THE GEOLOGY OF THE ROCKY INTERIORS OF ENCELADUS, EUROPA, TITAN, AND GANYMEDE.

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Introduction: The icy satellites of Jupiter and Saturn have been the subjects of substantial geological study. Much of this work has focused on their outer shells [e.g., 1–3], because that part is most readily amenable to analysis. Yet many of these satellites feature known or suspected subsurface oceans [e.g., 4–6], likely situated atop rocky interiors [e.g., 7], and several are of considerable astrobiological significance. For example, chemical reactions at the rock–water interface might support chemoautotrophic habitats there [e.g., 8], and hydrothermal systems and even seafloor volcanism might be present within some moons [e.g., 9]. Here, we combine rock mechanics techniques with remotely sensed geophysical data for four icy satellites, to place first-order estimates on the mechanical and geological properties of their rocky interiors.

Enceladus: With published values for the interior structure of Enceladus [10], we find that the pressure at the ocean floor is about 7 MPa, comparable to that at the bottom of the North Sea on Earth. Given the very low gravitational acceleration (g) at Enceladus, a modest porosity (e.g., 10%) at the rock–water interface results in some void space even at the center of the rocky interior. If this interior were permeable, then it is likely that the entire rock volume of Enceladus is saturated with water—or, at least, has been entirely serpentinized by earlier hydrothermal activity [e.g., 8]. Such a finding supports the inference that sustained geological activity inside the moon has been facilitated by a largely unconsolidated silicate interior [11].

Europa: The deeper ocean at Europa [7,12], coupled with that body's higher value for g, results in an ocean floor pressure of about 210 MPa (equivalent to almost twice that at the bottom of the Marianas Trench). Further, even very high porosities (~40%) at the ocean floor reduce to zero within a few kilometers; pore space, and thus hydrothermal alteration, likely does not prevail below this depth. We calculated likely fault strength profiles for the brittle rocky portion of Europa, as well as a strength envelope for a putative, ductile lower part of the moon's rocky interior. (We assumed minimum and maximum strain rates (ε) of 10^{-20} s^{-1} and 10^{-14} s^{-1}, respectively, with temperature calculated from thermal gradients bracketed by 5 K km^{-1} and 20 K km^{-1}.) We find the brittle–ductile transition (BDT) within Europa—the maximum depth to which faults can penetrate before strain is accommodated via crystal plasticity and other ductile deformation mechanisms—to range from as little as 160 km (for the highest thermal gradient and lowest strain rate) to more than 800 km (for the lowest thermal gradient and highest strain rate).

Titan and Ganymede: The pressures at the Titanean and Ganymedean rock–water/ice interfaces are substantial. For the likely interior structures of Titan [13] and Ganymede [14], this pressure is about 1.1 GPa and 1.2 GPa, respectively. Any porosity that might exist at the rock surface is therefore negligible at a depth of only a few hundred meters. Depths to the BDT within Titan and Ganymede (calculated for the same values as for Europa) are very similar, ranging from about 150 km (highest thermal gradient and lowest strain rate) to 780 km (lowest thermal gradient and highest strain rate).

Outlook: The results we report here place broad constraints on the mechanical behavior and properties of the silicate interiors of several notable icy satellites. This approach can be applied to other rocky bodies ensconced in water/ice, whether fully differentiated or not, e.g., Dione, Tethys, Pluto, Charon, Triton, or Titania. Future measurements of these worlds by visiting spacecraft will refine our input parameters, such as those planned for the Europa Clipper mission [15]; those missions could even test for evidence of geological activity at the ocean floor [e.g., 16].

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