Evidence for a subsurface ocean on Europa

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Ground-based spectroscopy of Jupiter's moon Europa, combined with gravity data, suggests that the satellite has an icy crust roughly 150 km thick and a rocky interior[1–4]. In addition, images obtained by the Voyager spacecraft revealed that Europa's surface is crossed by numerous intersecting ridges and dark bands (called lineae) and is sparsely cratered, indicating that the terrain is probably significantly younger than that of Ganymede and Callisto[5]. It has been suggested that Europa's thin outer ice shell might be separated from the moon's silicate interior by a liquid water layer, delayed or prevented from freezing by tidal heating[6–10]; in this model, the lineae could be explained by repetitive tidal deformation of the outer ice shell[11–13]. However, observational confirmation of a subsurface ocean was largely frustrated by the low resolution (>2 km per pixel) of the Voyager images[14]. Here we present high-resolution (54 m per pixel) Galileo spacecraft images of Europa, in which we find evidence for mobile 'icebergs'. The detailed morphology of the terrain strongly supports the presence of liquid water at shallow depths below the surface, either today or at some time in the past. Moreover, lower-resolution observations of much larger regions suggest that the phenomena reported here are widespread.

The observations are of a region near 13° N, 273° W, just south of the intersection of two prominent ridges, Asterius Linea and Agava Linea (Fig. 1). These and similar ridges appear in Voyager images as bright lines with dark margins, so were called 'triple bands'. From Voyager data much of Europa's surface had been categorized as mottled terrain or plains[15]. The area discussed here is mostly mottled terrain. It is crossed by numerous triple bands mostly trending roughly southeast–northwest, and by discontinuous rays from the crater Pwyll, 700 km to the south. Nested images were taken at 1.2 km per pixel, 180 m per pixel and 54 m per pixel.

This terrain can be divided into four components: the general background plains, the lineae, locally disrupted areas, and the large disrupted area south of the main ridge crossing in Fig. 1. The background plains are composed of ridges superimposed on ridges, so that the surface resembles that of a ball of string. The lineae are mostly long, linear bundles of ridges and furrows that stand at a higher elevation than the surrounding plains. Elevations derived from shadows and photometric measurements indicate that the youngest of the prominent ridges have elevations of 100–200 m. Older ridges have much more subdued relief. Our main concern here is with places where the plains are locally disrupted as seen in Fig. 2, and broad areas of disruption as seen in Fig. 1 and in detail in Fig. 3.

Around the periphery of the area seen in Fig. 1, the plains are locally disrupted to form quasi-circular spots which are generally darker than their surroundings. The spots are mostly 10–20 km across and appear to be local upwellings of some kind (Fig. 2). In some of the spots, the surface is simply raised to form a low, flat-topped dome on which the original texture of the surrounding plains is preserved. In more advanced states of development, parts or all of the original surface texture are replaced by a fine-scale blocky texture and the disrupted zone is bound by an inward-facing escarpment. The disruptions cut across ridges, even those ridges that are relatively young. Most of the spots have a lower albedo than the unaffected terrain, which gives the terrain a mottled appearance. The mottled terrain covers large areas of Europa, which suggests that the disruptive process just described is widespread.

To the south of the prominent ridge crossing in Fig. 1 is a dark, diamond-shaped area, 100 km across, where widespread disruption of the crust has occurred. Within the area the crust has broken into pieces up to 20 km across. The individual crustal blocks are flat-topped and surrounded by cliffs that are 100–200 m high, as indicated by shadows. Preserved on the surface of the blocks is the original plain's surface texture of criss-crossing ridges. The texture on many of the blocks enables the reconstruction of the

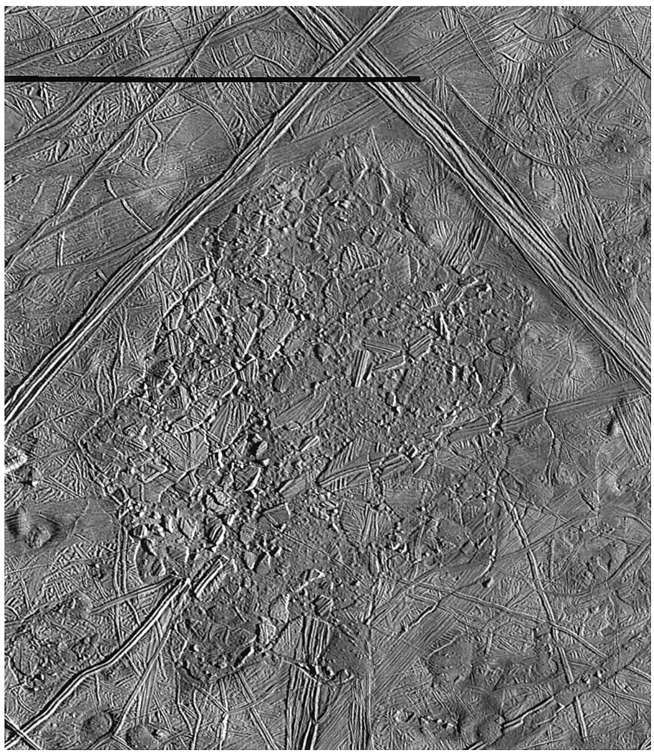

Figure 1 Disrupted zone at 13° N, 273° W. The scene is 200 km across. Just south of the prominent ridge crossing at the top of the image, the surface has been broken into blocks that have moved laterally from their original positions, as indicated by the texture of the pre-existing terrain preserved on the block surfaces. Around the periphery of the large disrupted zone are many additional, smaller and roughly circular areas where the original surface texture has been destroyed. Illumination is from the lower right.

original surface before its disruption. The reconstruction indicates that the blocks have moved laterally as much as several kilometres, and rotated. The area between the blocks has a much finer texture than the surface of the blocks. The texture resembles that in the locally disrupted areas described above. Some of the blocks appear to be tilted, thereby allowing the intervening hummocky material to lap onto one side of the block (Fig. 3). Other blocks are barely visible and appear to have been almost completely engulfed by the hummocky inter-block material. Whereas fracturing of the former surface has clearly formed the blocks, and the surfaces of the blocks themselves retain remnants of pre-existing fractures, fractures are rare in the intervening low-lying materials. The entire disrupted area is enclosed by an inward-facing cliff.

In the diamond-shaped disruption zone, lateral motion, rotation and tilting of sections of rigid icy shell have clearly taken place. As the surface is level, the lateral motion of the plates cannot be the result of downhill sliding but must rather be the result of movement of the materials in which the plates are embedded. As the plates moved, the underlying materials must have flowed upwards into the gaps that opened behind the plates, and sections of the ice crust must have foundered or been destroyed ahead of the plates. We have no model-independent measure of the thickness of the rigid shell, but when the breakup of the area being discussed here occurred, the thickness of the ice shell was probably comparable to or less than the horizontal dimensions of the smallest shell fragments that still retain their original surface texture. Thus the rigid shell was probably a few kilometres thick or less, and much thinner than the 150-km best estimate for the thickness of the whole water/ice layer.

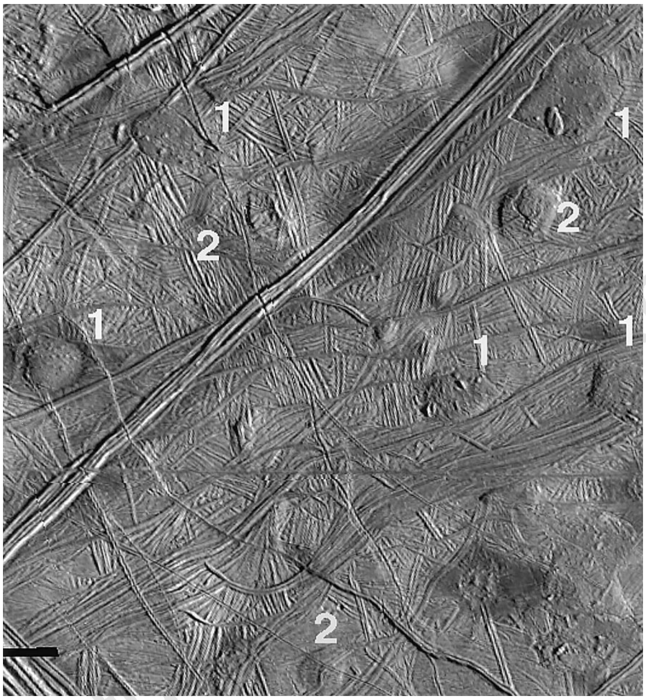

Figure 2 Detail from an area of mottled terrain 95 km across, just to the northeast of the area shown in Fig. 1. Most of the surface is composed of criss-crossing ridges and grooves. The features marked with a 1 are low domes on which almost all the ridge-and-groove surface texture has been destroyed. On domes marked with a 2 the original surface texture has been mostly preserved. The domes are thought to have been caused by columns of water or warm ice that erupted through the rigid ice shell[18].

We cannot tell from the images whether the breakup was relatively fast with the rigid plates floating in liquid water (which filled the opening gaps between the plates) or whether the process was slow, with the rigid plates overlying viscous ice that slowly filled the gaps. In the first case, the process would have been similar to the breakup of sea ice on the Earth[16], and the 200-m height of the "icebergs" would imply that the plates were ~ 2 km thick. Some support for the water hypothesis is a "puddle" imaged in another area[17] which suggests that an inviscid liquid (water) may have risen to the surface. In the alternative case where ice filled the gaps, water at relatively shallow depths may still be implied. Crude modelling of solid-state convection beneath a rigid crust on Europa suggests that effective viscosities of 10^8–10^9 MPa s, corresponding to an average temperature of 230–240 K (ref. 18), are probably needed. The presence of mobile ice below the rigid plates, at depths of several kilometres or less, implies local, near-surface thermal gradients of at least 10 K km^{-1} and temperatures approaching the melting point of ice at depths that are still very shallow compared with the 150-km thickness of the ice/water layer. Thus even with this alternative model, transient, modest increases in temperature could still result in melting, and water at shallow depths.

A number of observations suggest that the mobile layer (water or warm ice) is or was widespread, and not restricted to the small area discussed here. First, the quasi-circular spots that we now know to cause the mottling of at least half of Europa's surface are probably the result of diapirs, that is, of columns of mobile material (water or ice) rising to the surface from some mobile layer below[18]. Second, rotation and lateral movement of large sections of Europa's crust, and filling of the wedge-shaped gaps with materials darker than the surroundings, as found in several areas[19–22], also imply a mobile layer at depth. Last, the generally low surface relief despite abundant evidence of tectonic activity supports the presence of some accommodating, planet-wide mobile layer.

The time of formation of the various features described here is controversial. Whatever process caused the disruption, it took place at a later time than almost all other deformation. The paucity of

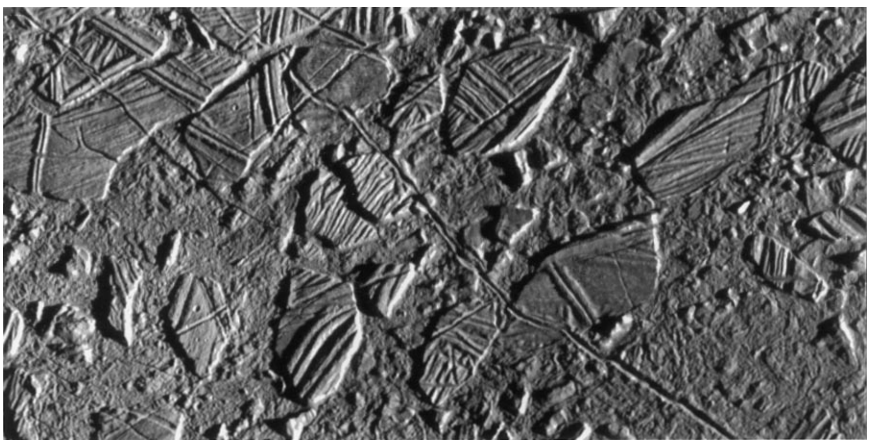

Figure 3 Detail of part of the lower left quadrant of Fig. 1. The scene is 40 km across. The terrain consists of high-standing blocks, on which the pre-existing surface texture is preserved, and low-lying terrain with a finer-scale texture, on which most of the features that characterize the original surface have been destroyed. Several small impact craters can be seen on the blocks, but none on the intervening terrain. Two prominent blocks in the right half of the picture are tilted to the south. The blocks are believed to be of the rigid ice shell and to have moved as a result of convection in the underlying water or warmer ice.

impact craters in all the images shown here is obvious. A number of small impact craters can be seen on top of some of the translated and rotated blocks in Fig. 3, but the low-lying material between the blocks is practically devoid of craters. From the latest estimate of the comet impact flux on Europa[23], and assuming plausible ratios of smaller comets to the observable larger ones[24], and that the observed craters are primaries, not secondaries, the age of the fractured surface is estimated to be of the order of 10^7 yr. With the same assumptions, the intervening materials are younger, perhaps a few million years old. Parts of the disrupted zone are overlain by rays from Pwyll crater and some of the craters appear to be Pwyll secondaries, not primaries. If this were taken into account, the derived ages would be even younger. As the uniquely prominent ray system of Pwyll suggests, it is the most recent large crater to have formed on Europa. Such craters are expected to form about every 10^6 yr. According to this model, even with the uncertainties in the cratering rates[23], it is difficult to see how the inter-block material, appearing so sparsely cratered at a resolution of 54 m per pixel, could be much older than 10^8 yr. (However, a minority of the authors of this Letter hold that the age of the surface can be better estimated by assuming that the youngest basin of Ganymede is 3.8×10^9 yr old, then deriving subsequent cratering rates from the number of craters superimposed on the basin and assuming a lunar decay constant for the cratering rate. This method yields a date of $\sim 3 \times 10^9$ yr for the area discussed here; G.N., manuscript in preparation). Although we cannot assert unequivocally that water is present today below the region shown in Fig. 1, if the young age of 10^8 yr—only a few per cent of the age of Europa—is correct, then the processes that have disrupted the plains are almost certainly continuing today, and liquid water is widely present at depths that are shallow compared with the 150-km estimated thickness of the water/ice layer. □

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Geological evidence for solid-state convection in Europa's ice shell

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The ice-rich surface of the jovian satellite Europa is sparsely cratered, suggesting that this moon might be geologically active today[1]. Moreover, models of the satellite's interior indicate that tidal interactions with Jupiter might produce enough heat to maintain a subsurface liquid water layer[2–5]. But the mechanisms of interior heat loss and resurfacing are currently unclear, as is the question of whether Europa has (or had at one time) a liquid water ocean[6,7]. Here we report on the morphology and geological interpretation of distinct surface features—pits, domes and spots—discovered in high-resolution images of Europa obtained by the Galileo spacecraft. The features are interpreted as the surface manifestation of diapirs, relatively warm localized ice masses that have risen buoyantly through the subsurface. We find that the formation of the features can be explained by thermally induced solid-state convection within an ice shell, possibly overlying a liquid water layer. Our results are consistent with the possibility that Europa has a liquid water ocean beneath a surface layer of ice, but further tests and observations are needed to demonstrate this conclusively.

During its sixth orbit through the jovian system the Galileo spacecraft obtained high-resolution images ($\sim$70 and 180 m per pixel) covering a $\sim 10^5\ km^2$ region of Europa centred near latitude 15° N, longitude 270° W. These images reveal that the satellite's late-stage geology is dominated by circular to elliptical pits, domes and dark spots $\sim$7–15 km in diameter, spaced 5–20 km apart. These features generally modify and disrupt the pre-existing plains, which are widespread and are composed of subparallel ridges and grooves that overlap in successive generations[1]. Lower-resolution images show that these features appear to constitute terrain like that of the previously defined "mottled plains" unit of Europa, which occurs over a large portion of the satellite's imaged surface[6]. Therefore, we infer that these pits, domes and spots are probably widespread across Europa, and are suspected to exist where mottled plains units occur.

In the region imaged at high resolution, a range of circular to elliptical features is observed with diverse specific morphologies (Fig. 1). The similarity in size and spacing of pits, domes and spots, and the gradation in morphology among them, suggests that they are genetically related. The features all have altered the original topography through positive or negative vertical deformation, and the vast majority are characterized by a surface morphology which is disrupted. The least-altered structures are characterized by a topo-