RESEARCH: PLANETARY SCIENCE

The Salt of Europa

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In 1972, astronomers confirmed earlier suspicions that Jupiter's satellite Europa has an icy surface and hinted that this moon-sized body has a rocky interior. *Voyager* spacecraft flybys in 1979 further revealed a young, torn-up surface likened to that of a cracked eggshell. Tidal dissipative heating, driven by resonant orbital motions with sister satellites Io and Ganymede, were immediately suspected of driving Europa's geologic activity. Many researchers even considered whether Europa might be hiding an ocean, possibly 100 km deep, beneath an icy crust. We went into the Galileo mission expecting Europa to live up to its high billing. Nobody expected Europa to be exactly as Arthur C. Clarke had envisioned in his novel *2010: Odyssey Two*, but certainly we find Europa to be a planetary blockbuster. As reported on page 1242 of this issue, McCord *et al.* (*1*) present the latest in a series of stunning discoveries about this enigmatic moon.

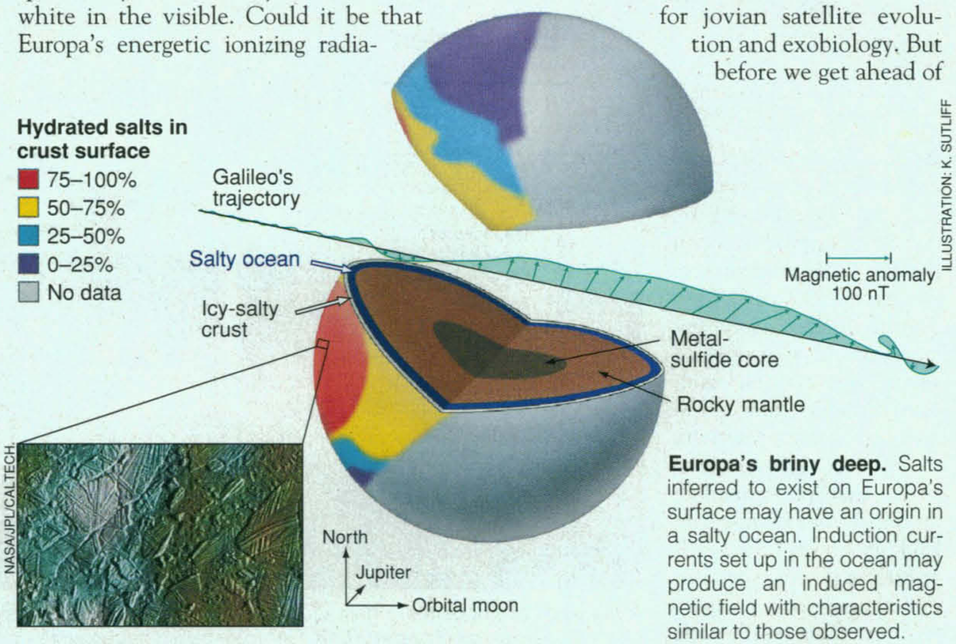
Two years of Galileo results at Europa include images showing geologic relations that, without question, support the ocean hypothesis (*2*); gravity data best explained by the existence of a metallic core, rocky mantle, and an ice-water surface layer >100 km thick (*3*); and magnetometer readings that reveal a peculiar Europan magnetic field (*4*). Now McCord *et al.*, basing their findings on infrared spectrometry, suggest that whole landscapes are paved with hydrated salts, whereas others consist of nearly pure ice.

Europa's bright white regions contain expected spectral absorptions due to water ice, but terrains that possess reddish and yellowish hues contain water absorption bands that are not the same shape as those of water ice. These water bands are severely distorted, mimicked by a small set of plausible mineral analogs—all of them hydrated salts, such as epsom salt ($MgSO_4 \cdot 7H_2O$) and natron ($Na_2CO_3 \cdot 10H_2O$). These bands relate to water of hydration, "$\cdot nH_2O$," rather than water ice or chemically bound hydroxyl. Certain other types of hydrated phases, such as clay minerals, do not offer good matches to the reflectance of the reddish terrains. The discovery is that of hydrated water; the interpretation is that the water is bound to salts. Hydrated water is associated with reddish terrains, all regions where material from below has been erupted volcanically, extruded from below in the solid state, or exposed by deep penetrating impacts or internally driven disruptions of the surface. Does salty crust therefore equal salty ocean?

Suppose that the salt interpretation of McCord *et al.* is correct. Good questions remain. Why are the most hydrated (saltiest) areas red and yellow? Salts generally (and specifically those cited by McCord *et al.*) are white in the visible. Could it be that Europa's energetic ionizing radiation environment partly alters the salts to red and yellow substances? Perhaps, but why do some reddish geologic features fade and brighten with time? Perhaps they eventually become coated with water frost.

Or perhaps we should just take the interpretation of McCord *et al.* with a pinch of salt. We currently lack any definitive means to identify the substance to which Europa's hydrated water is attached. It is safe to consider, as do McCord *et al.*, that this new result is a discovery regarding the nature of the hydrated water and a plausible interpretation of the substance to which the water is bound.

The putative existence on Europa of hydrated salts adds fuel to a general class of models that has been pushed for Europa's fiery neighbor Io for over two decades—for lack of a better term, the "evaporite models" (*5*)—and now we can apply such models to Europa. A different twist on the same theme is that of "brine volcanism" and differentiation of salty icy satellites (*6*). A simple model of Europa's evolution, starting from a primordial chondritic precursor, yields a crust consisting of ice and hydrated salts, mainly magnesium sulfate hydrate ($MgSO_4 \cdot 12H_2O$) and sodium sulfate hydrate ($Na_2SO_4 \cdot 10H_2O$). However, sulfates in a brine ocean would be chemically reduced to less soluble sulfides, as they are in Earth's oceanic system, if hydrothermal processes cycle the ocean water through a basaltic sea floor. A potent implication of the sulfate interpretation of McCord *et al.* is that such circulation does not occur on Europa or, alternatively, that the sea-floor material with which hydrothermal fluids interact is not basaltic. Many more implications will flow from these new discoveries for jovian satellite evolution and exobiology. But before we get ahead of ourselves, just where does the ocean hypothesis stand?



Europa's briny deep. Salts inferred to exist on Europa's surface may have an origin in a salty ocean. Induction currents set up in the ocean may produce an induced magnetic field with characteristics similar to those observed.

Before Galileo, it was recognized that if Europa has a salty ocean, then the ocean represents a giant electrical circuit subject to induction effects by Jupiter's magnetic field (*7*). The major characteristics of a Europan magnetic field induced in a brine ocean were predicted before Galileo data (*8*); thus, a geophysical means exists to detect a Europan ocean. The discovery of what appears to be an induced field with the right characteristics (*4*) seems to support the brine ocean hypothesis (*9*). The magnetometer data pose a rapidly developing story and with the new results by McCord *et al.* pose a consistency argument; dissolved solutes are needed in the ocean to make it responsive to induction.

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Taken with the gravity data and awesome imagery, the Europan ocean hypothesis is on solid ground (or beneath solid salt and ice). Before the Voyager flybys, theoretical evidence suggested that Europa's icy crust might be warm and perhaps even melted at its base, and those suggestions were made even before the discovery of tidal heating of Europa (*10–12*). This is an amazing confluence of observations and interpretations that rarely happens so neatly in planetary science.

We look forward to continued scrutiny during the Galileo Extended Mission. Ultimately, we will need to take closeup images and other measurements from orbit, land on and chemically analyze Europa's surface, geophysically probe the interior by surface instruments, and eventually take a dip in the ocean before we can conclude with certainty that the ocean exists. But I haven't heard any recent bets against the ocean.

References

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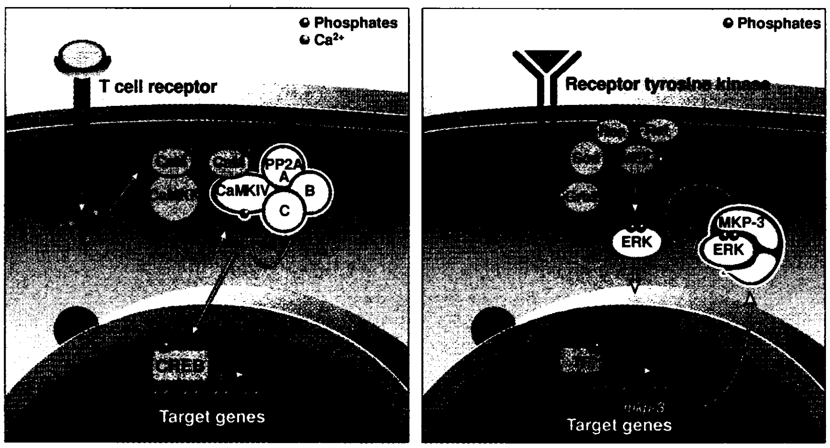
SIGNAL TRANSDUCTION

Kinases and Phosphatases–A Marriage Is Consummated

Ernst Hafen

Successful marriages, according to the age-old wisdom, often result from the union of opposites. Each partner counterbalances the excesses of the other. Within cells, such excesses on the part of some signal transduction molecules can have dire consequences. Runaway activity of protein kinases (enzymes that phosphorylate proteins), for example, can lead to uncontrolled cell growth and tumorigenesis. But kinases have prospective partners—the wide variety of protein phosphatases that keep the kinases in check by performing the opposite operation, dephosphorylation of the substrate. As two reports published on pages 1258 and 1262 of this issue (*1, 2*) now demonstrate, kinases and phosphatases are indeed joined in a physical union.



A marriage of opposites. Tight regulation of kinases occurs by physical association with their respective phosphatases. (**Left**) Ca^{2+}/calmodulin-dependent kinase IV is constitutively associated with phosphatase 2A (PP2A), resulting in the kinase's rapid inactivation even in the presence of high intracellular Ca^{2+} (*1*). (**Right**) ERK2 activation triggers synthesis of MKP-3. Binding of MKP-3 ERK2 stimulates its catalytic activity and inactivates ERK (*2*).

The characterization of oncogenes in vertebrates and the systematic genetic analysis of signal transduction processes in model systems like yeast, *Caenorhabditis elegans*, and *Drosophila* have identified many more positively acting kinases than negatively acting phosphatases (*3, 4*). This finding has led to the view that phosphatases may act constitutively by a hit-and-run mechanism, with little specificity for distinct kinases. Now, however, the number of molecularly characterized phosphatases is rapidly increasing. Some are highly specific for their substrate, and their transcription is regulated in a complex way (*5*). Indeed, the two new studies by the groups of Wadzinski and of Arkinstall point to an intricate regulation of kinases and phosphatases. Westphal *et al.* (*1*) examine the mechanism by which persistent, high concentrations of intracellular Ca^{2+} cause only a transient activation of CREB-dependent transcription. This sudden turning off of the response in spite of the continued presence of the activating signal occurs because, shortly after Ca^{2+}-calmodulin–dependent kinase IV (CaMKIV) activates CREB by phosphorylation, the kinase is inactivated by dephosphorylation via phosphatase 2A (PP2A) (see the figure, left panel). The authors show that CaMKIV and the PP2A heterotrimeric holoenzyme can be isolated as a stable complex from cultured cells and from brain extracts. Formation of this complex can occur without the phosphorylation of CaMKIV by its upstream activating kinase, CaMKK, but does require the CaMKIV kinase domain. PP2A function is required for the transitory activation of CREB in response to prolonged high intracellular Ca^{2+} because inhibition of PP2A by SV40 small t antigen results in the prolonged activation of a CREB-dependent reporter construct in Jurkat T cells.

This permanent association of a kinase with its phosphatase allows tight control of the activity of the corresponding kinase. It also raises a question, however. How can this kinase ever be activated sufficiently to increase CREB activity if the phosphatase is always present to undo the kinase's work? It is possible that phosphorylation of CaMKIV by CaMKK transiently outpaces the inactivation by PP2A. Alternatively, PP2A activity may be altered by posttranslational modification or by the activation of CaMKIV itself. Posttranslational activation of a phosphatase by its own substrate is described by Camps *et al.* in the second report (*2*).

Mitogen-activated protein (MAP) kinases, also known as extracellular signal–

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