SUBDUCTION ON EUROPA: THE CASE FOR PLATE TECTONICS IN THE ICE SHELL

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Introduction: The 2003 Planetary Decadal Survey, "New Horizons in the Solar System," and 2011 Planetary Decadal Survey, "Vision and Voyages," both emphasize the importance of Europa exploration as "the first step in understanding the potential of the outer solar system as an abode for life" [1]. A tidally heated global ocean beneath its ice shell is important for astrobiological considerations; however, habitability requires a source of chemical nutrients. Europa's radiolytically processed surface is a potential source, but a means of delivery of compounds to the ocean is required. We describe a region in Europa's northern trailing hemisphere where large portions of the surface have been removed along discrete tectonic boundaries that we hypothesize to be subduction zones. A prolonged history of subduction is evidenced by numerous, tabular deformation zones where portions of the surface seemingly vanished. These zones are commonly ~30 km wide and can be traced up to 1700 km across the surface in low-resolution imagery. Geological features in a portion of the zone imaged at moderate resolution were used to tectonically reconstruct the geologically most recent subduction event, indicating a 92-km-wide swath of missing surface.

We infer that these surface materials were subsumed into the interior of the ice shell along a candidate subduction zone. Not only does such a process provide a means for accounting for the young surface age of Europa, it also implies that the outer, brittle portion of the ice shell behaves in a similar way to Earth's lithospheric plates, with the warmer, deeper portions of the shell behaving like Earth's thermally convecting asthenosphere, into which the brittle portion can subduct. Just as plate tectonics on Earth was fundamental for creating a habitable environment, plate tectonics on Europa may have provided a means to recycle nutrient-rich chemical compounds from the surface into the Europan interior and thus contribute a potential energy source for astrobiological development.

Europa's Surface Age Paradox: Past studies of Europa's surface have been unable to explain an abundance of extensional features (e.g., dilational bands) yet scant evidence of contraction [e.g., 2]. Moreover, the crater-based surface age (40-90 Myr) [3] indicates one of the solar system's youngest surfaces, implying Europa's surface (3.09 x 10^7 km^2) may have been recycled in this time frame (i.e., 0.3-0.8 km^2 per year).

Dilational bands represent areas of new icy crust via the emplacement of warm ice from below between diverging crack walls. The process of dilational band development has been suggested to bear a strong resemblance to the formation of mid-ocean ridges on Earth [4, 5]. Thermal buoyancy of warm ice in the convecting portion of the ice shell pushes material up into cracks, forcing the walls apart and creating new surface area. As such, dilational bands may provide a "ridge-push" mechanism for lateral plate motions, analogous to Earth. The creation of new surface area nonetheless provides a space problem. Unless Europa has been steadily expanding, the large amounts of new surface area created at Europa's ubiquitous dilational bands requires an area balance through the removal of an equivalent amount of surface area at comparable strain rates. For dilational bands, spreading rates of 0.2-40 mm/yr have been suggested (similar to terrestrial mid-ocean ridge spreading rates) [6].

Despite the need for a means for surface area removal, no mechanism has been previously identified to account for this area balance. In fact, contractional features have proven to be very elusive on Europa. Small amounts of contraction may be taken up along low-amplitude folds [7], and it has been suggested that Europa's ubiquitous ridges may be somewhat contractional [4, 8]. However, neither of these features can explain the global resetting of the surface age in that they are unable to remove the crater population. More effective candidates are previously identified band-like features referred to as convergence bands, where complex internal morphologies and non-matching boundaries have been used to infer sites of convergence [8, 9]. None of these documented convergence bands have been demonstrated to be sites of significant surface removal, however.

Tectonic Reconstruction: We address the enigma of surface age resetting and surface area balance by presenting evidence for subduction, and hence plate tectonics, on Europa. We have reconstructed geologic features in a 106,000 km^2 candidate region (Fig. 1) in Europa's northern trailing hemisphere, imaged at 170-228 m/pixel, to show that the current surface configuration involved numerous translations and rotations of rigid plates. The reconstruction reveals ~92 km of missing surface that seemingly vanished along a 23-km-wide, >300-km-long, band-like zone with unusual color characteristics. We refer to this and analogous bands as "subsumption bands" and hypothesize that they represent candidate subduction zones.

We have identified numerous lines of evidence to show that the geological history of the region involved mobile plates, portions of which were subsumed into the interior of the ice shell along the candidate subduction zones. These lines of evidence include the mismatch of older geological features across discrete boundaries, missing surface area in tectonic reconstructions, distinctive and unique surface morphologies at plate edges (both transform-like and subduction-like boundaries), a lack of topographic expression (implying area removal, not contractional strain within a narrow zone), cryovolcanic or thermal disruption features restricted to the overriding plate, spatially distinct color or albedo characteristics, and partitioning of strain along portions of plate boundaries that are obliquely convergent (transpressive).

The candidate subduction zone is arcuate, has no topographic expression at image resolutions, and is partially bounded by transform faults. Tectonic reconstructions of mismatching geological features across this zone suggests that at least 75% of the missing surface disappeared at this discrete plate boundary. If the 23-km-wide band represents a deformed zone of upper plate material (analogous to plate collision orogenic belts on Earth), it is possible that 100% of the missing surface area was removed along the plate boundary. Missing surface area can be shown to belong to a distinct plate that experienced a complex history of motion events along boundaries that are variably divergent, transform, or convergent as the plate is circumnavigated.

The transform boundaries have either linear or en echelon geometries and unique morphologies, composed of rough, hummocky material that extends up to 5 km to either side of the transform edges. The subsumption bands have interiors with elongate hummocks parallel to the margins, which are dissected by small faults. The bands have internal lineaments that juxtapose disparate morphological zones, some of which are smooth regions with small pits. In contrast to dilational bands, there is no evidence of central troughs, bilaterally symmetrical morphological zones about a central axis, or matching geology to either side of discrete margins.

The overriding plate has numerous strike-slip faults consistent with strain partitioning related to oblique convergence. The surface of the overriding plate is also pervasively dotted with isolated patches of disrupted terrain, some of which may be erupted cryolava, implying a significant subsurface thermal perturbation related to the underlying subduction.

Discussion: If a subduction model for Europa is accurate, buoyancy constraints and a lack of contractional topography imply that the subducting slab does not enter the ocean directly. We thus interpret a thin (~several km), brittle lid overlying a thicker, convecting ice layer, with plate motions and subduction restricted to the brittle lid. The subducting plate is presumably consumed at a rate conducive to complete subsumption into the convecting layer as it moves into the underlying, warmer, slightly less dense portion of the ice shell. On Earth, oceanic lithosphere removal along a cumulative 55,000 km length of subduction zones occurred in <200 Myr at 20-80 mm/yr. Similar subduction rates on Europa (if valid) along only 30,000 km total length of subduction zones could recycle its surface area (~6% of Earth's) over a time frame consistent with its surface age.

Our work potentially provides a new paradigm for interpreting Europa's surface features and age, and provides a mechanism to deliver nutrients from the surface to either the ocean or pockets of liquid water within the ice shell [10]: crucial for astrobiology and habitability. If subduction exists, Europa would become the only other solar system body beyond Earth to exhibit plate tectonics, involving subduction (surface area removal), mid-ocean-ridge-like spreading (surface area creation at dilational bands), and transform motions. Such motions are potentially driven by convection in the deeper, warmer ice, evidenced by thermal upwellings at sites of chaos and lenticulae.

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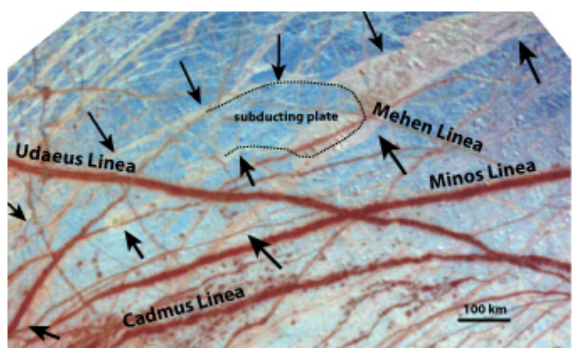

Figure 1. *Candidate subduction zones (light colored regions identified by arrows) in the northern trailing hemisphere of Europa. The study region shows evidence of a subducting plate with discrete boundaries, one of which shows evidence of the removal of 92 km of the surface along a NE-SW oriented band at its southern margin.*