Impact Features on Europa: Results of the Galileo Europa Mission (GEM)

Jeffrey M. Moore
NASA Ames Research Center, MS 245-3, Moffett Field, California 94035
E-mail: jmoore@mail.arc.nasa.gov

Erik Asphaug
Earth Sciences Department, University of California—Santa Cruz, Santa Cruz, California 95064

Michael J. S. Belton
Kitt Peak National Observatory, 950 North Cherry Avenue, Tucson, Arizona 85726

Beau Bierhaus
Southwest Research Institute, 1051 Walnut Street, Suite 426, Boulder, Colorado 80302

H. Herbert Breneman
Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109

Shawn M. Brooks and Clark R. Chapman
Southwest Research Institute, 1051 Walnut Street, Suite 426, Boulder, Colorado 80302

Frank C. Chuang
Department of Geological Sciences, Arizona State University, Tempe, Arizona 85287

Geoffrey C. Collins
Department of Geological Sciences, Brown University, Providence, Rhode Island 02912

Bernd Giese
DLR, Institute of Planetary Exploration, Rudower Chaussee 5, 12489 Berlin, Germany

Ronald Greeley
Department of Geological Sciences, Arizona State University, Tempe, Arizona 85287

James W. Head III
Department of Geological Sciences, Brown University, Providence, Rhode Island 02912

Steve Kandel
Department of Geological Sciences, Arizona State University, Tempe, Arizona 85287

Kenneth P. Klaasen
Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109

James E. Klemaszewski
Department of Geological Sciences, Arizona State University, Tempe, Arizona 85287
During the *Galileo Europa Mission* (GEM), impact features on Europa were observed with improved resolution and coverage was compared with *Voyager* or the *Galileo* nominal mission. We surveyed all primary impact features $>4$ km in diameter seen on Europa (through orbit E19). The transition from simple to complex crater morphology occurs at a diameter of about 5 km. We calculated the transient crater dimensions and excavation depths of all craters surveyed. The largest impact feature (Tyre) probably had a transient crater depth between 5 and 10 km and transported material to the surface from a depth of not greater than $\sim 4$ km. Craters $<30$ km in diameter, such as Manannán and Pwyll, formed within targets whose immediate subcrater materials exhibited nonfluid behavior on time scales of the impact event, and that are capable, especially in the case of Pwyll, of supporting significant local topographic loads such as a central peak. These craters are nevertheless quite shallow, with very subdued floors, and we suspect that Manannán and Pwyll’s small depth-to-diameter ratios are due to the isostatic adjustment of large-scale topography, facilitated by warm, plastically deformable ice at depth. Morphological similarities between Callanish and Tyre strongly imply that conclusions reached regarding Callanish in J. Moore *et al.* (1998, *Icarus* 135, 127–145) also apply to Tyre, which was that Callanish is the consequence of impact into target materials that are mechanically very weak at depth. New evidence that Callanish’s circumferential rings formed before the proximal ejecta became immobile implies a low-viscosity substrate at the time of impact. We also report additional evidence that a component of the proximal ejecta of Callanish was emplaced as a fluid. Our observations of Pwyll secondaries support the conclusions stated in Alpert and Melosh (1999) that impacts...
on icy bodies eject smaller fragments and that fragment size decreases more gradually as velocity increases than observed for impacts on silicate bodies at equivalent ejection velocities. Examination of Pwyll’s secondary craters reveals azimuthal variations, with ejecta fragment sizes being larger near the center of a ray than off the ray. Our initial analysis of the characteristic size distribution of Pwyll’s secondary craters shows that they form a differential slope slightly shallower than $-4$. Similar steep slopes for small craters on Ganymede imply that small craters there are mostly formed by secondary impact, and the jovian system may thus be deficient in small impacts relative to the environment of the terrestrial planets.

Key Words: Europa; cratering; satellites of Jupiter.

INTRODUCTION

The Galileo Orbiter, during the Galileo Europa Mission (GEM) phase of its mission, has observed a number of impact features on Europa with improved resolution and coverage compared with Voyager and the Galileo nominal mission. Observations during the Galileo nominal mission (Moore et al. 1998) revealed two basic types of impact features: (1) “classic” complex impact craters that grossly resemble well-preserved lunar craters of similar size but are more topographically subdued (e.g., Pwyll); and (2) very flat circular features surrounded by concentric ring troughs that lack many typical geomorphic features of impact craters (e.g., raised rim, bowlshaped depressed floor, central peak), and which owe their identification as impact features largely to the field of secondary craters distributed radially around them (e.g., Callanish). Impact simulations suggest that features such as Callanish and Tyre would not be produced by impact into a solid ice target, but might be explained by impact into an ice layer of order of 10 km thick overlying a low-viscosity material. Moore et al. (1998) speculated that this low-viscosity material might be a global water layer.

This paper discusses analyses of europan impact features observed in SSI (Solid-State Imager) data obtained during GEM, and focuses on: (1) a survey of all primary impact features seen on Europa $>4$ km; (2) the ejecta deposits of certain impact features, principally Cilix, Manannan, and Tyre; (3) the “transitional” impact feature Tegid; (4) the implications of the topography of Manannan, Pwyll, Cilix, and Rhiannon; and (5) the distribution of energy in impacts into icy targets as revealed by the distribution of Pwyll secondaries.

MORPHOMETRY OF EUROPAN IMPACT CRATERS

Although Europa’s surface is lightly cratered compared with many other surfaces in the Solar System, the observed impact craters span a wide range of sizes and exhibit a variety of morphologies (Fig. 1). Crater morphology is influenced by the target’s material properties and near-surface structure. For example, (1) the minimum diameter at which complex craters form depends upon the strength of the target material (e.g., Melosh, 1989, pp. 144–150; Schenk, 1991); (2) Europa’s craters appear to be anomalously shallow compared to similarly sized craters on other solid-surfaced bodies, which may be due to post-impact isostatic adjustment; and (3) the rings around the two largest impact structures may have formed as a result of Europa’s near-surface structure (e.g., Turtle et al. 1999). Examination of europan craters reveals much about the nature of Europa’s near subsurface. To fully understand an impact event and the implications of the resulting crater morphology, it is necessary to know the dimensions of the transient crater that is excavated upon impact. We have measured the diameters of all europan craters observed through the 19th orbit (E19) that are larger than 4 km (Table I). Along with final crater diameters, Table I lists estimates of transient crater diameters and excavation depths.

Crater diameters were measured using SSI images orthographically reprojected around each crater’s center so that viewing geometry would not affect the crater’s apparent shape. Each crater diameter was determined from a circle fitted to several points selected along the crater rim. The resulting diameters and their RMS errors are listed in Table I. In some cases the RMS error is less than the resolution of the image because the image was interpolated to a larger pixel scale. Two of Europa’s impact structures, Callanish and Tyre, have no obvious raised rims, so different methods were used to estimate their diameters. If the edge of the concentric massifs corresponds to the final crater rim, Callanish’s diameter is 29 km and Tyre’s is 44 km. Another method involves scaling from the edge of the continuous ejecta blanket using the relation derived by Jones et al. (1997) for palimpsests on Ganymede, and this predicts final rim diameters of 35 km for Callanish and 43 km for Tyre. Finally, an upper limit on Callanish’s diameter can be determined from the locations at which two preexisting ridges were truncated by the impact. Fitting a circle through these points results in a diameter of 47.4 $\pm$ 1.0 km, yielding a result similar to that reported in Moore et al. (1998). Unfortunately, there are no obvious preexisting features at Tyre upon which to base such an upper limit. For these two craters we used the full ranges of final crater diameter estimates in calculating the dimensions of the transient crater and excavation depths.

McKinnon and Schenk (1995) derived the following relationship between final and transient crater diameters for Ganymede, which has similar gravity and crustal composition, based on volume conservation during crater collapse, $D_f \sim 1.176 D_t^{1.08}$, where $D_t$ is the diameter of the final crater and $D_f$ is the diameter of the transient crater. They estimate that this relationship is accurate to 15%. The ranges of transient crater diameters predicted by combining our fits’ RMS errors with the scaling relation’s uncertainty are listed in Table I. Craters in ice may undergo post-impact isostatic adjustment that modify the dimensions of the final crater (e.g., Melosh 1989, pp. 154–161). However, our calculated ranges are consistent with those predicted based on observations that indicate terrestrial transient crater diameters are 50 to 65% of their final crater diameters (e.g., Melosh 1989.
FIG. 1. All unambiguously identified craters >4 km on Europa observed through the GEM phase (end of orbit E 19) of the Galileo mission arranged in order of decreasing size. Italicized names are provisional.
ranges of transient crater depths calculated from the ranges of transient crater diameters based on the observation that transient crater depths are typically 1 to 3 their diameters (e.g., Melosh 1989, p. 78). The final column lists ranges of excavation depths (i.e., the maximum depth from which material can be entrained from the crater cavity) were also calculated using the experimental result that the excavation depth is roughly 1 to 3 the transient crater depth (e.g., Melosh 1989, p. 78). Ranges of final crater diameter estimates are given for Callanish and Tyre, which do not have obvious rims.

p. 138). Therefore, we assume that the effect of such isostatic adjustment on the scaling relation is negligible (but this does not imply that isostatic adjustment itself is negligible).

The transition between simple bowl-shaped europan craters and more complex morphologies occurs at a diameter of approximately 5 km. Craters with diameters of 6 km already exhibit central peaks, but several 5-km-diameter craters do not (Fig. 2). Simple craters probably formed from transient cavities that were too small to undergo crater collapse. It should be noted that for simple craters McKinnon and Schenk’s scaling relation underestimates the transient crater diameters. Transient crater depths were calculated from transient crater diameters in Table I, based on the observations that the depth of a transient crater is 1/4 to 1/3 its diameter (Melosh 1989, p. 78). The larger craters Cilix, “Maeve” (proposed name), and Pwyll appear to exhibit central peaks (or central peak complexes); therefore, if there is a liquid water layer on Europa, the overlying ice must be sufficiently thick that the disrupted regions around ~10–18 km diameter, ~3–6 km deep transient craters do not penetrate it completely. As noted in Moore et al. (1998), this suggests that the ice must be at least several kilometers thick. The calculated depths of transient cavities for the largest diameter values for Callanish and Tyre are ~10–11 km, which perhaps may represent the depth to a fluid-rich region if their morphologies are a manifestation of such a region (Moore et al. 1998).

Ranges of excavation depths (the maximum depth from which material is ejected from the crater cavity) were also calculated using the experimental result that the excavation depth is ~1/3...
the transient crater depth (e.g., Melosh 1989, p. 78). In general the excavation depths are quite small; using the largest possible diameter estimate for Callanish, the maximum depth from which ejecta can originate is only 3.6 km. This implies that the source of the dark, red material observed around some europa craters is within a few kilometers of the surface, which may have implications for the red material’s origin.

**INDIVIDUAL IMPACT FEATURES**

**Cilix**

Although the characterization of an impact crater is relatively straightforward, sometimes its recognition is not. The impact crater Cilix provides an excellent example of how image resolution, lighting conditions, and surface albedo influence interpretation. Based on ~2 km/pixel Voyager data, the 15-km-diameter, roughly circular feature located at 2°S, 180°W was interpreted to be an impact crater (Smith et al. 1979), and was given the name Cilix. In 1996, Cilix was imaged by the Galileo SSI at 1.6 km/pixel under moderate-Sun illumination (incidence angle ~53°). Based on these data and a stereo complement image acquired by Voyager at similar resolution, Cilix was interpreted as a positive-relief feature, perhaps a dome or flat-topped butte standing 1.0 ± 0.5 km above the plains, surrounded by a dark annulus (Belton et al. 1996). The positive relief of Cilix was observed again when the feature was imaged just beyond the terminator, with glancing sunlight illuminating an indistinct circular form barely extending above the local horizon. During the Galileo Europa Mission an opportunity arose on the 15th orbit (E15) for Cilix to be imaged at higher resolution (at about 40 and 165 m/pixel) under lower incidence angles (Fig. 3). Stereo and color (green, violet, and 1-μm filter) data obtained on this orbit revealed that Cilix is, in fact, an 18-km-diameter impact crater with a central peak complex. The stereo coverage of Cilix was used for generating a digital terrain model (DTM) of the region (see Fig. 4) whose preliminary analysis was reported in Giese et al. (1999).

Cilix exhibits an elongate central peak complex surrounded by a flat crater floor, terraced walls, a circular rim, and reddish-brown continuous ejecta blanket. The central peak complex is composed of two prominent massifs (Fig. 3, black arrows). The larger of these massifs is oriented roughly NW–SE and is 1 by 2.5 km. The smaller 0.5 by 1 km, NE–SW-oriented massif is located immediately east of the larger massif. Both massifs exhibit ~300 m relief. The central peak complex is located in the center of the crater floor. The crater floor exhibits only a few tens of meters of relief and is mottled by numerous subkilometer reddish-brown patches. Although these patches are evident in nearly every quadrant of the crater floor, they are relatively more abundant in the southeast quadrant, and less abundant in the northeast and northwest. The western crater walls have one to two terraces, while terraces are typically absent on the walls in the eastern half of the crater. Ejecta deposits just beyond the eastern side of the crater rim appear to partly obscure a pre-existing ridge system, suggesting these deposits are thick. In some places along Cilix’s rim, the combination of the ejecta deposit and the old ridge system develops local relief of ~500 m (determined from stereo photogrammetry measurements of E15 images), which probably represents the relief measured early in the mission that led to the butte misinterpretation (Belton et al. 1996). Elsewhere the rim is typically ~300 m above the local surface. Cilix’s rim is seen to be circular and continuous in both the E15 data and on-terminator data obtained on the third orbit. The floor of Cilix is at the same general elevation as the surrounding terrain beyond its continuous ejecta blanket. Cilix’s dark continuous ejecta blanket ranges in width from 8 to 20 km measured from the crater rim with diffusely bounded ray-like extensions. Within the continuous ejecta there is a deposit of very dark material in a topographic low forming a partial moat around the southeast portion of crater lying ~3–5 km beyond the rim crest (Fig. 3, white arrows). The plains beyond the continuous ejecta exhibit numerous secondary impact craters.

Cilix exhibits the same suite of landforms seen for craters its size on other icy satellites (although Cilix is significantly shallower). The “classical” crater landform suite of Cilix implies that it formed entirely within a target that behaved brittlely over the crater-forming event. As can be seen from Table I, Cilix had a modeled transient crater depth between 2.4 and 4.7 km. If this transient crater depth range is valid, and our interpretation of Cilix forming entirely within a brittle substrate is correct, then we infer that Europa’s crust is solid, and over short time scales
brittle, at least to a depth comparable with the range transient crater depth estimates at this location.

Manannàn

The ∼22-km-diameter impact crater Manannàn (3°N, 240°W) was imaged during orbit E14 in color, in stereo, and at resolutions as high as 20 m/pixel, although at high (∼20°) incidence angles. These images complement others acquired during orbits G1 and E11. Manannàn (Fig. 5 and Fig. 6) is about the same size as crater Pwyll (diameter ∼24 km) described and discussed in Moore et al. (1998), but Manannàn has fewer characteristics in common with classic (or lunar-like) crater morphology. Seen under comparable illumination, Manannàn’s rays are less prominent than those of Pwyll, suggesting that Manannàn is older. Manannàn has no central peak, but several massifs are distributed across its floor. A DTM constructed from stereo coverage indicates the largest massif, located about half a crater radius east of the crater center, is about ∼5 km across and ∼200 m high. Smaller massifs and ridges are distributed across the crater floor, but the DTM indicates the floor itself is, on average, level. Local relief of the rim massifs above the crater floor interior is ∼200 m. Like Cilix, Manannàn’s crater floor appears to lie at the same general elevation as the surface exterior to the crater and its proximal ejecta. There is a scarp-bounded ∼5-km-diameter pit ∼80 m deep located just east of the crater floor center (Fig. 4). This pit corresponds to the bright spot seen within the crater in the G1 image reported by Moore et al. (1998). Since no ejecta is observed associated with the pit, its origin as a smaller, more recent impact crater seems unlikely. Centered within this pit is a well-defined asterisk-shaped dark feature of no perceptible relief, which may be an extrusion emerging from radial fissures (dark central unit in Fig. 6, see de).

There is no well-developed nested terracing along the interior of Manannàn’s rim. Uplifted material forming the rim is massively exposed along the west wall of the crater, extending in places ∼5 km into the crater interior (crater rim and interior massif unit in Fig. 6, see crm). In contrast, rim material has limited exposure on the east rim, appearing only in a few inward-facing scarps. A pedestal-like break in slope occurs in the continuous ejecta at ∼4 to 7 km beyond the rim crest. The DTM indicates that the pedestal ramparts rise a few tens of meters higher than the rest of the pedestal (see point “P” on the Manannàn topographic profile in Fig. 4).
We find two obvious and interesting deposits just inside and outside Manannän. The inner deposit, which is largely confined within the crater rim, forms a rolling surface that is textured with small blocks or hills <100 m across (crater floor unit in Fig. 6, see cf). At the margin of the deposit, near the crater rim, the hilly texture gives way to a roughly radial texture and ultimately a lobate margin. This marginal presentation is best seen where this deposit is in contact with the patch of dark ejecta (Fig. 7A, arrow). The contact here is broadly lobate. We interpret crater floor material to be mostly impact melt that collected within the initial cavity of the crater and in some places lapping over the eastern crater rim (as at point “D” on the Manannän topographic profile in Fig. 4, and Fig. 7A, arrow).

The second deposit is material seen just outside the crater rim. We are not (yet) referring to the dark patches but instead the thick, radially lineated deposit of continuous ejecta (continuous ejecta unit in Fig. 6, see ce). The margin of this deposit is lobate in many places. Individual lobes are typically 1 to 1.5 km long and up to ~500 m wide. Examples of these lobes can be seen in Fig. 7B (arrows). This deposit was described from E11 data as a “pedestal” deposit by Moore et al. (1998), who proposed that pedestal topography around craters on Europa formed by minor glacier-like deformation of warm continuous ejecta deposits of mostly water ice. If this hypothesis is valid, then the lobes associated with this deposit may represent warm, plastically deforming ice coming from the lower portion of the deposit. Alternatively, the lobes may be a different material emerging (draining?) from or under the main pedestal deposit.

The dark patches on the pedestal deposit appear as coalescing radially arrayed streaks with diffuse boundaries in some locations (Fig. 5). Surface texture within the dark patches is similar to adjacent brighter patches elsewhere within the continuous ejecta unit, so if the dark materials are deposits they are too thin to be resolved, or at least sufficiently thin that the underlying surface shows through. The dark patches most likely represent a veneer of primary, late-stage ejecta emplaced ballistically on top of an earlier pedestal deposit, although an erosional origin or albedo patterning in a coherent ejecta unit cannot be
ruled out. The darker material may represent either impactor-contaminated melt, or melt excavated from a deeper, dark layer beneath Europa’s surface.

The radial orientation of individual linear streaks within the dark patches implies that the top of the underlying “pedestal” deposit did not undergo significant nonradial distortion following deposition of the dark patches. This lack of differential (azimuthal) distortion in the pedestal deposit is consistent with our 1998 hypothesis that the pedestal topography is due to radial strain due to the downslope (off-rim) slow, laminar “glacial” flow of warm ice. If “pedestal” deposits were formed by the flow of an ejected fluid-like slurry whose motion continued for several minutes after emplacement (which is an alternative hypothesis for pedestal deposit formation), then we might expect that flow of this slurry would continue beyond the time the dark patches were ballistically emplaced and that this movement would be expressed by turbulence-induced distortions (e.g., curls and swirls) of the dark patch streaks. This appears not to be the case. If the “pedestal” deposit underlying the streaks did deform, this deformation had to be very laminar and radial with no curvilinear displacement.

Manannán has fewer characteristics in common with classic (or lunar-like) crater morphology than does Cilix or Pwyll. Nevertheless, it exhibits an intact inward-facing rim, tall interior massifs, and a ~100-m-thick pedestal deposit. Manannán much more resembles other “classic” europa craters than it does the ringed impact features Callanish and Tyre. Thus we infer as we did for Cilix that Manannán formed entirely within a brittle substrate. Consequently, we suggest that Europa’s crust was solid at this location at least to a depth comparable with the
range of Manannán transient crater depth estimates of 2.86 to 5.47 km.

**Tegid**

The crater Tegid (0.5°S, 164°W) was imaged under near-terminator conditions in a ~1.5 km/pixel global mosaic acquired in E14 (Fig. 8). An inward-facing enclosed scarp ~30 km in diameter is most likely the crater rim. A circular unit with somewhat less relief extends ~30 km from the crater center. The central portion of the crater floor appears to be a raised disk, or an broad flattened dome. Tegid may represent a class of crater that is transitional between the “classic” (though very flattened)
FIG. 8. The crater Tegid (0.5° S, 164° W) was imaged at low Sun in a ~1.5 km/pixel global mosaic acquired in E14 (PICNO 14E0055) and at high Sun and high phase during E19 at ~900 m/pixel (PICNO 19E0001). Both images are reprojected around the center of Tegid and to the same scale. We interpret the inward-facing ~30 km-diameter scarp to represent the crater rim. Tegid may represent a class of crater that is transitional between the “classic” (though very flattened) complex impact craters just smaller than Tegid (e.g., Manannán) and the “rimless” multiringed impact features Callanish and Tyre. Black arrow points to dark crescent-shaped albedo mark on top of the topographic dome seen in the E14 image.

complex impact craters just smaller than Tegid (e.g., Pwyll) and the “rimless” multiringed impact features Callanish and Tyre.

A second image of Tegid was obtained on orbit E19 at lower phase angle and ~900 m/pixel. Comparisons of E19 and E14 images of Tegid (both reprojected around the center of Tegid and to the same scale in Fig. 8) show that the dark central crescent visible in the E19 image does not correspond to minor relief along the margin of the central dome, but is actually an albedo feature located on top of the central dome in the E14 image (Fig. 8, black arrow). Also interesting is that the pedestal ejecta deposit visible in the E14 image corresponds to some of the albedo features visible in the E19 image.

One of the main science objectives of the E19 Tegid observation was to determine the size distribution of secondaries about the impact feature as a measure of the size of its transient crater, which, in turn, would provide an estimate of the location of its rim. At ~900 m/pixel no dark dot patterns were seen that might indicate secondaries (as were seen around Tyre under similar lighting at ~600 m/pixel). One possibility is that no secondaries ≥1 km were formed, which would imply that Tegid’s crater rim diameter is considerably smaller than the (~45-km-diameter) equivalent crater rim of Tyre (consistent with our estimate of a ~30-km diameter for Tegid). Tegid thus remains an unusual impact-generated landform whose gross features are now somewhat characterized but whose close inspection awaits another day.

Tyre and Callanish

A 170 m/pixel mosaic of Tyre (centered at 34° N, 146° W) was acquired under near-terminator conditions during E14 (Fig. 6). A general geologic map focusing on the endogenic landforms within this region beyond Tyre was given in Kadel et al. (2000). Here we will limit ourselves to landforms associated exclusively with Tyre and provide a more detailed analysis of the impact feature. Tyre was seen less well by Voyager and by Galileo on orbit G7 (Moore et al. 1998). With the E14 images we can now recognize and characterize the geologic units of Tyre and compare them with those seen at Callanish, which is similar in both morphology and size, and was analyzed by Moore et al. (1998) using 120 m/pixel, near-terminator images acquired during orbit E4.

Tyre, like Callanish, can be divided into several morphological units and other associated features (Fig. 6). At the center of the Tyre impact feature is a 15–20 km wide, flat, relatively high-albedo and smooth textured patch of material located within a shallow scarp-enclosed depression (smooth central unit in Fig. 6, see sc), interpreted to be impact melt and/or possibly material emplaced as a fluid from a source beneath the brittle crust. The main, ~45-km-diameter inner deposit (rough inner unit in Fig. 6, see ri) surrounds the smooth central unit. The rough inner unit is interpreted to be composed of impact melt and broken up target material.

The material beyond and encircling the rough inner unit is characterized by a relatively smoother surface (continuous ejecta unit in Fig. 6, see ce), in those places where it is not disrupted by subsequent tectonics. This unit largely corresponds with the darker, redder surface forming annular deposits imaged at G7 (see Moore et al. 1998, for details).

The corresponding continuous ejecta unit at Callanish, which was imaged at ~5 times better resolution and at similar lighting during orbit E26 as Tyre on orbit E14 (Fig. 10), displays a
range of textures. At one textural endmember, the unit consists of patches of very small, equidimensional hills that mantle preexisting topography, and at the other endmember it forms smooth material that appears to pond in low areas and embay preexisting relief. As can be seen in Fig. 10, there are many places within this unit in which the texture is transitional between these two endmembers. Moore et al. (1998) speculated that the Callanish continuous ejecta unit was emplaced in a fluidized state, perhaps as a slurry of liquid and solid material. The E26 observations reinforce this interpretation.

Tyre’s continuous ejecta unit extends as far as ~100 km from the impact feature’s center. Within the continuous ejecta unit are a number of elongate concentric massifs (annular massif unit in Fig. 6, see ann) that are interpreted as uplifted target material around which the continuous ejecta unit was emplaced. These same unit types were recognized at Callanish. As at Callanish,
the continuous ejecta unit appears to be confined to locally slightly lower areas (as inferred from subtle shape from shading). This unit is broken by a number of concentric troughs and numerous fractures. These troughs are more abundant east of the crater center. The troughs are interpreted to be tectonic in origin and may be graben.

E26 images of Callanish (Fig. 10) show that the circumferential troughs largely predate the emplacement, or at least solidification, of the continuous ejecta unit, which is opposite the inferred sequence of events based on lower resolution E4 images reported in Moore et al. (1998). The apparently very rapid formation of the troughs (i.e., after impact but before ejecta immobilization) strongly supports the conclusion (Turtle 1998, Turtle et al. 1999) that a near surface layer of the target, at least at Callanish, behaved as a low-viscosity material, such as liquid water. A similar relationship between ring troughs and the continuous ejecta unit cannot be verified at Tyre in the existing imaging.

Beyond Tyre’s continuous ejecta unit, there are numerous small pits, many with raised rims, some of which form pit chains oriented radially to the center of Tyre. These pits probably are secondary impact craters. It is the presence of these secondaries that permits an unambiguous interpretation of Tyre as an impact feature. We estimate the equivalent crater diameter (i.e., where the rim would be, if it were more prominent) of Tyre to be ~45 km, based on the onset of ejecta sculpting, and the periphery of the rough inner unit. If Tyre’s equivalent crater diameter is ~45 km, then its transient crater depth is estimated to be 5.59 to 9.98 km.

In Moore et al. (1998) we concluded that Tyre and Callanish were not the consequence of impact into a solid ice target, but instead might be explained by impact into an ice layer of order of 10 km thick overlying a low-viscosity material. This conclusion was based on the liquid behavior at the time of emplacement of the proximal ejecta, the lack of any classic crater-rim facies, and our modeling of concentric ring formation. Our understanding of the data examined through E26 continues to support our 1998 conclusion. However, it must be noted that a low-viscosity, fluid-rich layer at ~10 km depth may be equally well explained by a brine-rich zone associated with convecting ice (Head and Pappalardo 1999, Collins et al. 1999), as it could be by the top of a purely liquid layer (e.g., ocean).

FIG. 10. A 25 m/pixel view of Callanish continuous ejecta along the east side of the feature acquired during orbit E26. Callanish’s continuous ejecta are characterized by a range of textures. At one textural endmember, the unit constitutes patches of very small, equidimensional hills that mantle preexisting topography (such as around the location marked with an X), and at the other endmember forms smooth material that appears to pond in low areas and embay preexisting relief (such as the areas pointed out with arrows). Also note that Callanish’s circumferential troughs largely predate the emplacement of the continuous ejecta unit, as the ejecta deposit marked at “X” has flowed into the troughs above and below the “X”. The apparently very rapid formation of the troughs (i.e., after impact but before ejecta immobilization) strongly supports the conclusion (Turtle 1998, Turtle et al. 1999) that a near surface layer of the target, at least at Callanish, behaved as a very low-viscosity material. (Portion of image PICNO 26E0005. Centered at 16°S, 333°W. Illumination is moderately low and from the left. North is up.) Inset at top shows location of E26 high-resolution view on E4 coverage of Callanish.

Crater Topography

The craters on Europa > 10 km in diameter are substantially shallower than similarly sized craters reported on Ganymede and Callisto (Schenk 1991). This can be explained by isostatic adjustment involving near-surface materials too soft to support significant long-wavelength topography over time, or by flooding of crater cavities by fluid or melt. Either of these explanations might either posit or refute the existence of a very-near-surface (~2 km) europan ocean such as proposed by Greenberg et al. (1999), so further study of these larger craters is warranted. For now we provide some first-order analysis of these structures and implications for the europan interior. Moore et al. 1998 proposed
that craters smaller than 30 km in diameter such as Pwyll and Manann'n formed within an initially brittle crust, then isostatically adjusted to their present form. This still appears to be the best explanation.

Stereo coverage of Cilix, Pwyll, and Manann'n was acquired during GEM (Fig. 4). Additionally, in an attempt to assess the effects of a potentially colder and stiffer polar lithosphere (Ojakangas and Stevenson 1989), we imaged the crater Rhiannon to evaluate its depth/diameter ratio from shadow measurements. Rhiannon (81°S, 197°W) has a diameter of ~15 km, a rim-to-floor depth of ~400 m, and an average rim to ejecta blanket height of ~175 m (Fig. 11). The depth/diameter ratio of ~1:40 makes Rhiannon proportionally much deeper than Manann'n or Pwyll, whose floors are essentially level with the surface beyond the continuous ejecta. However, the rim-to-floor relief for Rhiannon is similar to that for 18-km-diameter Cilix (Fig. 4), implying that the rheology of the lithosphere under Cilix and Rhiannon was similarly stiff, even though one is located at the equator and the other near a pole, and has remained at least as stiff since these events. Recent work by Stevenson (2000) suggests that the rheology of Europa’s ice shell has no latitudinal dependence.

Digital topography models (DTMs) of several europaen craters have been generated from stereo coverage of these features with typical vertical resolution of a few tens of meters (Fig. 4) (Giese et al. 1999, where details of the DTM generation are given). An important result of this work is that the largest “classic” craters, Pwyll and Manann'n, have floors that are at the same elevation as the plains beyond their rims. The greatest relief associated with these features is that of their central peaks. In the case of Pwyll, the central peak rises ~800 m above the floor, some ~300 m above the average rim height (Fig. 4). By contrast, central peaks rising above rims are rare for the Moon and Mars (Schenk 1989). The presence of a significant central peak implies load-bearing materials exist in the excavation zone immediately beneath the crater, rather than, for instance, liquid water. Assuming that the ice beneath the crater maintains its strength despite disruption during the impact, a lower limit on the thickness of the ice needed to support the central peak can be estimated from flexure. Assuming that 100 m of vertical displacement from flexure, if present, would be recognizable in the DTM of Pwyll, the ice under the central peak would have to be at least 0.9 km thick (as derived using an expression from Turcotte and Schubert, 1982, Eq. 3–131, p. 126) to prevent flexure-induced vertical displacement of this amount. Since 1.0–2.0 km of ice is ejected during the impact the preimpact ice thickness must have been at least 2.6–3.6 km, and it was probably even thicker.

The overall shallowness of Pwyll and Manann'n may be explained by plastic deformation of the crust due to warm ice under these craters in order to restore the broader impact-generated mass loads upon the local crust to a gravitational equipotential. Only the topography of very short (horizontal) wavelength features, such as central peaks and crater rim-ridges, have not relaxed in the time since crater formation. Central peaks are in this scenario passively carried by the rising floor to their anomalous elevation relative to the crater rim. This may explain the relatively unusual height of Pwyll’s central peak.

**Pwyll Secondaries**

No major events on Europa are known to postdate the ~24-km-diameter impact crater Pwyll, although Bierhaus et al. (2000) discuss possible modification in the Conamara Chaos region after the emplacement of Pwyll secondaries. Either Pwyll formed quite recently or smaller impacts are extraordinarily infrequent. In either case, Pwyll formed on a rather “clean slate,” with little cratering history underlying the crater, its rays, and its secondaries. Bierhaus et al. (1998) compared crater densities inside and outside a Pwyll ray and determined that Pwyll secondaries compose at least 90% of the small craters along portions of its ray traces. Pwyll secondaries are readily identified near the crater as well as across the trailing hemisphere of Europa associated with extensive crater rays, providing an enormous boon to impact modeling and crater statistics. For this reason, Europa is a perfect “witness plate” for studying large-scale impact outcomes on icy satellites.

Europa’s crust may not be typical of planetary lithospheres, so some caution should be taken in using cratering models and

![FIG. 11. Rhiannon (81°S, 197°W) has a diameter of ~15.4 km and a rim-to-floor depth of ~400 m. Rhiannon’s relief is similar to that of 18-km-diameter Cilix. This implies that the rheology of the lithosphere under Cilix and Rhiannon are similar, even though one is located at the equator and the other near a pole. This is a crater-centered orthographic reprojection of 25 m/pixel image PICNO 17E0070. North is up.](image-url)
model constraints derived from studying Europa impact features and applying the results to other bodies. Ejection of secondaries mainly involves the near-surface rheology at “early time” in the impact event (e.g., Melosh 1989, p. 92), but for a lithospheric thickness perhaps only equal to several projectile diameters, this boundary effect may be important (Moore et al. 1998). And so, while we can study Europa secondaries to learn about the impact behavior of ice, we must keep in mind that there may be differences between cratering on Europa, and, for instance, cratering on Ganymede where the brittle crust may be thicker.

Vickery (1986, 1987) developed a simple and robust technique for transforming secondary crater locations and diameters into plots of ejection velocity versus ejecta diameter. We have applied this same technique to derive the size-velocity distribution of Pwyll’s ejecta fragments from the diameter and distance of Pwyll secondary craters by measuring secondaries at a distant site where there was very-high-resolution coverage of a Pwyll ray and those in the Pwyll near field. Distance from the primary crater, assuming a spherical Europa, gives us the fragment ejection velocity, which equals the impact speed of a secondary projectile on an airless world. Secondary crater diameter, combined with this speed, assuming an ejection/impact angle of 45°, together with scaling assumptions for how secondary crater diameters relate to impactor diameters, then provides an estimate for ejecta fragment diameter. The advantage of Pwyll in this regard is that ejecta fragments launched at 1 km/s have been observed (as secondary craters) 1000 km away in the Conamara region. In contrast, Vickery’s analysis of cratering on Mars, the Moon, and Mercury could not be extended to ejection velocities beyond a few 100 m/s, since distant (faster) secondaries are lost among the much more numerous background craters on these bodies.

Our analysis is presented in Fig. 12. Our findings are similar to Alpert and Melosh (1999), except that our fragment diameters are a few percent larger, likely due to systematic differences in measuring the original crater diameters. Our data show that ejecta fragments reached velocities over 1 km/s. Since Pwyll rays extend beyond the region we measured, ejection velocities must have been even higher in some cases. The distance traveled by ejecta from Pwyll to the secondaries we measured is over 10% the circumference of Europa; larger impacts such as those that formed Callanish and Tyre must send ejecta over greater portions of the surface, if the speed of launched ejecta scales with crater diameter.

We have also investigated (Asphaug et al. 1999) how the sizes and speeds of secondary craters around Pwyll and Tyre vary as a function of azimuth, measured in a radial coordinate frame centered upon the source crater. For Pwyll, we find that secondary craters near the Conamara Chaos, ~1000 km from the primary, range from 100 m (the smallest we measured in each frame) to 0.5 km diameter and were created by fragments ~10 to ~100 m in diameter, depending on the particular scaling relation used (cf. Vickery 1986, 1987). Figure 13 summarizes these results. By studying these azimuthal variations, we find that average fragment sizes decrease away from the center of the ray. This implies that ejecta fragment masses may approach an order of magnitude larger along a ray center than elsewhere, for a given ejection speed. We also observed azimuthal variation in secondary craters adjacent to Tyre, which implies that relatively large masses can be ejected at high speed as a result of

FIG. 12. A plot of Pwyll secondary-crater-producing fragment diameters against ejection velocity. The diameters of the fragments were derived from measurements of secondary craters and then scaled using the relationship reported in Vickerey (1986). Secondaries were measured both at a site ~1000 km from the impact where there was very-high-resolution coverage of a ray and those in the Pwyll near field. See text for discussion.

FIG. 13. Fragment diameter versus azimuth, for Pwyll. Secondary craters associated with a ray near the Conamara Chaos, ~1000 km from the primary, range from 100 m (the smallest we measured in each frame) to 0.5 km diameter, measured in a radial coordinate frame centered upon the source crater. Secondary crater diameters were then converted to fragment sizes (circles = gravity regime, porous target; triangles = strength regime). See text for discussion.
asymmetries in the distribution of energy within the ejecta curtain. Such ejecta size asymmetries have provided insight toward understanding the ejection of large, intact fragments from the surfaces of planets, since large fragments launched along a ray have a greater likelihood of escaping a planet.

We have also conducted a general statistical analysis of secondary craters on Europa. Again, this work is uniquely possible on Europa because the secondary cratering flux is easily discerned from the primary flux. Detailed information about secondaries is required to assess two fundamental questions about icy satellite surfaces. First, determination of the characteristic size distribution of secondary craters on icy targets provides a quantitative means of disentangling the secondary from the primary cratering fluxes. The relative contribution of primaries and secondaries to Europa’s crater population continues to be a matter of important dispute (e.g., Zahnle et al. 1998, Neukum et al. 1997), which has led to divergent age estimates for Europa’s surface. Second, these data provide an opportunity to compare the distribution of secondary craters around Europa impact features against secondary fields on terrestrial planets, and also against the outcome of numerical models (Moore et al. 1998). Such analyses could have direct bearing, for instance, on the production, abundance, and size distribution of purported circumjovian debris from very large impact events on the Galilean satellites, such as the Gilgamesh collision on Ganymede (Shoemaker and Wolfe 1982, Shoemaker 1996, Zahnle et al. 1998).

Our preliminary analysis of the characteristic size distribution of secondary craters shows that distant Pwyll secondaries measured in the Conamara Chaos region possess a differential slope slightly shallower than −4. This is similar to the −4.4 slope measured by Chapman (1968) for a population of lunar craters that he classified as likely secondaries (Fig. 14). We cannot take this comparison too far, however, because the Europa data are from only one secondary cluster at a single distance from one crater, while the Chapman counts are from several regions, likely sampling numerous secondary clusters at varying distances from their primary crater. With this caveat in mind, our results nonetheless suggest that the steep slope in the crater size distribution below 1 km on Europa reported in Chapman et al. (1998) is caused by distant secondary craters. Similar steep slopes for small craters on the other icy Galilean satellites might imply that small craters on these objects are mostly formed by secondary impact. If so, the jovian system may be deficient in small impacts relative to the environment of the terrestrial planets (Chapman et al. 1998).

CONCLUSIONS

1. A survey of all primary impact features >4 km in diameter seen on Europa (in images from Galileo’s nominal and Europa missions, through orbit E19) was performed. We calculated the transient crater dimensions and excavation depths of these craters and note that even the largest impact feature (Tyre) probably had a transient crater depth between 5 and 10 km and transported material to the surface from a depth not greater than ~4 km. Craters the size of Pwyll and Manannán (~22 km diameter) had transient crater depths of between 3 and 6 km and transported material to the surface from a depth not greater than ~2 km. This implies that the source of the dark, red material observed around some europa craters is within a few kilometers of the surface. A simple-to-complex transition in europian crater morphology is observed to occur at diameters of ~5 km. Craters with diameters ≥6 km exhibit central peaks, whereas several 5-km-diameter craters do not.

2. We are now convinced that Callanish and Tyre are both impact features. This conclusion is based on the presence of pits and radially arrayed chains of pits we interpret to be secondary craters surrounding both features. Tyre has now been observed at comparable resolution and lighting to that of the Callanish nominal mission observations. Tyre’s strong resemblance to Callanish implies that the conclusions reached regarding Callanish in Moore et al. (1998) also apply to Tyre, which was that Callanish is the consequence of impact into target materials that are mechanically very weak at depth. A new observation that Callanish’s circumferential rings formed before the proximal ejecta became immobile further supports the inference.
of a very-low-viscosity substrate at the time of formation. We also observe new evidence for the fluid behavior of the proximal ejecta material around Callanish at the time of emplacement. However, it must be noted that a low-viscosity, fluid-rich layer at depth may be equally well explained by a brine-rich zone associated with convecting ice, as it could be the top of a purely liquid layer (e.g., ocean).

3. Craters <30 km in diameter, such as Manannán and Pwyll, formed within targets whose immediate subcrater materials exhibited coherent behavior on time scales of the impact event, and that are capable, especially in the case of Pwyll, of supporting significant local topographic loads such as a central peak. These craters are nevertheless quite shallow, with very subdued floors, and we suspect that Manannán’s and Pwyll’s small depth-to-diameter ratios are due to the isostatic adjustment of large-scale topography facilitated by warm, plastically deformable ice at depth.

4. Europa’s nearly pristine surface provides a unique “witness plate” recording the outcome of a recent large-scale cratering event (Pwyll) into an icy target. We previously found, on the basis of a numerical experiment (Moore et al. 1998), that the number and distribution of Pwyll secondaries are more consistent with impact into solid ice than impact into a thin shell overlying liquid water. Our analysis supports the conclusions of Alpert and Melosh (1999) that impacts on icy bodies eject smaller fragments than impacts on silicate bodies at equivalent ejection velocities, and that fragment size decreases more gradually as velocity increases. Further analyses of Pwyll secondaries have revealed an azimuthal variance, with ejecta fragment sizes being larger near the center of a ray than off the ray. Our preliminary analysis of the characteristic size distribution of Pwyll’s secondary craters shows that it forms a differential slope slightly shallower than −4. Similar steep slopes for small craters on Ganymede imply that small craters there are mostly formed by secondary impact, and the jovian system may thus be deficient in small impacts relative to the environment of the terrestrial planets.

ACKNOWLEDGMENTS

We thank Louise Prockter and Nadine Barlow for their careful reviews of this paper. We also thank Moses Milazzo for processing some of the images used in this report. This investigation was funded by NASA’s Galileo Project.

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