PERSPECTIVES: PLANETARY SCIENCE

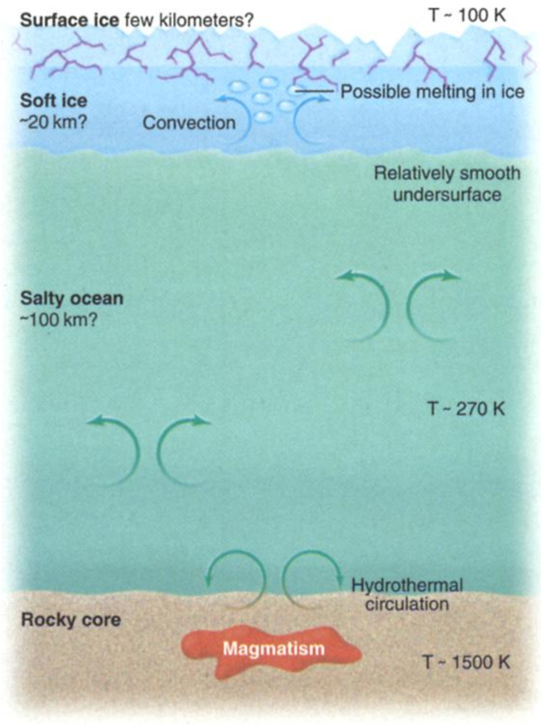
Europa's Ocean—the Case Strengthens

David Stevenson

When a conductor is placed in a time-varying magnetic field, electrical currents are induced. These currents in turn create magnetic fields that can be detected. It is these physical principles that underlie the operation of metal detectors at airports and that give the magnetometer on the Galileo spacecraft the ability to "see" electrical conductors inside the moons of Jupiter. On page 1340 of this issue, Kivelson *et al.* (*1*) present overwhelming evidence for a conducting layer near the surface of one of these moons, Europa. The most likely explanation is that Europa has a salty, global water ocean beneath its ice shell.

Europa is similar in size to Earth's moon and is thought to be mostly Earth-like in composition, but with a layer of some 100 km or so of water on top, which may be either liquid or solid (*2*). The very cold surface ice is extensively cracked and deformed, a testament to the flexing by tides as Europa follows its forced eccentric orbit about Jupiter. The possibility of water beneath this ice, perhaps as little as 10 km below the surface, has excited those interested in extraterrestrial environments for life and established a major role for Europa in NASA's plans for outer solar system missions (*3*).

Theoretical (*4*), geological (*5*), and spectroscopic (*6*) arguments have all been used to support the presence of an ocean beneath Europa's icy shell, but none of these arguments are compelling (see the table). In contrast, the magnetic field evidence is remarkably strong. To appreciate this, consider the behavior expected for a sufficiently conducting shell close to Europa's surface. In this "high conductivity" limit (reached for a conductivity many orders of magnitude lower than those for a metal), a simple induction model (*1*) predicts that the time-dependent field created by the induced currents almost exactly cancels the component of the time-dependent external field perpendicular to Europa's surface. The largest contribution to the latter comes from Jupiter's dipole tilt, which causes the field direction at Europa's location to oscillate with an amplitude of roughly 20° and a period of about 10 hours. The predicted strength and direction of Europa's induced magnetic dipole depend on the instantaneous position of Europa in the reference frame defined by Jupiter's rotating magnetic field (*7*).



Possible processes in Europa. This is a montage; it is unlikely that all of these processes happen in the same place at the same time.

The observational data match the model well (*1*). This is all the more remarkable considering that the model has no adjustable parameters. Moreover, these most recent data show that the field arising from currents or magnetization within Europa changes direction by 180° for spacecraft encounters 180° apart in longitude, as the induction model requires. This behavior is very different from that expected for a fixed field [such as the core dynamo that appears to dominate at Ganymede (*2*)]. The model does not represent the data perfectly: Europa is deeply immersed in the jovian magnetosphere and in the plasma contained within that field, and understandable (though quite complex) field disturbances arise from this interaction of Europa with this environment.

To a good approximation, the induction response depends on the product of conducting layer thickness and conductivity. However, the layer must be a nearly complete spherical shell; the data cannot be explained by a patchwork of highly conducting regions with much less than global coverage. A global layer of water with a composition similar to Earth seawater and a thickness greater than about 10 km could explain the data. The dominant

EVIDENCE FOR EUROPA'S OCEAN

Technique	Implications	Challenge
Theoretical study of tidal deformation and heating	Predicts that an ocean will persist once formed	Rheology of ice is poorly known, especially at tidal frequencies, so predictions are uncertain
Observations of surface deformation, especially "chaotic" regions, rafting, cycloidal ridges, possible low-viscosity surface flows	Suggests thin ice and highly mobilized ice, consistent with an underlying ocean	Might be explained by thin, cold, brittle ice "floating" on thick, warm, soft, easily deformed ice
Near-infrared spectroscopy suggesting salt deposits on surface	Salt could arise from sublimation of a salty water "eruption"	Even if water is implicated, it need not come from an ocean–there may be melting within the ice
Magnetic field evidence for an induction response	Requires a near surface, global conducting layer, most readily explained by a salty ocean	Is there any other possible conducting layer?
Altimetry and gravity field with sufficient resolution to determine tidal variation	Clear determination of whether there is an ocean; information on ice thickness	Requires Europa orbiter

The author is in the Division of Geology and Planetary Science, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA. E-mail: djs@gps.caltech.edu

source of ions in Europa's ocean may be different from those in Earth's oceans (*8*), but they should satisfy the conductivity requirement. A much thicker layer of water ice, even if it is heavily contaminated with frozen brine, cannot explain the data because the ions are relatively immobile compared with those in liquid water. Any plausible ocean flow (fluid currents relative to the ice shell) is unimportant because it will have a much lower velocity than the rotational motion of Europa's surface. A partially melted ice layer could match the required conductivity but is physically implausible because the melt would have to be interconnected over large distances, which would result in the melt percolating through and separating from the ice driven by the density difference of ice and water. Kivelson *et al.* (*1*) argue that Europa's tenous, external ionosphere also cannot provide the required conducting layer. The induced field declines as the inverse cube of the radius from the surface of the conducting layer, and any deep-seated conducting layer (such as a metallic core or a magma ocean in the rocky core) would therefore lead to a much lower field than is observed.

Some more exotic possibilities cannot be excluded (such as graphite or some other relatively high conductivity material, plausibly carbon-rich, intermingled within the ice but interconnected at the grain size scale), but a water layer is the most plausible explanation. A compelling demonstration of its existence or absence may be reached from gravity and altimetry data in the proposed Europa orbiter. The predicted diurnal tidal amplitude is over an order of magnitude larger for a Europa with a global ocean than for a Europa without one. More complex, intermediate scenarios can be envisaged (such as ice "grounding" on the underlying rocky topography in some places and not others). But the orbiter results will likely settle the fascinating question of whether Europa has an ocean. Defined broadly enough, oceans may not be that rare, but Europa's case may be special because the tidal heating may allow liquid water to get closer to the surface, possibly including occasional eruptions or flows. After Mars, it remains the most attractive extraterrestrial environment within our solar system in which to seek evidence of past or present life.

References and Notes

1. M. G. Kivelson *et al.*, *Science* **289**, 1340 (2000).
2. For a review of the Galilean satellites and Galileo results, see A. P. Showman and R. Malhotra, *Science* **286**, 77 (1999).
3. See sse.jpl.nasa.gov/missions/jup_missns/europa.html.
4. The history of theoretical work is long and complex; the pioneers were P. Cassen, R. T. Reynolds, and S. J. Peale [*Geophys. Res. Lett.* **6**, 731 (1979)] [corrected subsequently in *Geophys. Res. Lett.* **7**, 987 (1980)].
5. R. T. Pappalardo *et al.*, *J. Geophys. Res.* **104**, 24015 (1999); R. T. Pappalardo *et al.*, *Sci. Am.* **281**, 54 (October 1999); G. V. Hoppa, B. R. Tufts, R. Greenberg, P. E. Geissler, *Science* **285**, 1899 (1999).
6. T. B. McCord, G. B. Hansen, D. L. Matson, *J. Geophys. Res.* **104**, 11827 (1999); R. W. Carlson, R. E. Johnson, M. S. Anderson, *Science* **286**, 97 (1999).
7. Jupiter is a fluid planet and, unlike Earth, does not have a valid coordinate system fixed to actual objects. For example, we can talk about a satellite being "over" North America, but we have no corresponding meaningful language for Jupiter. The great red spot is not fixed. The location of Europa relative to Jupiter's field (called System III longitude) is central to the interpretation of the data.
8. J. S. Kargel, *Science* **280**, 1211 (1998).

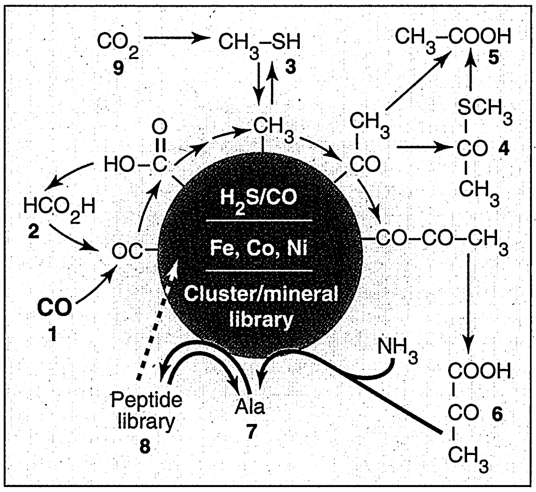
PERSPECTIVES: ORIGIN OF LIFE

Life as We Don't Know It

Günter Wächtershäuser

Theories of the origin of life on Earth fall into two general categories. Prebiotic broth theories postulate a protracted origin by the self-assembly of high–molecular weight structures, such as RNA, proteins, and vesicles, in a cold prebiotic broth of preaccumulated modules (*1*). More recently, theories based on a hydrothermal origin have gained ground. For example, the theory of a pressurized iron-sulfur world (*2*) suggests a fast origin by an autotrophic metabolism of low–molecular weight constituents, in an environment of iron sulfide and hot magmatic exhalations. Cody *et al.*'s (*3*) results on page 1337 of this issue provide key support for the latter theory and greatly strengthen the hope that it may one day be possible to understand and reconstruct the beginnings of life on Earth.

Pyruvic acid, CH_3-CO-COOH, is one of the most crucial constituents of extant intermediary metabolism. It occurs in numerous metabolic pathways, notably the reductive citric acid cycle and the pathways that produce amino acids and sugars. It has been suggested that pyruvic acid or its anion pyruvate formed primordially by double carbonylation (*4*). Cody *et al.* provide experimental support for this suggestion. They show that pyruvic acid forms from formic acid in the presence of nonylmercaptane and iron sulfide at 250°C and 200 MPa. Water is initially absent and forms only by the dehydration of the formic acid. This result poses fascinating thermodynamic and kinetic questions. Pyruvic acid is an extremely heat-sensitive compound that decomposes at its boiling point of 165°C. It appears paradoxical that at the very high temperature required for dehydration of formic acid, the relatively unstable pyruvic acid can form and exist at detectable concentrations. Moreover, it is astonishing that acetic acid is formed at a lower yield than pyruvic acid. The explanation may well lie in the very high pressure.



Reactions in the iron-sulfur world. Reaction conditions are given in the table on the next page. The dotted arrow represents ligand feedback.

The work is particularly exciting because experience with organic synthesis in the high-pressure/high-temperature regime is very limited. The experiments require a combination of 200 MPa (corresponding to a rock depth of about 7 km or a 20-km water column) and 250°C, in addition to high CO pressure in the absence of water. It remains to be established whether such conditions are geophysically possible.

The new finding, if it holds, fills a critical gap in the experimental picture of the iron-sulfur world (see the figure). All individual reaction steps for a conversion of carbon monoxide **1** to peptides **8** have now been demonstrated: formation of methyl thioacetate **4** (*4*), of pyruvate **6** (*1*), of alanine **9** by reductive amination of pyruvate **6** (*5*), and of peptides **8** by activation of amino acids with CO/H_2S (*6*). The challenge will now be to overcome the discrepancies in

The author is at Tal 29, 80331 Munich, Germany. E-mail: info@patent.de