USING EUROPAN DOUBLE RIDGE MORPHOLOGY TO TEST PROPOSED MODELS OF FORMATION. A. C. Dameron[1] and D. M. Burr[1], [1]Earth and Planetary Sciences Department, University of Tennessee, Knoxville, TN, USA (adameron@vols.utk.edu)

Introduction: Double ridges are ubiquitous surface features on Europa. These features consist of two raised ridges on either side of a central trough (Figure 1). Several models have been proposed to explain their formation. Existing models can be grouped into two classes: mechanisms that produce steep interior slopes (i.e. diapirism, compression, shear heating) and mechanisms that produce shallow interior slopes (i.e. cryovolcanism, tidal squeezing). Slope data derived from two independent sources are used to test between two classes of proposed formation mechanisms based on two criteria: both measured and calculated values for double ridge interior slopes, and the symmetry of interior and exterior slopes.

Formation Models: Each of the proposed formation models involves a vertical fracture formed in a prior crustal stress state and has its own implications for the Europan subsurface.

Shallow interior slope-angle mechanisms. Double ridges have been proposed to form via cryovolcanic mechanisms [1]. On Europa, cryovolcanism involves the eruption or emplacement of H_2O-rich materials. Explosive cryovolcanic eruptions would result in granular ice deposited on either side of a fracture, lying at or below the angle of repose of ice. Effusive cryovolcanism would emplace cryolava flows, which would also have shallow large-scale slopes. A tidal squeezing mechanism has also been proposed [2]. In this model, the diurnal stresses experienced on Europan fractures cause vertical fractures to open and close. As a fracture opens, water rises up to the surface, where it then freezes. As the fracture closes, crushed ice particles and slush rise up through the conduit and are deposited on either side of the fracture. This material may fall inward, further shallowing the final slope.

These mechanisms should produce double ridges with interior and exterior slopes at or less than the angle of repose. This angle, taken to be ~34° for terrestrial materials, may steepen slightly under lower gravity as on Europa [3]. Interior and exterior slope symmetry is expected for ridges created via explosive cryovolcanism, although it is not expected for tidal squeezing or extrusive volcanism.

Steep interior slope-angle mechanisms. Another model for the formation of double ridges is linear diapirism, which involves ductile plumes of ice rising under previously fractured brittle surface ice [4]. Plumes of locally warmer ice rise due to density differences with the brittle ice above, which cause surface deformation to produce double ridges.

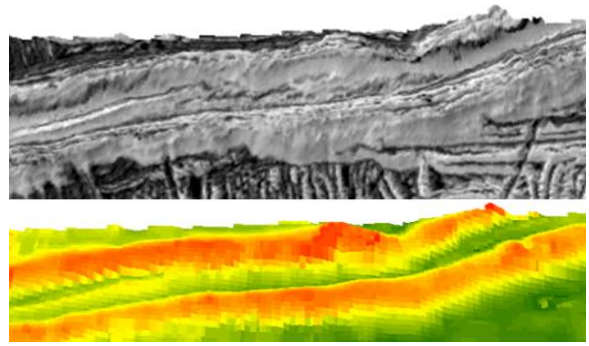

Figure 1. Double ridge (upper) and DEM (lower).

Ice on either side of fractures can also be warmed by shearing . A shear heating model also involves a rising, more ductile ice layer deforming brittle, fractured surface ice [5]. A compression model requires a stress state sufficient to produce symmetric lithospheric buckling to form double ridges [6].

For each of these mechanisms, uplift of preexisting vertical fractures would result in steep interior slopes and asymmetry between these steeper interior and shallower exterior slopes.

Methods: Data derived from double ridge digital elevation models (DEMs) and shadow measurements are used to classify double ridges as having shallow or steep slope-angles.

DEMs: Eight DEMs were generated in this work. Five DEMs were created using SOCET-SET software, and three DEMs were created using Ames Stereo Pipeline (ASP) in ISIS. Individual profile lines were taken in ArcMap and exported to Excel to find the interior and exterior slopes.

Shadow Measurement Techniques. Two shadow measurement techniques were used to derive double ridge interior slopes: a more rigorous technique measuring the shadow length interior to the double ridge, and a simplified technique measuring exterior shadow length (Figure 2). Slope values from both techniques were compared along individual profiles to determine whether a gap existed between the double ridge.

The double ridge height and midpoint are used in the simplified technique. The height, h, is found by measuring the exterior shadow length, s:

$$h = \frac{s}{\tan\phi} \qquad (1)$$

where ϕ is the solar incidence angle. The interior angle β is then derived as:

$$\beta = \tan^{-1}\left[\frac{h}{m}\right] \qquad (2)$$

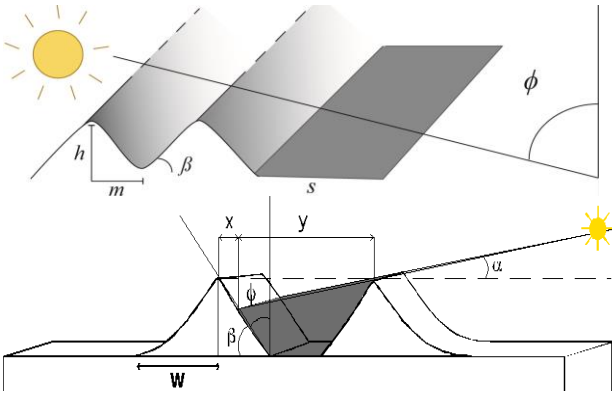

Figure 2. Variables in the simple (upper) and more rigorous (lower) shadow measurement techniques.

where m is the midpoint (half the peak-to-peak distance). This technique assumes that a gap does not exist between the two ridges. Thus, it provides a lower bound on interior slopes.

The more rigorous technique has been used in previous studies [1]. This technique assumes that the two ridge heights are equal, such that:

$$x \tan\beta = y \tan\alpha \quad (3)$$

$$\beta = \tan^{-1}\left[\frac{y}{x}\tan\alpha\right] \quad (4)$$

where x is the illuminated interior length, y is the interior length in shadow, and α is the geometric complement to ϕ (i.e., the altitude of the Sun). This technique accommodates the potential presence of a gap.

Results: *DEMs*. Eight DEMs total were generated in the Cilix region (2.0°N, 184.0°W) and a region of banded terrain (15°S, 195°W). For SOCET-SET DEMs in the Cilix region, double ridge interior slopes range from 11-23°, and exterior slopes range from 6-17°, with averages of 14 and 13°, respectively. ASP DEMs in the same region had slightly lower minimum interior slope values ranging from 6-23°, and exterior slopes ranging from 3-17°, with average values of 12 and 8°, respectively. SOCET-SET DEMs in banded terrain focus on one prominent double ridge (near 300m in height) and two smaller ridges. Locally higher values for both interior and exterior slopes (up to ~70°) were derived along individual profiles for the largest ridge, while slope map values were generally shallower (~55° maximum). These locally steeper slopes were also seen for the ASP DEM of the same ridge, which gave shallower values than SOCET-SET (~60° maximum). For both SOCET-SET and ASP DEMS, most interior and exterior slope values range from 10-40°. Average values for all double ridge interior and exterior slopes in this region are 33 and 32°, respectively. Only a few cases of interior and exterior slope symmetry (slope values within error of one another) were seen along individual profiles in this region.

Table 1. Interior slopes derived from two techniques from an area mapped in Figueredo and Greeley (2004).

	Simple technique		More rigorous technique	
Relative Age	Range	Avg.	Range	Avg.
Pwyllian	42-11°	22°	44-12°	25°
Annwnian	32-16°	22°	31-17°	25°
Argadnellian	17-9°	13°	22-12°	15°

Shadow Measurements. Over 300 individual profiles were taken along 40 double ridges that have a range of relative ages as defined from previous work; interior slope values for ridges with defined relative ages are shown in Table 1 [7, 8, 9, 10]. Given relative age relationships mapped near Androgeos Linea, younger ridges have steeper interior slopes (36° average) than older ridges (20° average), as derived from the simple shadow length technique. For double ridges in an equatorial region (5°N, 327°W), interior slopes range from 19-40° for the simple technique and 16-50° for the more rigorous technique. The locations where the more rigorous techniques yields steeper slopes are suggestive of the presence of gaps between the ridges. Average values for the interior slopes are 29 and 37°, respectively.

Conclusions: The more rigorous shadow length technique typically produces values that are higher than the simple technique, suggesting the presence of a gap between most ridge sets. Younger double ridges tend to have steeper interior slopes than older double ridges for both shadow measurement techniques. Based on results from both DEMs and shadow measurements, the majority of double ridge interior slopes fall between 10° and 40°. This range of derived slopes suggests that it is more likely that these features form from shallow slope-angle mechanisms such as cryovolcanism or tidal squeezing than steep slope-angle mechanisms such as linear diapirism. The lack of symmetry between interior and exterior slopes for individual DEM profiles may also suggest that explosive cryovolcanism is not the dominant formation mechanism.

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