moscoviensis* can also use H_2 as an energy source for aerobic


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respiration when nitrite is not available (*Science* **345,** 1052–1054; 2014).

Holger Daims and colleagues observed cultures of *N. moscoviensis* growing with no nitrite available, as long as H_2 and O_2 were present. The uptake of CO_2 by these microbes occurred even when H_2 concentrations were low, but no net growth occurred. This indicates that only a fraction of the cells in the culture were highly metabolically active under these conditions.

Genome sequencing of *N. moscoviensis* identified a series of genes associated with the hydrogen oxidizing enzyme hydrogenase, known as the *hup* locus. The best explanation for the appearance of these genes in *N. moscoviensis* is lateral gene transfer from a different phylum of bacteria. Intriguingly, the *hup* locus only appears in one of the phylogenetic lineages of *Nitrospira* (lineage II), suggesting that either only this lineage acquired the gene through lateral gene transfer or that the gene was later lost by lineage I.

The ability of *N. moscoviensis* to remain metabolically active without the continued presence of nitrite provides a strong ecological advantage, and probably explains why *Nitrospira* can be found in some low oxygen environments with available H_2, such as rice paddies, deep hydrothermal fields and hot springs.

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