THE CASTALIA MACULA REGION: NUMERICAL ANALYSIS OF A PROPOSED CONVERGENT BOUNDARY ON EUROPA.

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Introduction. Voyager and Galileo images of Europa have shown its surface to be highly deformed by tectonic features. Extensional and strike-slip structures are ubiquitous [1,2,3] with examples of extension on the order of tens of percent regionally [1,4]. Conspicuous however, is a general lack of evidence for compressive features on the scales necessary to compensate the observed extension.

The reconstruction of offset features along tectonic plate margins is one method of locating such features and two have been proposed, based on this method, in a region near the prominent dark spot Castalia Macula [5,6]. Reconstructions of this sort implicitly assume that the plates involved act rigidly and the validity of the reconstruction performed, as well as the assumption of plate rigidity, can be confirmed in a quantitative manner by the determination of an Euler pole of rotation. An Euler pole is a pivot point that can describe the motion of one plate relative to another on a sphere by a rotation about the pole [7]. Such poles were not determined for either of the reconstructions that have suggested possible convergent boundaries.

Here we show the results of a numerical technique we have developed [8] to test the validity of the proposed convergent boundaries located in the Castalia Macula region. This is accomplished by the determination of a finite pole of rotation about which the plate boundaries identified in the region can be reconstructed. We will show, using this technique, that the assumption that the plates involved in these reconstruction behaved rigidly is incorrect and, as a result, previous reconstructions by Sarid et al. (2002) and Patterson and Pappalardo (2002) need to be reassessed. Our analysis will instead demonstrate that the deformation inferred by the rotation of the tectonic plates defined in this region with respect to one another was most likely accommodated by internal deformation. Furthermore, this result casts doubt on the hypothesis that some Europan bands display a morphology that is characteristic of convergent boundaries [5,9].

Background. The Castalia Macula region is located on the trailing hemisphere of Europa's equator and extends from -11° to 10° latitude and 208° to 232° longitude (Fig. 1). The prominent dark spot Castalia Macula is located within this region at -2° lat. and 226° lon. The resolution coverage of this area ranges from ~220 m/pix in the western portion of the image to ~1.5 km/pix in the eastern portion. A diverse assemblage of structural features can be found in this region (Fig. 2). They include bands and cycloidal ridges trending predominately east-west across the image, ridges and complex ridges with no preferred orientation, isolated lenticulae found throughout the image, and a region of chaos in the northeastern portion of the image. Our analysis will focus on a band-like complex and set of cycloidal ridges in this region (Fig. 1 – dashed lines).

Cross-cutting relationships indicate these features divide the region into six plates that have rotated with respect to each other (Fig. 1). Examination of 60 offset features along the margins of the plates outlined by the cycloidal ridge set suggest, to first order, that they are dextral transform boundaries (Fig. 2). However, the offset of features along the boundaries varies from ~1.5 to 6.0 km and thirteen of the features appear to have a sinistral offset indicating that one or more of the dextral transform boundaries may be transpressive. In order to determine quantitatively if this is the case, we need to identify Euler poles for the various plates in this region.

The inverse technique we have developed [8] determines an Euler pole of rotation using the trend and offset of preexisting features as inputs. This method employs an iterative grid-search technique that allows us to test all combinations of Euler pole location and rotation within a specified grid. The result is a map of the rotation for each possible Euler pole location that yields a least-squares minimum for the offset of all the features input. The pole location with the minimum value of offset for this map is designated as the best-fit Euler pole for the features input.

Results. The location and magnitude of five finite rotations (Euler poles) representing the best-fit reconstructions of four plates in the Castalia Macula region are shown in Table 1 (Analyses for plates 5 and 6 were not performed

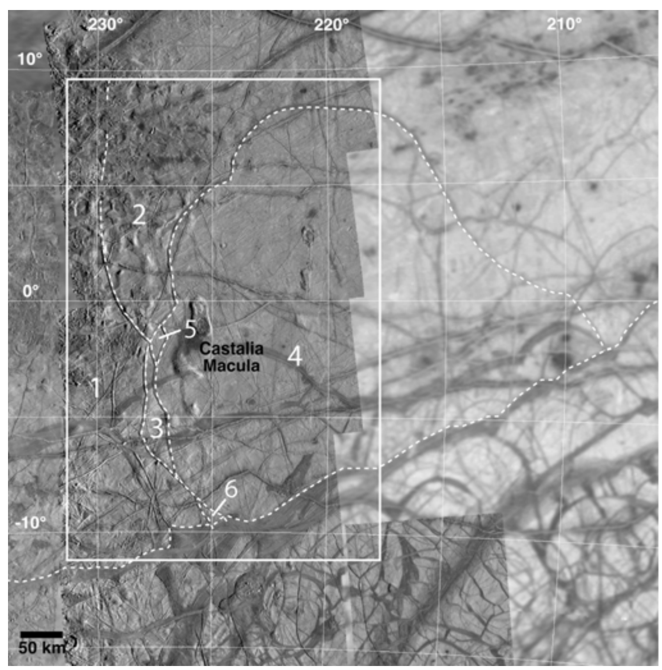

Fig. 1. Mosaic of Galileo and Voyager images of the Castalia Macula region taken from the USGS controlled photomosaic map of Europa (I-2757). The resolution of the mosaic ranges from <500 m/pix to ~2 km/pix. Dashed lines indicate plate margins with plates numbered 1 through 6.

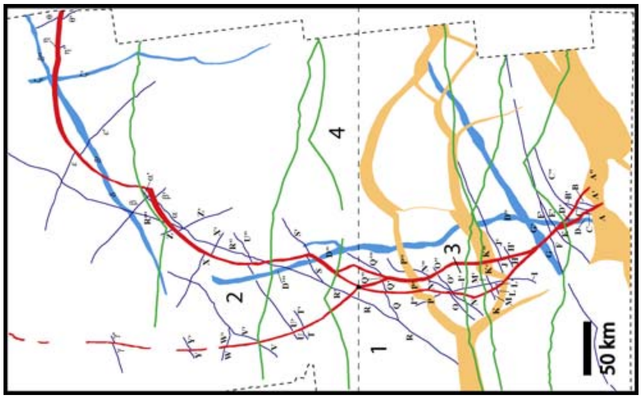

Fig. 2. Sketch map of the Castalia Macula region from ~-10˚ to 11˚ lat. and ~218˚ to 232˚ lon. The sequence of structures from youngest to oldest proceeds as follows; E-W trending cycloidal ridges (green), N-S trending cycloidal ridge set (red), E-W trending band-like complexes (yellow), and ridges and complex ridges (dark/light blue). Tectonic plates used in our analysis are numbered 1-4. Dashed line and dot indicates one location of an arbitrary plate boundary and point used in determination of amount of distributed deformation in this multi-plate system. The image is rotated such that north is to the left.

because the modeling technique we employ requires at least four offset features in order to determine a pole of rotation). The relationships between these plates offer us a unique opportunity to test the assumption by Sarid et al. (2002) and Patterson and Pappalardo (2002) that they behaved rigidly while they deformed. If we consider that the matrix addition of the Euler poles ${}_1E_2$ and ${}_2E_4$ as well as ${}_1E_3$ and ${}_3E_4$ will both yield a pole location and magnitude for ${}_1E_4$, then we will have three independent determinations of a single Euler pole. If these plates behaved in a rigid manner during deformation then the three determinations of ${}_1E_4$ should be equivalent. If they are not equivalent then deformation must be distributed within one or more of the plates.

The determination of ${}_1E_4$ by addition ${}_1E_2$ and ${}_2E_4$ indicates a pole located at ~2.6˚ lat., 211˚ lon. with a rotation of 0.99˚. Determination of ${}_1E_4$ by addition of ${}_1E_3$ and ${}_3E_4$ indicates a location of ~4.2˚ lat., 50˚ lon. with a rotation of 5.2˚. The discrepancy between these two determinations of ${}_1E_4$, as well as that determined by direct application of our numerical technique (Table 1), indicates that the plates in this system did not behave as if they were perfectly rigid.

An approximation of the degree to which this system deviated from perfect rigidity can be determined by calculating a difference pole between any two of the three values of ${}_1E_4$. An arbitrary boundary can then be placed between the plates that constitute those two values and a point on that boundary can be rotated about the difference pole. The distance between the original location of the point and its location after rotation about the difference pole will then yield an approximate value for the amount of deformation that has been distributed within one or more of the plates involved.

As an example, the difference pole between the determinations of ${}_1E_4$ by the matrix additions of ${}_1E_2+{}_2E_4$ and ${}_1E_3+{}_3E_4$ is located at ~-3˚ lat., 227˚ lon. with 6˚ of rotation. We then define an arbitrary boundary at ~1.85˚ lat. extending east and west across the image and rotate a point on the boundary at ~227.5˚ lon. about the determined difference pole (Fig. 2). Using that pole, the point is rotated ~2.6 km to the northeast. This is equivalent to the average offset of features along the ridges that constitute the plate boundaries in this region. The rotation also indicates that the deformation that produced the non-rigidity in this system was compressive.

Euler pole	Location (º)		Rotation (º)	V_i (km^2)	V_f (km^2)
	Lat.	Lon.			
${}_1E_2$	8	217	0.32	3.70	0.0904
${}_2E_4$	0	28	-0.67	14.54	0.691
${}_1E_3$	5	53	0.93	3.49	0.236
${}_3E_4$	4	49	4.31	11.12	0.331
${}_1E_4$	9	47	1.9	1.92	0.0363

Table 1. Determined Euler poles for the finite rotations involving the plates identified in the Castalia Macula region. The terminology ${}_xE_y$ from Table 1 indicates that plate y has been rotated with respect to plate x. Rotations are counterclockwise when positive. V_i and V_f indicate the pre- and post-reconstruction variance of offset features about zero respectively.

Conclusions. Previous reconstructions of a set of ridges in the region surrounding Castalia Macula (which did not include a pole of rotation) suggested the presence of a convergent boundary along the southern [5] or eastern [6] margin of plate 4 (Fig. 1). However, determination and analysis of five finite rotation poles for four of the tectonic plates in this region indicates that, while deformation of the region was compressive, the plates did not behave rigidly. Furthermore, the amount of deformation that was distributed within one or more of the plates in this region is equivalent to the average offset of features along the plate boundaries. This indicates that distributed deformation plays a significant role in accommodating compressive stress and that previous reconstructions [5,6] suggesting a portion of the boundary that constitutes plate 4 was convergent need to be reevaluated with this in mind. Furthermore, this analysis suggests the assertion that the morphology of one of the boundaries in this region is characteristic of convergence on Europa [5,9] needs to be reassessed.

References. [1] Schenk and McKinnon, *Icarus*, 79, 75-100, 1989; [2] Hoppa et al., *Icarus*, 141, 287-298, 1999; [3] Prockter et al., *JGR*, 107, 10.1029/2000JE001458, 2002; [4] Sullivan et al., *Nature*, 391, 371-373, 1998; [5] Sarid et al., *Icarus*, 158, 24-41, 2002; [6] Patterson and Pappalardo, *Lunar Planet. Sci. Conf. XXXIII*, abstract # 1681; [7] Cox and Hart, *Plate tectonics*, Blackwell Scientific Publication, 1986; [8] Patterson and Head, *Lunar Planet. Sci. Conf. XXXV*, abstract # 1590; [9] Greenberg, *Icarus*, 167, 313-319, 2004