Geofísica Internacional (2004), Vol. 43, Num. 2, pp. 301-306

Evidence for the origin of ridges on Europa by means of photoclinometric data from E4 Galileo orbit

Guadalupe Cordero and Blanca Mendoza
Instituto de Geofísica UNAM, México, D. F., México

Received: March 31, 2002; accepted: August 28, 2002

RESUMEN

Las estructuras más comunes observables en la superficie del satélite joviano Europa son las crestas. La evidencia geológica muestra que estas estructuras se han formado continuamente durante los últimos 10 millones de años. Entender el mecanismo que origina las crestas es fundamental para comprender la historia geológica del satélite y en la búsqueda de agua líquida bajo la corteza de hielo de Europa. En el presente trabajo mostramos evidencias que sugieren que el terreno aledaño a una fractura se deformó debido a la formación de una cresta. Concluímos que ni el modelo volcánico ni él de marea parecen adecuados para explicar las crestas. Sin embargo, el modelo diapírico o un mecanismo similar sí pueden ser responsables de la formación de crestas en Europa.

PALABRAS CLAVE: Europa, crestas, fotoclinometría.

ABSTACT

The most commonly observable structures on the surface of the Jovian satellite Europa are the ridges. Geological evidences show that the ridges have been formed continuously for the last 10 million years. Understanding the mechanism that is originating the ridges is fundamental in order to know the geological history of the satellite, and in the search for liquid water under the icy-surface of Europa. In this work, we show some evidence suggesting that the terrain adjacent to a crack was upwarped due to the formation of ridges. We conclude that neither the volcanic nor the tidal squeezing mechanisms seem to form ridges; however, it is very probable that diapirism or a similar process can form ridges.

KEY WORDS: Europa, ridges, photoclinometry.

INTRODUCTION

Since the flybys of Voyager 1 and Voyager 2, it was evident that the surface of Europa was covered by a series of lineaments whose formation has been a challenge to explain. In recent years, several models have been proposed to account for the origin of these structures (Pappalardo *et al*., 1999, and references therein; Gaidos and Nimmo, 2000): volcanism model, tidal squeezing model, diapirism model, compression model, incremental wedging model and strike-slip model. In all these models, except the last one, the formation of the ridges starts with the formation of a fracture due to tidal stresses. In a general way, the volcanism model proposes that double ridges are formed by gas-driven fissure eruptions; in this case, exsolving gases drag material onto the surface depositing it ballistically on both sides of the crack (Kadel *et al*., 1998). The tidal squeezing model indicates that when a fracture is created the space is occupied by liquid water; some hours later, this water is frozen and when the pattern of stresses changes closing the fracture the frozen water is pumped onto the surface. This process repeats itself several times (Greenberg *et al*., 1998). The diapirism model proposes that a double ridge is formed when a diapir upwarps the ice crust while ascending (Head *et al*., 1998). The compression model says that due to the thermal gradient, the subsurface material is warmer and easier to deform that the near surface ice, then compressive stresses produce more deformation in the subsurface material than in the shallower material, the result is an upwarped crust (Sullivan, 1997). The incremental wedging model indicates that the ridges are formed by the intrusion of a dike under the ridge's axe (Turtle *et al*., 1998). In each one of these models there are two basic ideas: that below the icy crust exists a layer of liquid water or at least warmer ice, and that the fractures pass trough the entire ice layer. Finally, Gaidos and Nimmo (2000) indicate that the fractures cannot cross all the icy crust therefore their formation do not trigger the ridges formation. Instead, they suggest that along the ridges axe there is a strike-slip movement that is able to heat the material in that area, this heating decreases the viscosity of the material which will have a buoyancy force that pushes it toward the surface. According with them, the ascent of this material will produce a double ridge. In this later model liquid water is also required but it is does not need to be shallow.

In order to distinguish among the different formation mechanisms, it is useful to observe what type of structures appear on the outer slopes of the ridges in the places where they cut pre-existing ridges. If mechanisms such as volcanic or tidal squeezing were operating (Kadel *et al*., 1998 and Greenberg *et al*., 1998), we should observe recent ridges covering older ridges. On the other hand, if diapiric, compressional or strike-slip mechanisms were acting (Head and Pappalardo, 1999a, 1999b; Gaidos and Nimmo, 2000), then pre-existing structures should appear upwarped on the outer slopes of younger ridges as a product of late ridge formation.

In this context, the goal of the present work is to find observational support to decide what kind of formation mechanism could produce ridges classes 1, 2 and 3 in agreement with Greenberg *et al*. (1998) classification. In such classification, class 1 ridges are double ridges, class 2 are a series of parallel ridges formed on both sides of a crack and class 3 ridges are like class 2 plus braided ridges.

Since December 1995, the Galileo spacecraft has been exploring the jovian system. His nominal mission, consisting of 11 orbits, has been extended up to 34 orbits plus a final encounter with Jupiter on September 2003. To identify the data each orbit has a letter and a number. The letter indicates the body that Galileo flyby: I is for Io, E is for Europe, G for Ganymede, C for Callisto and J for Jupiter. The number indicates the number of times that Galileo has revolved around the jovian system. In particular, we work with profiles from photoclinometric data obtained during the E4 Galileo orbit as is described in the next section.

PHOTOCLINOMETRIC DATA

As we mentioned above, a key observation to distinguish among different formation mechanisms is to identify pre-existing structures on the outer slopes of the ridges. In particular, we looked for pre-existing ridges (hereafter R1) on the outer slopes of more recent ridges (hereafter R2).

In this section we study crossings between ridges by means of photoclinometric data from E4 Galileo orbit. Figure 1(a) is the image obtained by SSI camera while Figure 1(b) is its photoclinometric image. On this last image, the brighter a pixel the higher its altitude. Lines numbered 1 to 28 show the direction along which the topographical profiles were obtained. Each line was chosen to pass by the middle of the R1 ridge involved in the crossing in order to follow its topography near the R2 ridge and look for upwarps on R1 due to R2.

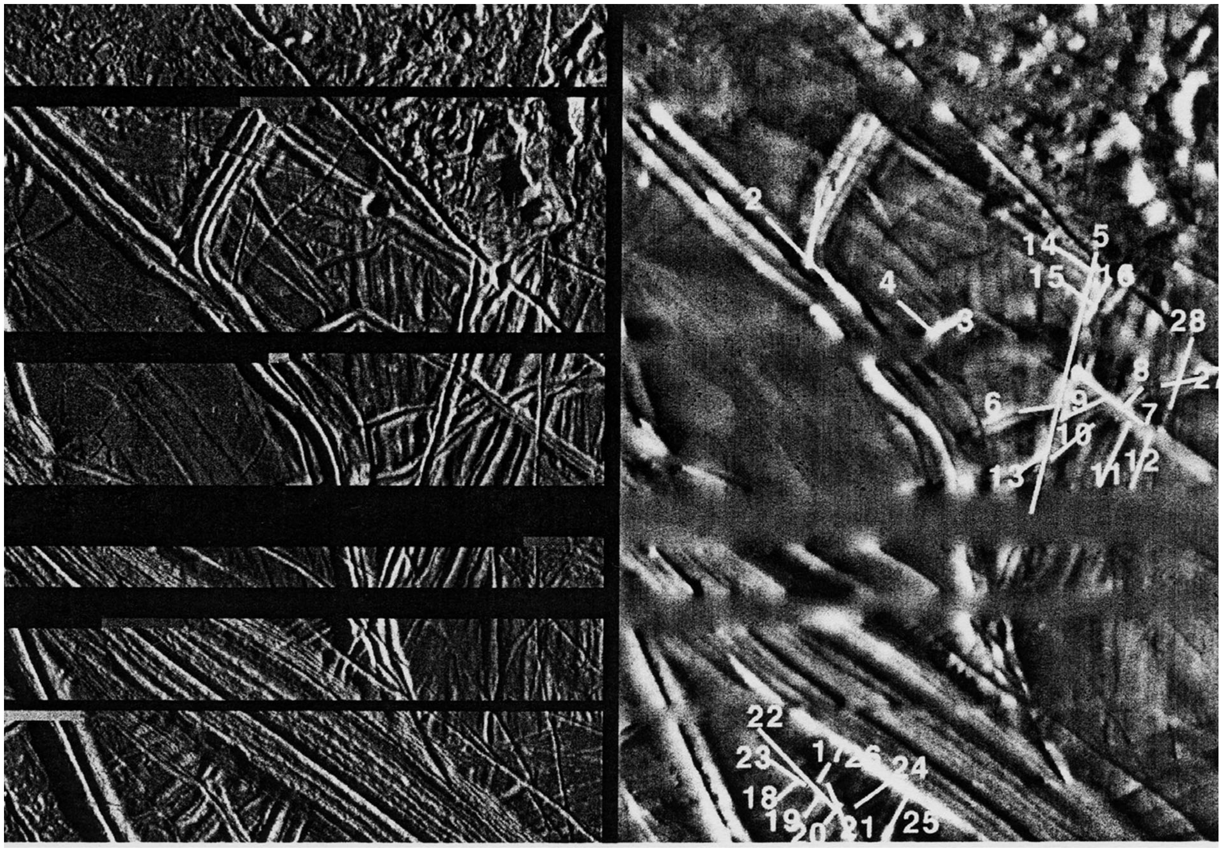
Because of computing problems, we could only obtain either horizontal or vertical profiles from the photoclinometric image, therefore if we wanted to extract the topographical profile along a given line in Figure 1(b), we had to rotate the image in order to make the chosen line horizontal. This process was carried out using the software VICAR.

The previous process left us with 28 rotated photoclinometric images, from which we obtained the topographical profiles along the lines marked in Figure 1(b). To obtain the profile of a given image, the cursor was on a point P through which it passed and the software produced a printed profile. The position of P was registered and the phoclinometric image was printed. Once we had the print the point P was localised on it and a horizontal line was drawn with a pencil through P in order to have a reference. Afterwards we digitised both the profiles and the photoclinometric images.

After digitised, we overlapped each profile with its corresponding rotated image using Surfer software (see Figure 2) in such a way that the line that showed a height of 0 m on the profile coincided with the line we drew on the photoclinometric image. The next step was to “follow” the profile and look for evidences indicating if in any crossing the topography of R1 was upwarped on the outer slope of R2.

In the process we have just described, there are a series of associated errors, mainly because the rotated images and the profiles were first printed and later digitised and because of the uncertainty in the drawing of the lines on the former. For the printing and digitising the errors were systematic, and as we want to study the profiles shape more than the exact values of the height, this kind of errors are not relevant for our purposes. However, a mayor source of uncertainty is the drawing itself of the line, due to the thickness of the pencil and the uncertainties in the localisation of the point. Analysing this problem we concluded that the profile could be ± 2 pixels from the drawn line on the photoclinometric image. Each profile was analysed taking this error into account. In fact, one of the reasons we could not reach a positive conclusion in some cases is due to this source of error.

The results of this analysis are summarised in Table 1. The first column indicates the number assigned to the older ridge associated in a crossing on Figure 1(b). The second column indicates the number associated with the younger ridge involved in that crossing. Here, old and young only indicate which ridge was formed first and which ridge was formed second. The third column indicates deformation "D", probable deformation “P”-, and no deformation or incomplete information "N". The fourth column has our remarks for each crossing, in this column, P1, P2, ... , P28 refers to the profile for which we make the observation. In each en-



(a) **(b)**

Fig. 1. (a) shows the image as it was taken by SSI Galileo camera. (b) is its photoclinometric image. On this image, the numbers identify the direction and the ridge from which we obtained topographic profiles.

try, a final comment is written down to summarise previous observations.

Figures 3 and 4 show two examples out of the 28 profiles that we used. In each profile, the letters indicate the regions where the analysed ridges are localised (see the caption of each figure).

DISCUSSION AND CONCLUSIONS

Although Head and Pappalardo (1999a) have already shown that some Europan ridges are upwarped on their flanks, it is necessary an assessment of how frequently this upwarped ridges appear.

From 23 crossings studied, 36% of them presented evidence of upwarping on pre-existing structures, 18% present a possible upwarp, while for the remaining 46 % either it was not possible to observe such upwarp or our method did not give confident results. The fact that more than 50% of

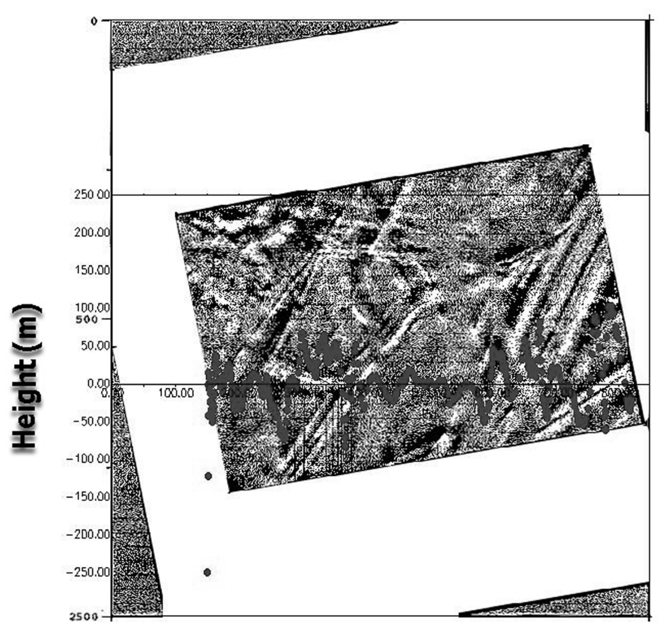


Fig. 2. An example of the way we superposed a topographic image and its profile to look for effects on the ridges' outer slopes.

Table 1

Results from topographical profiles.

R1	R2	NOTES	OBSERVATIONS
1	2	N	P1: In this profile, there is no intersection with R2. P2: Troughs in both sides of R1 matching troughs between R1 ridges (R1 and R2 are triple ridges) Troughs between R1 and R2 probably are due to the formation of R1.
4	3	N	P3: Possible crossing with R4. P4: We do not have information because the profile did not include the crossing. No obvious evidence of upwarp.
6	5	P	P5: There is a protuberance where R6 is, it is a possible upwarp of R6. P6: R6 upwarps on an “appendage” ridge of R5. It is possible that in this case there is an upwarping of the preexisting structure.
9	5	D	P5: We do not have information because this profile is along the ridge of R5 which does not cross R9 (R5 is a doublet ridge). P9: It is not obvious where the ends of R9 are but this ridge appears folded between R5 and R7. The upwarp is not on the outer slopes of R5 but between ridges R5 and R7
10	5	D	P5: We do not have information because this profile is along the ridge of R5 which does not cross R10 (R5 is doublet ridge). P10: One of its ends merges on R5 outer slope. This ridge is folded between R5 and R7. A little upwarp of R10 is observed on the outer slope of R5.
13	5	D	P5: R5 profile shows a protuberance where it crosses R13, it is probably due to the presence of the later ridge. P13: R13 “climbs” on R5 outer slope but it does not reach the top of R5. Very probable upwarp of R13.
14	5	D	P5: There is a protuberance probably related with R4. P14: R4 profile appears upwarped on R5 outer slope. There is evidence that R14 is upwarped.
15	5	N	P5: There is a protuberance probably related with R15. P15: There is no upwarping. R15 stays at the “base” of R5.
16	5	N	P5: R16 is part of R5.
8	7	D	P7: There are few protuberances related with R8. P8: R8 climbs outer slope of R7. There is evidence of upwarping.
9	7	D	P7: We do not have information because this profile is along the ridge of R7 which does not crosses R9 (R7 is doublet ridge). P9: R9 is folded between R5 y R7. R9 is upwarped.
10	7	P	P7: We do not have information because this profile is along the ridge of R7 which does not crosses R10 (R7 is doublet ridge). P10: There is no clear evidence of upwarping but it shows a fall before R7. Possible upwarping.
11	7	P	P7: We do not have information because this profile is along the ridge of R7 which does not crosses R11 (R7 is doublet ridge). P11: R11 is bended before it climbs a part on R7. Evidence of possible upwarping.
12	7	N	P7: We do not have information because this profile is along the ridge of R7 which does not crosses R12 (R7 is doublet ridge). P12: R12 stays at the base of R7. There is no evidence of upwarp.
17	22	N	P17: R17 ascends uniformly from its crosscut R26 to it crosscut R22. Evidence of upwarping is poor. P22: There is no information because R22 “start” at the center of R17. There is no evidence of upwarping.
17	26	N	P17: R17 starts at the base of R26, but it is difficult to identify it due to washboard texture parallel to R26. P26: There is not evidence of upwarping.
18	23	P	P18: It behaves like R17, but in this case R18 climbs on R23. P23: There is a protuberance in R23 due to R28. Possible upwarping (?)
19	22	D	P19: R19 climbs R22 as far as R22 top! P22: The crossing between R19 and R22 is the clearest evidence of upwarping.
20	21	N	P20: There is a little trough between ridges. There is no evidence of upwarping. P21: There is no evidence of upwarping
24	26	P	P24: R24 bends between R26 and R21. P26: In the intersections with R24 and R25 there are protuberances There are evidences that R24 climbs on R26.
25	26	P	P25: R25 bends before climbing R26. P26: In the intersections with R24 and R25 there are protuberances. There are evidences that R25 climbs on R26.
28	7	N	P7: Protuberances probably associated with R28. P28: Uncertain intersection. There is no evidence of upwarping.
28	27	P	P27: There is no evidence of upwarping. P28: R28 bends before it climbs a short part on R27. Possible upwarping (?)

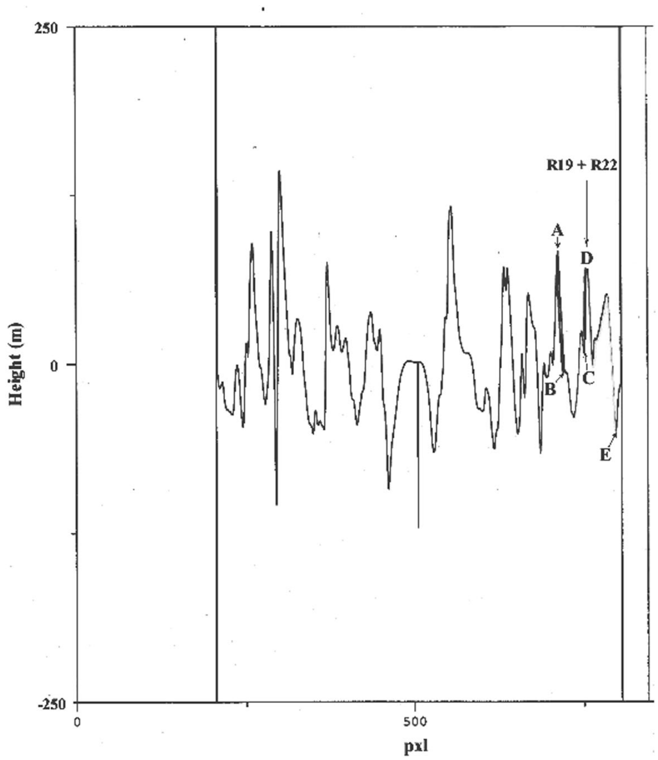


Fig. 3. Profile obtained along the line 19 in Figure 1(b). The topographic profile of ridge 19 is from point D to point E; P26 is from A to B; P17 is from B to C and P22 is from C to D. The longest arrow shows the combined topography of R19 and R22.

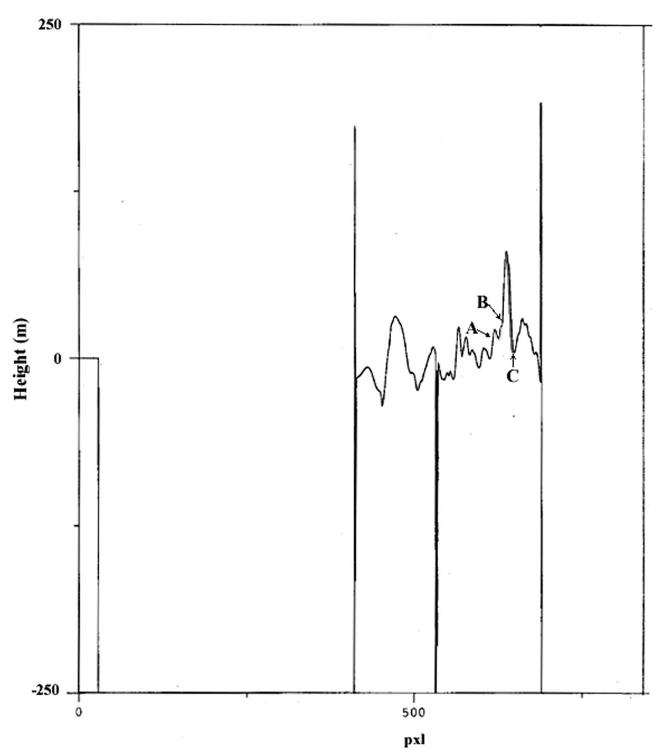


Fig. 4. Profile of R22. The topographic profile of R22 is from A to B, R19 is from B to C.

the analysed crossings presented evidences showing that the younger ridge upwarps on the pre-existing ridge, suggests that the process that forms ridges is a mechanism that deforms the surface. Why we can not see this upwarping on all the crossings? Kadel (1998) has pointed out that a process of mass wasting is masking the formation mechanism of the ridges. Moore *et al.* (1999) concluded that dry sliding or slumping and sputter ablation are the principal mechanisms of degradation of Europa's surface. During this work we noticed that the identification of upwarped ridges does not depend on their relative age. We interpreted this as an indication that the mayor degrading mechanism on the ridges is dry sliding or slumping and that this process occurred at the moment that the R2 ridge is formed or a little after, otherwise we could not notice upwarping on older ridges.

On the basis of our analysis, we find that the data are consistent with the diapirism or the stike-slip models. Due to the possible problems in the formation of fractures noticed by Gaidos and Nimmo (2000) perhaps the most probable mechanism is the later but we will have a definitive answer until the next decade when the Europa Orbiter will study the satellite.

ACKNOWLEDGEMENTS

This work was partially carried out while G. Cordero was a visiting scholar at Brown University in the Planetary Geosciences Group. Thanks are extended to the Galileo SSI team and members of the Planetary Geosciences group at Brown, especially to Dr. James W. Head III.

BIBLIOGRAPHY

GAIDOS, E. J. and F. NIMMO, 2000. Tectonics and water on Europa. *Nature, 405*, 637.

GREENBERG, R., P. GEISSLER, G. HOPPA, B. R. TUFTS, D. D. DURDA, R. PAPPALARDO, J. W. HEAD, R. GREELEY, R. SULLIVAN and M. H. CARR, 1998. Tectonic processes on Europa: tidal stresses, mechanical response, and visible features. *Icarus, 135,* 64-78.

HEAD, J. W., R. PAPPALARDO, 1999a. Europa: morphologic characteristics of ridges and triple bands from Galileo data (E4 and E6) and assessment of a linear diapirism model. *J. Geophys. Res., 104,* E10, 24223-24236.

HEAD, J. W., R. PAPPALARDO, 1999b. Brine mobilization during lithospheric heating on Europa: implications for formation of chaos terrain, lenticulae texture, and color variations. *J. Geophys. Res., 104,* E11, 27143-27155.

KADEL, S.D., S. A. FAGENTS, R. GREELEY and SSI GALILEO TEAM, 1998. Trough-bounding ridge pairs on Europa - considerations for an endogenic model of formation. Lunar Planet. Sci. Conf. XXIX, abstract # 1078, Lunar and Planetary Institute, Houston (CD-ROM).

MOORE, J. M., E. ASPHAUG, D. MORRISON, C. R. CHAPMAN, R. CLARK, B. BIERHAUS, J. R. SPENCER, R. J. SULLIVAN, F. C. CHUANG, J. E. KLEMASZEWSKI, R. GREELEY, K. C. BENDER, P. E. GEISSLER, P. HELFENSTEIN and C. B. PILCHER, 1999. Mass movement and landform degradation on the icy Galilean satellites: results of the Galileo Nominal Mission. *Icarus, 140,* 294-312.

PAPPALARDO, R.T., M.J.S. BELTON, H.H. BRENEMAN, M.H. CARR, C. R. CHAPMAN, G.C. COLLINS, T. DENK, S. FAGENTS, P.E. GEISSLER, B. GIESE, R. GREELEY, R. GREENBERG, J.W. HEAD, P. HELFENSTEIN, G. HOPPA, S. D. KADEL, K. P. KLAASEN, J. E. KLEMASZEWSKI, K. MAGEE, A. S. MCEWEN, J. M. MOORE, W. B. MOORE, G. NEUKUM, C. B. PHILLIPS, L. M. PROCKTER, G. SCHUBERT, D. A. SENSKE, R. J. SULLIVAN, B. R. TUFTS, E. P. TURTLE, R. WAGNER and K. K. WILLIAMS, 1999. Does Europa have a subsurface ocean? evaluation of the geological evidence. *J. Geophys. Res., 104,* E10, 24015-24056.

SULLIVAN, R., R. GREELEY, J. KLEMASZEWSKI, M. KRAFT, J. MOREAU, K. WILLIAMS, M.J.S. BELTON, M. CARR, C. CHAPMAN, B. CLARK, P. GEISSLER, R. GREENBERG, R. TUFTS, J. W. HEAD, R. PAPPALARDO and J. MOORE, 1997. Ridge formation on Europa: examples from Galileo high resolution images. GSA Abstr. with Prog., 29, A-312.

TURTLE, E. P., H. J. MELOSH and C. B. PHILLIPS, 1998. Europan ridges: tectonic response to dike intrusion. ESO, 79, S202.

Guadalupe Cordero and Blanca Mendoza
Instituto de Geofísica UNAM, Ciudad Universitaria, 04510 México, D. F., México
Email: gcordero@geofisica.unam.mx