

CRACK AZIMUTH SEQUENCES ON EUROPA: THE SOUTHERN LEADING HEMISPHERE.

A.R. Sarid¹, R. Greenberg¹, P. Geissler¹, and G.V. Hoppa², ¹Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721; ²Raytheon Missile Systems, Tucson, AZ.

Introduction: Galileo images of Europa's northern hemisphere taken at low resolution during the first orbit of Jupiter showed that regional-scale lineaments' orientations followed a systematic progression (clockwise going forward in time) consistent with predicted trends in tidal stress over $\sim 1/6$ of a period of non-synchronous rotation [1]. The fit is even better if diurnal tides, as well as non-synchronous effects, are taken into account [2]. Non-synchronous rotation, i.e. a gradual rotation relative to the direction of Jupiter, had been predicted [3], based on considerations of tidal torques caused by Europa's orbital eccentricity. The possibility that tectonic patterns might contain a record of non-synchronous rotation was noted by [4] and [5].

Other lines of evidence based on Galileo imaging corroborated the likelihood of nonsynchronous rotation, including studies of tidally driven strike-slip tectonics [6] and of the formation sites of cycloidal cracks under tidal stress [7]. The difference from synchronous rotation is small (the period relative to Jupiter is >12000 yr) according to a comparison of Voyager and Galileo images [8]. The evidence regarding Europa's rotation is reviewed in [9].

Geological mapping of other regions did not provide such compelling evidence of non-synchronous rotation. In the northern leading hemisphere, an azimuth sequence inferred from geological mapping, when compared with the tidal stress model from [2], required >2 non-synchronous rotation periods [10]. In high-resolution images of the densely ridged terrain north of Conamara, the sequence of crack azimuths seems to require >3 non-synchronous rotation periods [11]. Neither of those studies found a continuous (many cracks over a small fraction of a period), monotonic variation in azimuths that would strongly support the non-synchronous model.

Two other studies also raise questions about the simple relationship between Europa's rotation and monotonic change in the crack azimuth. First, in the Astypalaea region (the far south in the anti-Jovian hemisphere) the order in which the most recent cycloidal ridges formed does not match the sequence of longitudes at which they likely formed according to tidal stress theory, suggesting that only one or two cracks form in a given region per rotation period [12]. Second, a study of strike slip faults found evidence for significant polar wander, fairly recent in the age of Europa's surface [13].

A preliminary study of the southern leading hemisphere identified three sets of lineaments, each set

having a typical azimuth, that had formed in a time sequence based on cross-cutting relationships [14]. The result suggested that each set was produced during a particular phase of a single rotational period. However, as with the northern hemisphere results in [10], the azimuth variation reported for the south was neither continuous nor obviously monotonic. Thus, none of the prior results for the leading hemisphere provide independent evidence for non-synchronous rotation, in contrast to the compelling relationships from low resolution images of the other side of Europa [1].

We have now considered more completely the tectonic record in the southern leading hemisphere, systematically using cross-cutting lineaments to constrain the sequence. This approach has several advantages: Compared with [1], it uses images of higher resolution; compared with [10], it is not dependent on the implicit assumptions that underlie a particular geological scenario; and compared with [11] it avoids the special conditions of a small locale. We map tectonic lineaments in this area, and identify their order of formation from cross-cutting relationships. We then determine the sequence of longitudes at which they must have formed to fit the model of tidal stress in non-synchronous rotation, contributing constraints to the dynamical history of Europa.

Method: We have surveyed all tectonic lineaments recognizable in the Galileo E17 RegMap 02 images ($\sim 200\text{m/pixel}$) in longitudes from 20°S to 70°S (further north is dominated by chaotic terrain, and further south is foreshortened). The features of interest are those lineaments that have clear cross-cutting relationships with at least one other lineament. We have tabulated all intersections with a recognizable cross-cutting order, noting which lineament appears to be most recent on that basis. Most of the usable lineaments are double ridges, although ridge complexes and dilational ridges and bands are also represented. The cross-cutting order is based on the appearance of one feature clearly covering over another, except in the case where a crack has breached an apparently earlier ridge or band. Most of the very fine lines on the surface, where topography was unrecognizable, are probably cracks where ridges have not developed, so the cross-cutting relationships among them are not clear, but they are nearly all younger than the cracks with ridges. A set of broad bands that all run nearly north-south are also uncoupled from the crossing relationships with the rest of the population, except that they are all much older than all the other lineaments considered.

We also have measured the azimuthal orientation of the general trend of each lineament. Because lineaments often follow curved or irregular paths, this value is subject to interpretation but is probably meaningful to within several degrees. In most cases, the observed cross-cutting reflects the order in which ridges developed. We assume in this study that the order of ridge formation corresponds to the order of crack formation.

Fitting observations to the theoretical stress scenario: The model of stress changes during non-synchronous rotation predicts that in this region the progression of crack orientations should be counter-clockwise. In an ideal data set, each and every crack in the selected area would cross both the next oldest and next youngest, and the morphology of the intersection would unambiguously display their order of formation. Then, assuming counter-clockwise change in the stress field, the azimuth of the newer one must be greater than the older one or else it must have occurred in a subsequent cycle. By working through the chain of the sequence, one could construct a model "time line" (with azimuth along the abscissa) with each lineament plotted at its azimuth and in the sequence dictated by the cross-cutting order.

Unfortunately, on Europa, even within our limited study area, individual cracks only randomly cross other ones, and only a fraction of intersections display morphologies in which the crack sequence (or more precisely the ridge sequence that we use as its proxy) is evident. Nevertheless, we have been able to use what information is available to constrain the azimuthal formation sequence as well as possible within the limitations of the data.

We have constructed a sequence diagram, which shows that the minimum azimuth rotation is $\sim 740^\circ$, or just over 4 cycles of azimuth (indicating 2 cycles of European rotation). Roughly one additional azimuth cycle would be needed to accommodate the early bands and late cracks. It is important to bear in mind that the number of cycles could be arbitrarily longer, and still fit a monotonic (but not smooth) variation in azimuth. However, it is the minimal number of cycles that gives insight into the history and development of Europa's surface. If so many lineaments were found to fit into a single cycle, it would be powerful evidence for the non-synchronous rotation model. On the other hand, finding a minimum of many cycles could mean either that we are seeing further back into the tectonic record, or that the systematic variation used to infer non-synchronous rotation is not significant.

Discussion: In order to test the significance of our result, we attempted the same analysis with an alternative assumption that crack azimuths changed systematically clockwise (rather than counter-clockwise)

through time. Such a model would require at least 2 1/2 extra cycles of azimuth rotation to fit the observed cross-cutting sequence. Thus there does seem to be some indication that the tectonic record favors the azimuth sequence consistent with non-synchronous rotation.

However, observed tectonic patterns may record an even more complicated dynamical history, even during the fairly recent part of geological history visible in this study. During each crack azimuth cycle, we find that orientations are fairly evenly distributed, although, each cycle does have a range of azimuths that were seemingly avoided by cracks during that cycle. There are patterns in this record that may be indicative of tidal and rotational effects that have not yet been modeled.

If the record does indeed reflect tidal stress over two or three rotation periods, during one cycle a huge number of cracks all formed at the same orientation. This set of cracks is very prominent in regional mapping images (it is lineament set b in [14]). This result is surprising, given that once one crack formed at this orientation, the consequent relief of tension would prevent others from forming [12]. One possibility is that a polar wander event caused stress that created this set of lineaments, superimposed on the systematic record of tectonics driven by non-synchronous rotation.

The tectonic record studied so far covers only the most recent portion of the history of a very young surface. Although some systematic trends are consistent with tidal stress expected during non-synchronous rotation, the record has the potential to tell us much more about the history of tides and other sources of crustal stress.

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