

Does folding accommodate Europa's contractional strain? The effect of surface temperature on fold formation in ice lithospheres

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[1] On Europa, the mechanism by which contractional strains are accommodated remains a mystery. Subtle folds have been observed in the polar regions, but if folding is a dominant accommodation mechanism, ubiquitous large-amplitude folds might be expected across Europa's surface. Here we use finite element modeling to show that fold growth rates are a strong function of surface temperature: warm temperatures result in lower rates, whereas cold temperatures result in higher rates. Combining diurnally averaged European surface temperatures derived from Galileo photopolarimeter-radiometer data and new numerical simulations, we show that forming moderate-amplitude folds requires roughly twice the contraction, or shortening, in Europa's equatorial latitudes relative to polar latitudes. Relatively large contractional strains in Europa's equatorial and midlatitudes can therefore be accommodated primarily through passive shortening without producing obvious folds. Lithospheric folding and/or passive shortening therefore remain plausible mechanisms for strain accommodation on Europa. **Citation:** Bland, M. T., and W. B. McKinnon (2013), Does folding accommodate Europa's contractional strain? The effect of surface temperature on fold formation in ice lithospheres, *Geophys. Res. Lett.*, 40, 2534–2538, doi:10.1002/grl.50506.

1. Introduction

[2] Tectonic deformation observed on Europa's surface has been predominately interpreted to form in extension or shear (see *Kattenhorn and Hurford* [2009] for a review). In particular, the formation of bands, which cover 5% of Europa's surface and may involve emplacement of new surface ice, imply large global and local surface extension [*Kattenhorn and Hurford*, 2009]. The surface of Europa's neighbor, Ganymede, is also dominated by extensional features, but there differentiation [e.g., *Squyres*, 1980] or melting of high-pressure ice phases [*Showman et al.*, 1997] likely resulted in global expansion of the satellite. Europa lacks high-pressure ice, so a similar global expansion is precluded. Cooling and freezing of Europa's ice shell *does*

result in large isotropic tensile stresses, but the resulting strains are small [*Nimmo*, 2004b]. On Europa, large extensional strains *must* be balanced by contraction or shortening elsewhere on the satellite. Despite the potentially large strain magnitudes involved, few features unequivocally formed in contraction have been identified.

[3] Several mechanisms have been proposed for accommodating contractional strain on Europa (see *Bland and McKinnon* [2012] for a complete discussion). One of the more convincing mechanisms is folding of Europa's ice lithosphere. Putative folds have been identified at Astypalaea and Libya Linea at high southern latitudes [*Prockter and Pappalardo*, 2000]. Another (somewhat less convincing) fold has been proposed to occur in the Manannán region near Europa's equator [*Prockter and Pappalardo*, 2000]. Analysis of the most promising of these folds (those at Astypalaea) indicate a fold wavelength of 25 km [*Prockter and Pappalardo*, 2000] and an amplitude of 200–250 m [*Bland and McKinnon*, 2012; *Dombard and McKinnon*, 2006]. Using a simple geometrical analysis, *Prockter and Pappalardo* [2000] inferred that the folds at Astypalaea accommodated rather small contractional strains (0.02–0.2%) when referenced to the now-known vertical relief. The small strains inferred for the Astypalaea folds pose two difficulties. First, such fold formation clearly could not accommodate the large contractional strains expected on Europa and thus could not explain Europa's apparent strain imbalance. Second, if moderate-amplitude folds form at very small strains (0.5% or less), we might expect to observe numerous folds even in the sparse high-resolution imaging available (i.e., nearly *any* contraction would produce a fold); yet, only two or three candidates have been identified.

[4] Recently, *Bland and McKinnon* [2012] reexamined fold formation on Europa using finite element modeling of contraction of an ice lithosphere. This analysis indicated that, as with terrestrial folding, folds on icy satellites require larger strains to form (relative to those inferred from a purely geometrical analysis) due to an incipient nucleation stage of passive lithospheric shortening before actual folding (exponential growth) occurs. Under arguably nominal conditions appropriate for the Astypalaea region of Europa (strain rate of 10^{-13} s^{-1} , surface temperature of 80 K), the formation of 200 m amplitude folds required ~6% shortening of the lithosphere (a number we revise downward in this paper). By decreasing the strain rate and/or the ice grain size (both of which affect effective viscosity), *Bland and McKinnon* [2012] found that Astypalaea-like folds could be formed at strains as low as 2%, still an order of magnitude more than geometrical arguments suggested.

[5] Despite these results, the relative *lack* of observed folds on Europa remains puzzling. Contractional strains on Europa could be quite large. Adjacent to large bands (which

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average ~ 30 km in width [Prockter and Patterson, 2009]), local strains could reach $>15\%$ if strain is taken up over a 100 km wide swath on either side of the band. If these strains were accommodated by folding (as opposed to, e.g., thrust faulting, see section 2.2 in Kattenhorn and Hurford [2009]), the work of Bland and McKinnon [2012] indicates that fold amplitudes could reach 1 km or more. Large-amplitude folds should therefore be ubiquitous on Europa, but only a few subtle folds are observed. Here we address the fundamental question of why we do not see such folds across much of Europa: a question central to the feasibility of folding as a general mechanism of strain accommodation. Using finite element modeling, we show that fold growth is a strong function of surface temperature. Fold growth is promoted by the cold surface temperatures in Europa's polar region (where the best fold candidates are observed). Significantly, the analysis of Bland and McKinnon [2012], which focused on the folds at Astypalaea, assumed near-polar surface temperatures (80 K). In contrast, we find that fold formation is inhibited by Europa's relatively warm equatorial and midlatitude temperatures. Whereas folds are expected at high latitudes, larger strains can be accommodated through passive lithospheric thickening *without* producing large-amplitude, easily observable folds in the equatorial latitudes. We should therefore expect folds at low latitudes to be lower in amplitude and harder to observe than folds in the polar regions. Our models also constrain the form of strain weakening in compression on Europa that is consistent with the folding we do see.

2. Modeling Fold Formation

[6] We use the finite element code Tekton2.3 [Melosh and Raefsky, 1980] to simulate the compression of an ice lithosphere overlying ductile ice. Our model domain is 80 km to 160 km long and 16 km to 24 km deep (depending on the thermal structure), with a horizontal resolution of 333 m and a vertical resolution that varies from up to 167 m near the surface to 500 m at depth. A low-amplitude (15 m total relief), semi-random topographic perturbation is imposed on the initial domain, consisting of 80 co-added sinusoids with random wavelengths and phase shifts. The model results (i.e., final fold amplitude) are dependent on the amplitude of the initial perturbation [Bland and McKinnon, 2012], but 15 m of total relief is quite modest compared with fine-scale band topography, given that even the smoothest bands on Europa are rough at higher resolutions (10–100 m pixel⁻¹) [Prockter and Patterson, 2009]. Also, given the exponential nature of fold growth, the fundamental results of this paper are not affected by offsets in the percent shortening required for a given fold amplitude. Shortening is produced with a fixed horizontal (x direction) boundary condition on the left side of the domain and constant horizontal velocity condition on the right. A free-slip condition is imposed in the vertical direction (y) on the left and right boundaries and in the horizontal direction on the bottom boundary. The bottom boundary is fixed in the vertical, and the top of the domain is a free surface.

[7] Bierhaus *et al.* [2009] estimate a surface age for Europa of 65 ± 25 Ma, which sets a minimum strain rate of $\sim 10^{-17}$ s⁻¹ for contractional strains of order 0.1. However,

the rate of band formation [e.g., Stempel *et al.*, 2005; Nimmo, 2004a] (a process which may be linked to fold formation), and the intermediate age of the folds at Astypalaea Linea [Geissler *et al.*, 1998; Prockter and Patterson, 2009] argue for higher strain rates of $\sim 10^{-14}$ s⁻¹ to $\sim 10^{-13}$ s⁻¹. The effect of strain rate on fold growth was described in detail in Bland and McKinnon [2012]. Here we use a “nominal” strain rate of $\sim 10^{-13}$ s⁻¹, which corresponds to 10% shortening in 3.17×10^4 years. Lower strain rates generally produce larger-amplitude folds.

[8] The model is viscoelastic-plastic and uses a composite flow law that includes dislocation creep (three regimes), grain boundary sliding (GBS), basal slip, and diffusion creep (see Durham and Stern [2001] for a review). The GBS and diffusion creep mechanisms are grain-size sensitive. We use a nominal grain size (d) of 1 mm, consistent with grains found in terrestrial polar glaciers (the closest analog to ice in the outer Solar System) and models of grain-size evolution on icy satellites (see discussion in Bland and McKinnon [2012]). The Young's modulus and Poisson's ratio were 9.33 GPa and 0.325, respectively [Gammon *et al.*, 1983], appropriate for solid ice. The density was 930 kg m⁻³, consistent with slightly dirty ice. We utilize a von Mises yield criterion (which prevents element dilation during plastic failure) with an associated plastic flow law. The magnitude of the differential stress in each simulation was equated to the differential stress at the brittle-ductile transition (see Bland and McKinnon [2012] for details).

[9] The viscosity structure is determined by the vertical temperature profile. We examine heat fluxes (q) of 50, 75, and 100 mW m⁻², consistent with previous estimates of European fold formation [Dombard and McKinnon, 2006; Bland and McKinnon, 2012]. The thermal conductivity of pure, solid water ice (k) is temperature dependent such that $k = 651 \text{ W m}^{-1}/T$, where T is the temperature [Petrenko and Whitworth, 1999]. The temperature at a given depth (y) is then $T(y) = T_s \exp(qy/651 \text{ W m}^{-1})$, where T_s is the surface temperature. Surface temperatures were varied between 70 K and 120 K, consistent with diurnally averaged temperatures on Europa (see auxiliary material). Prescribing the heat flux rather than assuming a linear thermal gradient departs from previous modeling [e.g., Bland and McKinnon, 2012] and results in a modest increase in the strength contrast between the lithosphere and underlying ice “asthenosphere” but is more realistic. The increased strength contrast leads to modestly increased fold amplitudes for a given strain. The temperature field is advected as the elements deform but does not conductively reequilibrate. This does not affect our results given the small surface deflections modeled.

[10] For numerical efficiency, we limit the maximum temperature (T_{max}) at depth to 220 K. This temperature maximum slightly inhibits fold growth relative to a “real” ice shell where T_{max} is near 270 K (for a conductive ice shell) or 250–260 K (for a convective shell). The T_{max} used here is, however, 20 K greater than that used in Bland and McKinnon [2012], resulting in greater fold amplification at a given strain. Numerical tests increasing T_{max} above 220 K yield only slightly greater fold amplification and at substantial computational cost. Ultimate fold amplitudes at large shortenings are not affected, however. That is, fold amplitudes “top off” due to a transition to kinematic (accordion-like) shortening [Schmalholz, 2006].

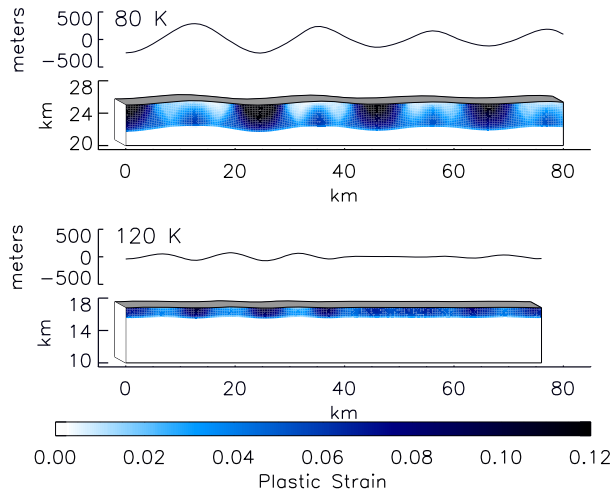


Figure 1. Upper portion of the finite element mesh and the trace of the surface deformation after 5% shortening for two simulations with $q = 100 \text{ mW m}^{-2}$ but with different surface temperatures. Note that only a portion of the domain is shown to reduce the vertical exaggeration.

3. Model Results

[11] Figure 1 shows the morphology of the surface deformation and distribution of plastic strain within our finite element mesh after 5% shortening and illustrates the effect of surface temperature on fold instability growth. In general, strain is concentrated in fold troughs, and the surface deformation is strongly periodic. Surface temperature clearly plays a strong role in controlling fold growth: cold surface temperatures result in thicker lithospheres and larger fold amplitudes than warm surface temperatures. The effect of surface temperature is illustrated under a broader range of conditions in Figure 2. For a given heat flux, each simulation was identical ($\dot{\epsilon} = 10^{-13} \text{ s}^{-1}$, $d = 1 \text{ mm}$) except for the surface temperature used. After 2% shortening, simulations with colder surface temperatures already exhibit larger fold amplitudes than simulations that used warmer surface temperatures. For a simulation with a heat flux of 100 mW m^{-2} , maximum fold amplitudes have reached 110 m with $T_s = 80 \text{ K}$ but only 22 m with $T_s = 120 \text{ K}$. At larger strains, substantial differences remain. For 10% shortening, simulations with $T_s = 80 \text{ K}$ yield folds amplitudes 3–4 \times larger than a simulation with $T_s = 120 \text{ K}$.

[12] In many cases, the local surface temperature is more important in determining fold growth rates than either the heat flux or the strain magnitude. After 5% shortening, larger fold amplitudes result from simulations with cold surface temperature (70–80 K) and a low heat flux (50 mW m^{-2}) than from a simulation with larger heat flux ($75\text{--}100 \text{ mW m}^{-2}$) and warmer surface temperatures. The effect of surface temperature is, however, convolved with the effect of a natural transition to kinematic fold growth (i.e., decreased instability growth rates), which occurs at lower strains for higher thermal gradients [Bland and McKinnon, 2012; Bland and Showman, 2007]. Furthermore, for a heat flux of 50 mW m^{-2} , fold amplitudes in simulations with $T_s \leq 80 \text{ K}$ are greater after 5% shortening than fold amplitudes in a simulation with $T_s = 120 \text{ K}$ after 10% shortening. Thus, under otherwise identical conditions, folds formed at $T_s = 120 \text{ K}$ can

accommodate roughly twice the contraction of folds formed at $T_s = 70 \text{ K}$ while producing similar fold amplitudes.

[13] The decrease in fold amplitudes at warm surface temperatures is fundamentally a result of the decrease in rheological contrast between near-surface ice and the ductile ice at depth. Figure 3 shows strength envelopes for ice lithospheres with surface temperatures of 80 K, 100 K, and 120 K. As the surface temperature increases, the lithosphere becomes thinner and unable to support large stresses (and ultimately large folds). Maximum stresses are nearly a factor of 2 larger for a cold lithosphere ($T_s = 80 \text{ K}$) than for a warm lithosphere ($T_s = 120 \text{ K}$). The growth rate of a single-layer fold instability depends principally on the strength contrast between the layer and the surrounding substrate: larger strength contrasts yield larger-amplitude folds (see, e.g., Hudleston and Treagus [2010] for a recent review). The viscosity of the warm ice at depth is largely independent of surface conditions (Figure 3). The strength contrast is therefore dictated by the strength of the lithosphere compared with how rapidly it decreases with depth (e-folding depth; see Dombard and McKinnon [2001]). The larger stresses supported by the cold lithosphere result in larger fold amplitudes, even though the e-folding depth of the viscosity is somewhat larger for a cold lithosphere than a warm lithosphere, due to the different rheological controls (dislocation creep “C” versus dislocation creep “B”).

4. Application to Europa and Beyond

[14] By combining a diurnally averaged latitudinal profile of Europa’s surface temperature (derived from Galileo photopolarimeter-radiometer data and theoretical calculations; see auxiliary material) and the numerical results shown in Figure 2, we can infer the conditions necessary for fold formation as a function of latitude on Europa. Figure 4a shows the maximum fold amplitudes after 3% contraction of the lithosphere. Fold amplitudes in the equatorial regions are one-half to one-eighth those in the polar region, depending on the heat flux: 51 m versus 410 m for $q = 50 \text{ mW m}^{-2}$ and 150 m versus 330 m for $q = 100 \text{ mW m}^{-2}$. Figure 4b

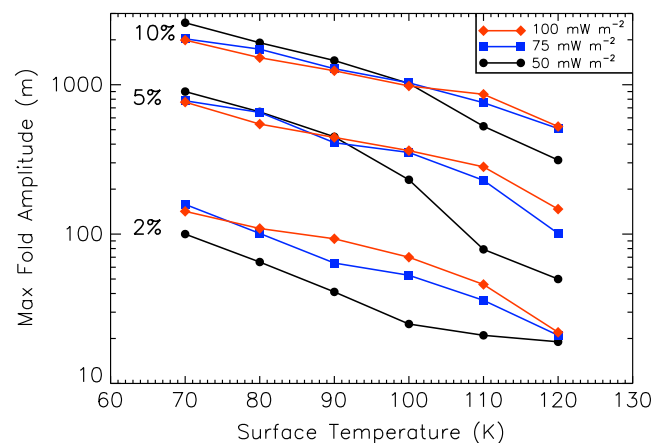


Figure 2. Maximum fold amplitudes (peak-to-trough) as a function of surface temperature at three different shortenings: 2%, 5%, and 10%. The pattern observed is not simple (note cross-overs) because of varying amounts of fold amplification in exponential and kinematic growth, respectively.

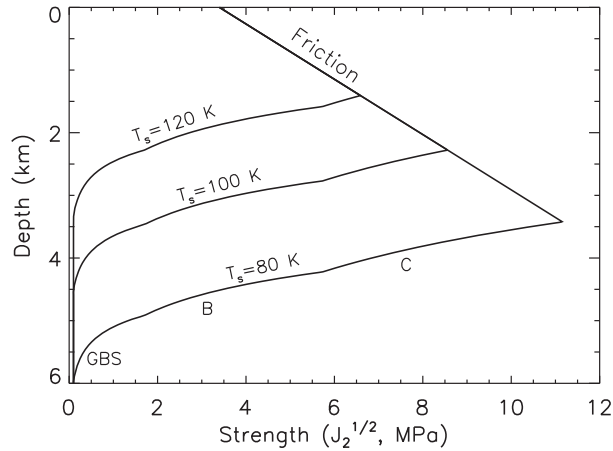


Figure 3. Theoretical strength envelopes for an ice lithosphere with surface temperatures of 80 K, 100 K, and 120 K. The frictional strength is that of *Beeman et al.* [1988]. The viscous portion of each envelope is dominated by dislocation creep (regimes ‘C’ and ‘B’ [see, e.g., *Durham and Stern*, 2001]) and grain boundary sliding (GBS). Rheological transitions appear as cusps in the viscous portion of the envelope.

shows the strain required to produce Astypalaea-like folds (i.e., 200 m amplitude) as a function of latitude. In the polar regions where temperatures are low, 200 m amplitude folds form with 2–3% lithospheric shortening. In contrast, producing similar folds in the equatorial region requires 3.5–5% shortening, nearly a factor of 2 increase. If an insulating regolith increased lithospheric temperatures by 10 K (as is likely for Europa [Moore et al., 2009]; see auxiliary material), forming even moderate-amplitude folds would require up to 9% contraction in the equatorial regions.

[15] Figure 4 illustrates the difficulty of forming folds over much of Europa’s surface. In Europa’s equatorial and midlatitudes, contractional strains of 3–9% can be accommodated primarily by lithospheric shortening rather than folding (assuming an insulating regolith), especially if heat fluxes remain modest (and in the absence of faulting, a point returned to below). In these regions, contraction can occur without producing obvious surface deformation. Europa’s apparent strain imbalance may therefore be just that. The greater abundance of tectonic features formed in extension relative to those formed in contraction may be a function not of strain magnitude but of the roughly order of magnitude difference between the failure strength of ice in tension and compression [e.g., *Schulson and Duval*, 2009, Figure 11.3]. Ice in tension will fracture readily, leading to the formation of obvious surface features such as troughs and bands. In contrast, ice in compression may be strong enough to avoid large-scale fracturing at typical European stress levels, consistent with a lack of observed large-scale thrust scarps on Europa (at least at the limits of current resolution) [Kattenhorn and Hurford, 2009]. Instead, the lithosphere may simply undergo passive shortening and moderate-amplitude folding as described here. Such subtle surface features are far more difficult to observe.

[16] The numerical models presented here update the results of *Bland and McKinnon* [2012]. Formation of folds at Astypalaea linea probably require no more than 2–3%

shortening, similar to the strain estimate adopted by *Dombard and McKinnon* [2006]. Fold amplification rates are also more similar to, though still not as great as, those in the analytical models. A natural question to ask is why folding as opposed to faulting? We do not claim faulting is not occurring, as it clearly dominates Europa’s tectonics, especially in extension [Kattenhorn and Hurford, 2009]. But the evidence from Europa itself is that young ice lithosphere is strong in compression and can tolerate up to 2–3% shortening with only minor secondary faults forming at fold hinges [Prockter and Pappalardo, 2000]. Presumably, even greater amounts of uniform shortening can be tolerated in Europa’s warmer, low-latitude regions (Figure 4b). We have run a series of numerical tests of lithospheric shortening including strain weakening [after *Bland et al.*, 2010] and find that simultaneously reproducing both low-amplitude folds and small-scale localized brittle failure is challenging. The simplest solution may be to set a critical strain that must be reached before weakening begins, as in the continental collision models of *Gerbaulet et al.* [2003]. This will be the subject of a future paper.

[17] The effect of surface temperature on icy satellite tectonics has been discussed previously [Herrick and

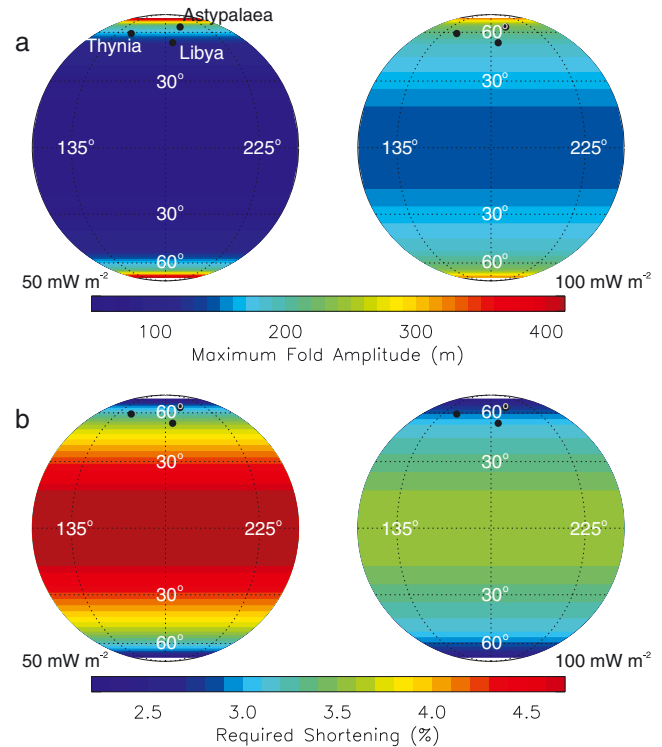


Figure 4. (a) Contours of the maximum fold amplitudes after 3% shortening for heat fluxes of 50 (left) and 100 mW m^{-2} (right) mapped onto the surface of Europa assuming diurnally averaged, PPR-derived latitudinal variations in surface temperature ($T_s \sim 70$ K at the poles and $T_s \sim 100$ K at the equator; see auxiliary material). Note that surface temperatures are effectively constant below 15° latitude. Black dots indicate the approximate location of Linea discussed in the text, though note that south is up. (b) As in Figure 4a but for the minimum strain required to produce Astypalaea-like (200 m amplitude) folds.

Stevenson, 1990; Dombard and McKinnon, 2001, 2006], and the results described here apply equally well to the other icy satellites. Satellites with relatively warm surfaces, such as Ganymede, can in principle accommodate several percent contraction through passive thickening *without* folding, which may significantly alter their inferred global strain balance [cf. Collins, 2006]. In contrast, the colder satellites beyond Jupiter might exhibit more obvious folding, such as those suggested to bound the South Polar Terrain of Enceladus [Beddingfield *et al.*, 2013].

5. Does Folding Accommodate Europa's Contractual Strain?

[18] We have demonstrated that warm surface temperatures inhibit fold growth. However, the corollary is also true: cold temperatures enhance fold growth. If contractual strains were large (as we argue in the introduction), we might expect to observe extensive sets of moderate or large-amplitude folds in Europa's polar regions. Yet few folds have been identified. The apparent absence of folds may be attributed to observational bias. Identification of folds on Europa requires moderate resolution images and low sun angles. Less than 10% of Europa's surface has been imaged at resolutions better than 200 m/pixel, and less than half of the polar regions (latitudes above 55°) have been imaged at resolutions better than 900 m/pixel [Schenk, 2010]. The folds at Astypalaea linea (65°S) were identified in high-resolution targeted imaging with a resolution of 40 m/pixel and a sun angle of just 13°, and the near-polar putative folds at Libya Linea (52°S) were identified in imaging with a resolution of 42 m/pixel and a sun angle of 31° [Prockter and Pappalardo, 2000]. Other polar regions have been imaged at equivalent resolutions and geometries (e.g., Thynia Linea, where folds have not yet been identified, at 59°S, imaged at 40 m/pixel and a sun angle of 22°), but coverage at the resolution and sun angles necessary to identify subtle fold features is far from complete. Furthermore, the relatively small surface area that constitutes the polar regions of Europa suggests that the absolute number of folds in the region may be low. Only ~10% of Europa's surface has a diurnally average surface temperature of 80 K or less (i.e., is above 65° latitude). In contrast, roughly half of Europa's surface has a temperature near 100 K.

[19] If much of Europa's extensional strain is balanced by folding and/or passive thickening, then two patterns should emerge that could be observed by future spacecraft. First, long-wavelength, low- to moderate-amplitude folds should be common on Europa. Given the complex tectonic disruption of Europa's surface, identifying such folds may be difficult even in future higher-resolution imaging (the folds at Astypalaea and Libya linea were identified on smooth bands). However, suitable low-sun imagery or topographic data sets from stereo imaging or laser altimetry may reveal their existence. Second, if folds can be identified, more folds (in a relative sense) or larger-amplitude folds are expected in the polar regions than at low latitudes.

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