WHAT WE DON'T KNOW ABOUT EUROPA. R. T. Pappalardo, Jet Propulsion Laboratory, California Institute of Technology (M/S 321-560, 4800 Oak Grove Dr., Pasadena, CA 91109).

Introduction: In our understanding of Europa's geology today, we are arguably about where understanding of Earth geology was prior to the plate tectonic revolution. We have catalogued Europa's feature types, and we have some ideas of how they formed; we have some ideas of Europa's composition, and its geophysics. However, we do not yet have a unified vision for how the satellite works overall, and where and how its surface is linked to the interior. Given Europa's high astrobiological potential, bizarre geology, and intriguing geophysical processes, twelve questions can be posed which, once answered, would contribute to changing our paradigm regarding Europa. Most answers will have to await future spacecraft exploration, but when obtained, will alter the way we think about Europa, other icy satellites, and possibly ourselves.

1. What is the three dimensional character of the icy shell?: Two end-member models have been posed based on the geology of Europa. In the "thin ice" model [1] the ice shell is just a few kilometers thick, while the "thick ice" model [2] posits an ice shell tens of kilometers thick. These end-member models have different implications for the geological processes at Europa, and for the potential means of surface-ocean material exchange, which is key to understanding Europa's potential habitability.

2. What are the mechanisms of icy shell cracking?: Many troughs cut across Europa's surface, and morphologies suggest that troughs build into ridges. Randy Tufts and Greg Hoppa first realized that "diurnal" (orbital) stresses on Europa, generated from the combination of a radial tide and libration tide, rotate over the course of each Europa orbit [3], potentially explaining the cycloidal patterns of some cracks. Understanding the stressing mechanisms that can crack the ice shell is key to elucidating its history and relationship to an ocean beneath.

3. What is the rotation history recorded in the icy shell?: Dynamical modeling suggests that the ice shell may rotate slightly faster than synchronous [4]. However, other effects may prevent such nonsynchronous rotation [5,6]. Observations of Europa's surface provide clues as to whether nonsynchronous rotation has actually occurred. Recent work [7] finds that it is not so much the goodness of fit of individual lineaments to the global stress pattern of nonsynchronous rotation which matters, but that backrotation of Europa's ice shell shows a spike in the lineament formation history, suggesting past lineament formation was concentrated in backrotation. Moreover, true polar wander might also induce stress in Europa's ice shell [8]. Once a future mission provides global high resolution coverage, the full story of Europa's complicated rotational history could be disentangled.

4. How do ridges form, and is liquid water involved?: Ridges are Europa's most ubiquitous surface features, yet we do not understand how they form. Various models have been suggested: volcanism, tidal pumping, diapirism, compression, diking, shear heating, and volumetric strain [9]. Some of these models directly involve liquid water, others operate with warm ice alone, and others require the indirect tidal effects enabled by an ocean. A future orbiter could map out the three-dimensional morphology of Europa's ridges, potentially coupled with ice-penetrating radar observations to understand their subsurface "plumbing" [10]. In this way, we will be able to understand ridge formation, and whether and how liquid water is involved.

5. How are chaotic regions formed, and is liquid water involved?: Europa's chaotic terrains are places where blocks of the ridged terrain have broken, translated, rotated, and tilted within a matrix of hummocky material. The two end-member "thin shell" (melting) and "thick shell" (diapirism and convection) models apply here, and a hybrid model may be plausible [11]. Chaos models have implications for Europa's habitability, because it is important to understand whether and how surface oxidants can reach the subsurface ocean. These models also have implications for whether oceanic materials can directly or indirectly reach the surface to be detected by spacecraft.

6. Is the icy shell convecting?: Pits, spots, domes pepper Europa's surface, composing much of its mottled terrain [12]. They have been related to the rise of warm ice diapirs toward the surface, the expression of solid-state convection of Europa's ice shell [13]. Multiple feedbacks of ice temperature, strain rate, and grain size are relevant to ice shell convection, making it a geophysically complex issue. Important issues are whether Europa's ice shell is in fact convecting, how convection is related to surface features, and whether convection is isolated or widespread in space and time.

7. What are the non-ice components of the icy shell?: Europa's non-ice materials are concentrated in the satellite's visibly darker and redder regions [14]. Examination of IR spectra suggests hydrated salts, such as magnesium sulfate hydrate and sulfuric acid hydrate [15]. Moreover, sulfuric acid hydrate may be produced on the surface through radiolysis, and the reddish color of endogenic materials could be explained if radiolysis forms chains of sulfur through high-energy particle bombardment of sulfur-bearing compounds [14]. Future observations with improved techniques could help to identify the make-up of Europa's surface materials, perhaps indicating the composition of its ocean.

8. How active is Europa today?: Given the youthful crater age of Europa's surface, is expected that tidal kneading of Europa probably still shapes the icy surface today. However, current-day activity has not been confirmed, and the kinds of dramatic heat flow and jetting activity observed at Enceladus by the Cassini spacecraft have not (yet) been observed at Europa. Resolution and areal coverage limitations mean that comparisons between Voyager and Galileo data have not revealed any visible changes [16]. The rate and level of current-day activity is unknown, and indeed Europa could be in a relatively inactive phase of its history today. Ultimately, being certain of whether Europa is active today may require placing a seismometer on the surface.

9. Is the rocky mantle hot?: The thermal state of Europa's rocky mantle is relevant to issues of ice shell thickness, geological style, and habitability. Models of heat transport in Io have been applied to Europa [17], suggesting that Europa's mantle should be in one of two stable states of temperature and heat flux: either the mantle is cold and Moon-like, or tidally heated and Io-like. An intermediate point, where modest tidal heating balances solid-state convective heat loss, is an unstable equilibrium. It might be possible that Europa's mantle oscillates about a constantly moving stable point, due to orbital evolution driven largely by Io, shifting its heat flux and temperature in response to cyclical changes in its orbital eccentricity [18].

10. Has Europa's activity changed over time?: Geological mapping suggests that chaos regions are generally newer than the ridged plains [19]. However, it would be strange for Europa's youthful surface to have gone through a transition in its geological style, in the last 1% of geological time. A possibility arises from the coupling of Europa's orbit to those of Io and Ganymede [20]: it is plausible that Europa's shell may have thickened in the geologically recent past, allowing convection to commence or intensify, triggering formation of mottled and chaotic terrain. Such might occur cyclically, with a ~100 Myr period.

11. How does Europa couple to the external environment?: Europa is immersed in and coupled to the powerful radiation belts of Jupiter. Particle bombardment is key to modifying Europa's surface composition through radiolysis and ion implantation [13,21]; sputtering generates Europa's tenuous atmosphere and may modify the surface through slow redistribution of water molecules [22,23]; and Europa's relative motion through Jupiter's magnetic field generates the induced magnetic field that betrays its ocean [24]. Understanding the composition and potential habitability of Europa's ocean are inherently linked to understanding the satellite's external environment.

12. Is Europa's ocean habitable, and inhabited?: Whether Europa's ocean is inhabited is one of the most significant questions of modern planetary exploration. The first step toward an answer is to assess from an orbiting spacecraft whether Europa is a habitable environment today. This requires identification of the three necessary "ingredients" for life: liquid water, bioessential elements, and energy for metabolism. These issues are key to the objectives of the planned Jupiter Europa Orbiter, currently in the development stage [25,26].

Denouement: It is reasonable to expect that when we investigate Europa more closely in the future with an orbiting spacecraft, things that we think we know today we will find we did not know so well. There will also be new questions that will arise, which today we can hardly imagine to ask. As we better understand Europa's ocean and its potential habitability, and ultimately whether Europa actually contains life, then like 400 years ago, Europa may contribute to changing a scientific paradigm: "Are we alone in the Universe?"

References: [1] Greenberg et al. (2002), *Rev. Geophysics*, *40*, 1004. [2] Pappalardo (2010), *Proc. IAU Symp. 269*, 101–114. [3] Hoppa et al. (1999), *Science*, *285*, 1899–1902. [4] Ojakangas and Stevenson (1989), *Icarus*, *81*, 220–241. [5] Bills et al. (2009), in *Europa*, Univ. Ariz. Press, 119–136. [6] Goldreich and Mitchell (2010), *Icarus*, *209*, 631–638. [7] Selvans (2009), PhD thesis, Univ. Colorado. [8] Schenk et al. (2008), *Nature*, *453*, 368–371. [9] Prockter and Patterson (2009), in *Europa*, Univ. Ariz. Press, 237–258. [10] Blankenship et al. (2009), in *Europa*, Univ. Ariz. Press, 631–654. [11] Collins and Nimmo (2009) in *Europa*, Univ. Ariz. Press, 259–282. [12] Pappalardo et al. (1998), *Nature*, 391, 365–368. [13] Barr and Showman (2009), in *Europa*, Univ. Ariz. Press, 405–430. [14] Carlson et al. (2009), in *Europa*, Univ. Ariz. Press, 283–328. [15] McCord et al. (1999), *JGR*, *104*, 11,827–851. [16] Phillips et al. (2000), *JGR*, *105*, 22,579-598. [17] Moore and Hussmann (2009), in *Europa*, Univ. Ariz. Press, 369–380. [18] W. Moore (2010), personal communication. [19] Doggett et al. (2009), in *Europa*, Univ. Ariz. Press, 137–160. [20] Hussmann and Spohn (2004), *Icarus*, *185*, 258–273. [21] Paranicas et al. (2009), in *Europa*, Univ. Ariz. Press, 529–544. [22] Johnson et al. (2009), in *Europa*, Univ. Ariz. Press, 507–528. [23] McGrath et al. (2009), in *Europa*, Univ. Ariz. Press, 485–506. [24] Khurana et al. (2009), in *Europa*, Univ. Ariz. Press, 571–587. [25] Greeley et al. (2009), in *Europa*, Univ. Ariz. Press, 655–695. [26] Clark et al. (2011), *Adv. Space Res*., in press.