A QUANTITATIVE ANALYSIS OF PLATE MOTION ON EUROPA: IMPLICATIONS FOR THE ROLE OF RIGID VS. NONRIGID BEHAVIOR OF THE LITHOSPHERE. G. W. Patterson[1], J. W. Head[1], R. T. Pappalardo[2], [1]Department of Geological Sciences, Brown University, Providence, RI, 02912 (Gerald_Patterson@brown.edu), [2]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, 80309.

Introduction. Voyager and Galileo images of Europa have shown its surface to be highly deformed by tectonic features. The formation of these features has been attributed to deformation of the outer ice shell from stresses induced by diurnal tides, nonsynchronous rotation, and/or polar wander [1-5]. The effects of these stress fields (acting independently and/or in concert) are inferred to fracture the ice shell into plates that subsequently rotate with respect to one another [e.g. see 4].

The expression of these plate rotations can be observed in the ubiquitous presence of strike-slip and extensional features on the surface. Dark, wedge-shaped bands on Europa (interpreted as extensional [1,3]) have been used to suggest that surface plates, up to 50-100 km across, have moved and rotated relative to each other [1]. Furthermore, it has been noted that the dark material of some of the features could be removed, allowing the margins of the bands to fit closely together and the surrounding preexisting lineaments to be reconstructed [1]. This has been used to suggest that these plates behaved rigidly during deformation (i.e. all deformation was accommodated at the margins of the plates). This assumption has been further reinforced by strike-slip zones on Europa with displacements of 1-10km [6,7]. It has been suggested that such motion is a plausible result of the accommodation of tidal strain in a crust broken into mobile, rigid blocks [8].

Assuming rigid plate behavior, a number of qualitative and quantitative reconstructions of Europa's tectonically disrupted surface have been performed [1,2,5,9-11]. The distinction we use between these two types of reconstruction is the determination of an Euler pole of rotation (a pivot point for the motion of two rigid plates relative to each other on a sphere). This is a commonly determined quantity when describing terrestrial plate motions but has been only sparingly determined when describing plate motions on Europa [e.g. 1,11]. Interestingly, one of these quantitative analyses indicated that Europa's lithosphere might behave nonrigidly [11].

We have developed a quantitative technique for determining the Euler pole of rotation between two rigid plates and use it here to help clarify the nature of deformation of Europa's lithosphere (rigid or nonrigid). This is an inverse modeling technique that uses an iterative grid-search method to test a wide range of possible rotation poles for the reconstruction of a two-plate system in which one plate has been displaced relative to another. The best-fit pole determined by this technique would represent the best approximation of the previous position of these plates (before rotation) and if preexisting features are realigned then we can assume that, to first order, these plates behaved rigidly. Of course, we cannot eliminate the possibility that nonrigid behavior could have occurred in a simple two-plate system and that features still closely realign upon reconstruction. We can, however, significantly reduce that possibility by looking at multi-plate systems and approximating them as a collection of two-plate pairs. This takes advantage of the additive behavior of finite poles of rotation such that nonrigid behavior in any two-plate pair within a multi-plate system would prevent the determination of a unique pole of rotation for the system.

We have chosen to use this method to attempt to reconstruct a region around the prominent dark spot Castalia Macula. Qualitative reconstructions of this region have been attempted previously and each suggested that compression might have occurred (Sarid et al., 2002; Patterson and Pappalardo, 2002). Reconstructions were performed under the assumption that the plates involved behaved rigidly on Europa during deformation. We show that a quantitative analysis of this region indicates that one or more of the plates involved did not behave rigidly. As a result, we conclude that the validity of reconstructions suggesting compression has occurred in this region cannot be determined.

Background. The prominent dark spot Castalia Macula is located near the equator of Europa's trailing hemisphere at -2° latitude and 226° longitude and it is surrounded by a diverse assemblage of structural features (Fig. 1). Our analysis will focus on a band-like complex and set of ridges that appear to be contemporaneous or penecontemporaneous in age and can be used to indicate the boundaries of seven plates in this region. 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 these features may record a more complex deformation history.

While the crosscutting relationships of preexisting features suggest that the ridge set we wish to reconstruct formed contemporaneously, crosscutting relationships of the ridge set itself indicate the possibility that they formed as a series of up to 3 deformation events. If this is the case then care must be taken

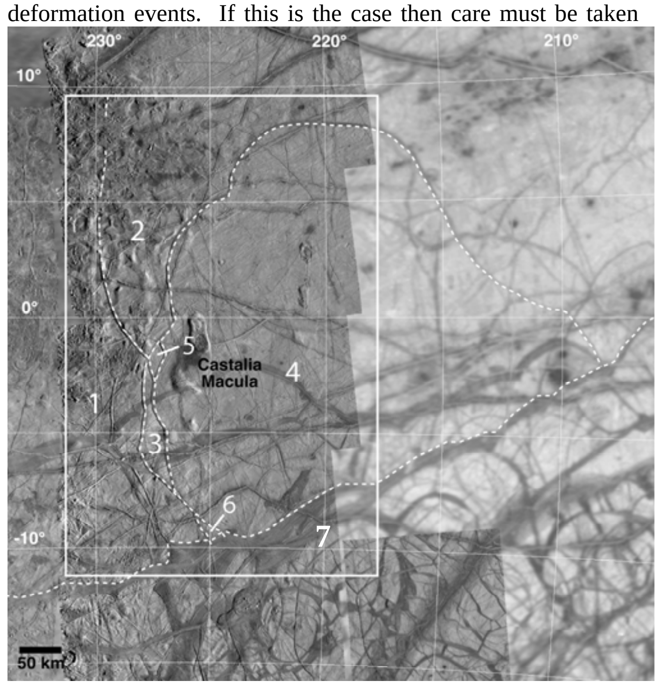

Fig. 1. Mosaic of Galileo and Voyager images of the Castalia Macula region taken from the USGS controlled photomosaic map of Europa (I-2757). The resolution of the mosaic ranges from <500 m/pix to ~2 km/pix. Dashed lines indicate plate margins with plates numbered 1 through 7.

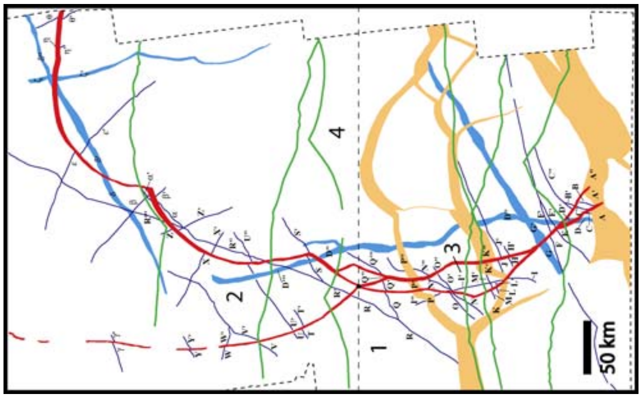

Fig. 2. Sketch map of the Castalia Macula region from ~-10˚ to 11˚ lat. and ~218˚ to 232˚ lon. The sequence of structures from youngest to oldest proceeds as follows; E-W trending cycloidal ridges (green), N-S trending cycloidal ridge set (red), E-W trending band-like complexes (yellow), and ridges and 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.

when trying to determine a pole of rotation for the region. Plate boundaries that have undergone different deformation events would have to be treated separately initially and then added to produce a pole of rotation for the region as a whole. This scenario represents a more conservative approach to interpreting the deformation history of the region and we have adopted it for this analysis.

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 because the modeling technique we employ requires at least four offset features in order to determine a pole of rotation and plate 7 was excluded because there are no identified preexisting features with which to perform a reconstruction. The poles determined for the remaining plates represent finite rotations for separate combinations of the 3 possible deformation events discussed previously.

The only pole of rotation that represents all of the deformation events this region may have experienced is that for ${}_1E_4$. However, the additive behavior of poles of rotation allows us the opportunity to determine ${}_1E_4$ also using two separate plate circuits. These include Euler poles ${}_1E_2$ and ${}_2E_4$ as well as ${}_1E_3$ and ${}_3E_4$ and this allows us three independent determinations of a single pole of rotation for the region. If these plates behaved in a rigid manner during deformation then the three determinations of ${}_1E_4$ should be equivalent. If however they are not equivalent then deformation must be distributed within one or more of the plates.

The determination of ${}_1E_4$ by addition of ${}_1E_2$ 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 one or more of the plates in this system did not behave rigidly.

An approximation of the degree to which this system deviates from rigid behavior 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) Lat.	Lon.	Rotation (º)	V_i (km^2)	V_f (km^2)
${}_1E_2$	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. The nature of plate deformation of Europa's lithosphere (rigid or nonrigid) has important implications for how we evaluate surface features and account for the ubiquitous amounts of extension that are observed. Quantitative analysis of plate motions around Castalia Macula indicate that nonrigid behavior occurs and the identification of other features that display nonrigid behavior [11] indicates that this is not isolated to a single region or event. These results indicate that ductile deformation of Europa's lithosphere may be an important factor in accommodating the significant amounts of extension that are observed.

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