MULTIRING BASINS ON ICY SATELLITES: A POST-*GALILEO* VIEW. William. B. McKinnon[1] and Paul M. Schenk[2], [1]Department of Earth and Planetary Sciences and the McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130 (mckinnon@wustl.edu), [2]Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058 (schenk@lpi.usra.edu).

Introduction: The collapse of large transient impact cavities may lead to the creation of one or more exterior rings [e.g., 1]. The existence and extent of such ring systems depend, at least in part, on the thickness of the mechanical lithosphere at the time and place of impact [2-4]. Icy satellites offer a valuable laboratory to explore this paradigm, in that icy lithospheres can be quite thin and ring systems quite extensive. *Galileo* images and other data have extended our understanding of multiring formation beyond earlier *Voyager*-based views. This is especially true of Europa, which was relatively poorly imaged by *Voyager*, but the focus of an extended campaign by *Galileo*. Post-*Galileo* reviews of cratering on the icy satellites of Jupiter can be found in [5-7]. Here we update and synthesize these works, with a special focus on Europa, because its surface is relatively youthful [5] and its craterforms well preserved.

Europan Multiring Structures: The two largest ring structures on Europa are Tyre (≈160 km across) and Callanish (≈95 km across) [8,9]. Tyre, in particular, was first noted in *Voyager* images as having a bull's-eye-like pattern, which turned out to be compact system of circumferential graben-like troughs, essentially a miniature version of the much larger Valhalla and Asgard/Utgard multiringed structures on Callisto [10], and plausibly related to the hemispherical-scale furrow systems on Ganymede [4,11]. The compact nature of these structures implies a relatively thin icy lithosphere, which is consistent with present-day steep temperature gradients due to strong tidal heating [12]. We can use measurement of trough width (and depth) to constrain heat flows at the time of impact [13].

Heat Flux at Tyre and Callanish: We interpret troughs as graben, and assume that the graben originated or nucleated at the brittle-ductile transition, or BDT (a major mechanical discontinuity) [4,14-16]. To estimate the depth to the BDT (fault intersection), we assume that the graben have a ≈62° sidewall dips (based on the coefficient of friction for water ice [17]). Topographic data for Callanish (Fig. 1) and Tyre [18] indicate trough depths approaching 100 m, which can be used to refine our BDT depth estimates. To first order, fault intersection depths are equal to graben width (within 10%).

Trough widths at Tyre average 1710 ± 610 m (from 57 measurements along several radial transects) and at Callanish 1640 ± 480 m (46 measurements). Graben on the west side of Callanish are generally narrower than those to the east, and there is also a modest trend for troughs to be narrower and shallower (lower strain) with greater distance along specific radial transects (especially for Tyre, where the azimuthal coverage is essentially complete). Our "lithosphere" thickness estimates are comparable to that in [19], ≤2.5 ± 0.5 km (when corrected for numerical error), especially as this estimate refers specifically to the impact site itself.

The depth to the brittle/ductile transition is related to the surface heat flux through the temperature profile in the ice shell and the rheology of water ice. The BDT occurs at a depth and temperature where the differential stress required for ductile flow (here dominated by dislocation creep) at a given strain rate is equal to brittle yield stress. We solve for the surface heat flux as a function of brittle/ductile transition depth for a variety of strain rates potentially appropriate for post-impact graben formation (Fig. 2).

Heat flows are quite high for the BDT depth (graben width) range above, easily exceeding 100 mW m^{-2} for "slow" (i.e., normal) geological strains (10^{-14} s^{-1}),

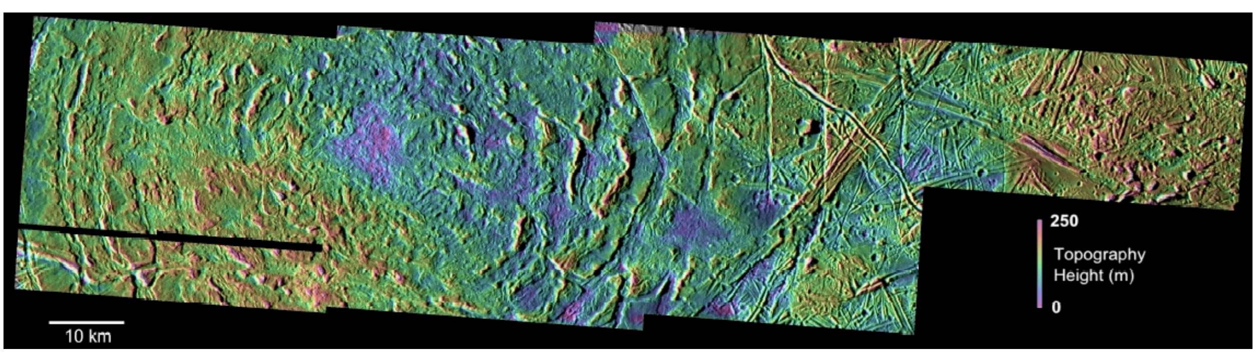

Fig. 1: Callanish topography derived photoclinometrically from and draped over a mosaic of *Galileo* E26 images (45 m/px), with stereo control from overlapping E4 frames. Note central and other depressions; north is up.

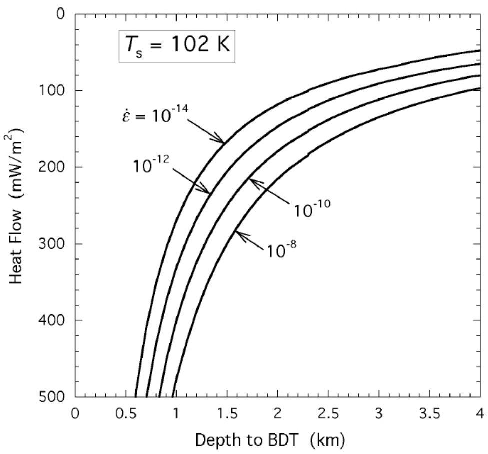

Fig. 2: Surface heat flux as a function of the depth to the brittle/ductile transition for Tyre (surface temperature $T_s \approx 100$ K) or Callanish ($T_s \approx 104$ K) on Europa, for strain rates ranging from the long-term geological ($\sim 10^{-14}$ s^{-1}) to high values more consistent with a post-impact response ($\geq 10^{-8}$ s^{-1}).

and exceeding 200 mW m^{-2} for rates more appropriate to post-impact crater collapse or adjustment (e.g., $\geq 10^{-8}$ s^{-1} [1]). Regardless, such heat flows indicate strong and tidal heating at the time of impact (values are similar to or greater than the terrestrial average). More significantly, these heat flows are similar to or much greater than values derived from folding instabilities [20] or flexure [21]. We suspect that fractures in the upper portion of Europa's ice shell reduced the effective thermal conductivity there from the very high values appropriate to cold solid ice.

Ring Mechanics. These results may, alternatively, point towards modification of the original multiring interpretation [1-4]. Conceivably, the viscous flow that extends the overlying ice lithosphere took place on a somewhat longer time scale than that governed by prompt collapse, although some observations of ejecta draping or flooding troughs may contradict this [8]. The Silverpit structure on the North Sea floor may be relevant in this regard. Whatever its origin, there is a central low and circumferential normal faults/graben formed by inward extension of brittle sediments (chalk), on either a collapse or longer time scale [22].

Strain rates for a collapsing transient crater are on the order of the inverse gravitational free-fall time, $\sqrt{g/D} \sim 5 \times 10^{-3}$ s^{-1}, where D is transient crater diameter (~25 km for Tyre) and g is local gravity (1.3 m s^{-2} for Europa). Strain rates decline with a r^{-4} radial dependence [2,15] (or less if the inward flow is channeled), which may explain the larger rift-like features closer to the centers of Tyre and Callanish.

Comparison with Callisto: Although *Galileo* coverage was not sufficient to complete a global inventory as originally hoped [5,11], many regional details at Valhalla, Asgard and elsewhere were revealed. Figure 3 illustrates a digital elevation model (DEM) for a portion of the Asgard radial transect [6]. The irregular, jogging trough is characteristic of "ring graben" in the apparently highly structurally flawed lithosphere of Callisto. We note that an earlier attempt to extract heat flows using the Asgard graben [15] was compromised by use of an incorrect (strong) brittle failure envelope, which led to very low heat flows being obtained. One new structure of note on Callisto is Lofn (Adlinda on *Voyager*-era maps), ~250-km in diameter [6], and surrounded by several low, inward-facing arcuate scarps. Relatively young, Lofn may be stratigraphically and structurally similar to Gilgamesh, the Orientale-class multiring basin on Ganymede [3,5].

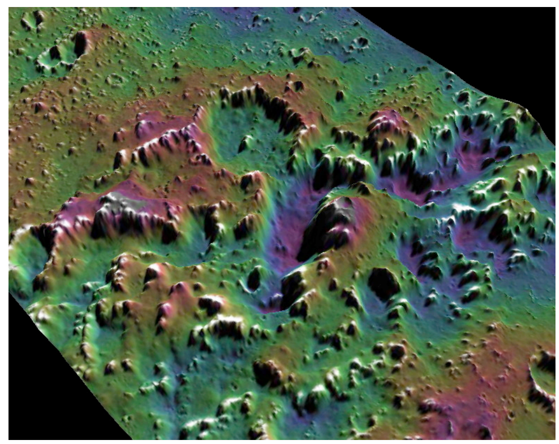

Fig. 3: DEM of portion of Asgard ring graben on Callisto. Swath is 72 km across; graben width ~10 km.

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