COMPOSITION OF EUROPA'S CRUST AND OCEAN.

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Introduction. Europa has a differentiated structure probably consisting of a dense metallic or sulfide core, a rocky mantle, and a volatile-rich icy crust (Anderson et al. 1997). Galileo's first images of Europa improve prospects that a proposed liquid ocean actually exists beneath thick ice floes (Belton et al. 1996), at least locally or at times in Europa's geologic history. Europa possesses an interesting array of features formed through tectonic and cryo-volcanic processes, some of which were recently or still are active. The recent NIMS evidence of magnesium sulfate hydrates and possible aldehydes or alcohols and other possible non-ice water-soluble substances (McCord et al. 1997, Fall 1997 AGU oral presentation and unpublished data) has renewed interest in the geochemistry of Europa's putative ocean and cryovolcanological processes. Besides these substances, CO_2 may have been detected on Ganymede and Callisto (McCord et al. 1997), and this same volatile may also exist on Europa. In this report I consider chemical stability of certain candidate substances on Europa. In summary, if magnesium sulfate is widespread on Europa, as suggested recently, then any NH_3 would have reacted to form ammonium compounds and organic salts; CO_2 likewise would have reacted to form carbonates, bicarbonates, or carbamates (depending on reactant stoichiometry). The presence of $MgSO_4$ also places sharp constraints on the nature of possible seafloor hydrothermal processes.

Chemical stability of non-ice constituents

Prior to Galileo observations the presence of sulfur dioxide or other S-O compounds was already known due to ultraviolet absorptions (Ockert et al. 1987). Galileo NIMS spectra have revealed additional substances that are infrared absorbers. The new Galileo data have shown that the darker mottled terrains (including sea-ice-like disrupted terrain) are deficient in or devoid of water ice but instead are dominated spectroscopically by a hydrated compound, perhaps Mg-Na-sulfate-hydrates (McCord et al. 1997 and Fall 1997 AGU oral presentation). This interpretation fits ideally with predictions made on the basis of hypothesized cryovolcanism related to dehydration of a carbonaceous chondrite precursory material (Kargel 1991). In one model, Europa's "ice" crust is composed dominantly of hydrated sulfates with just 5% or so of water ice. Fractional crystal-lization of Europa's ocean and flotation or diapirism of ice can result in icier surface compositions.

Other spectroscopic features in NIMS data sug-gest that alcohols, aldehydes, or ammonium com-pounds are present (McCord et al. 1997). The pre-eminent alcohol in the interstellar medium and comets is methanol (CH_3OH), and if alcohols occur on Europa, methanol is likely to be the major one. Formaldehyde (HCHO) and its polymerized long-chain hydrate polyoxymethylene, $HO(HCHO)_nH$ (known as "POM"), are also abundant in outer space. Carbon dioxide or CO_2-clathrate-hydrate have been given tentative identifica-tions on Ganymede and Callisto, and CO_2 certainly is abundant in most comets; it also is observed on Triton and occurs in the atmospheres of Venus, Earth, and Mars; CO_2 would not be a surprising find on Europa.

Ammonia is widely thought to exist in many parts of the outer solar system, and it could be present on Europa. H_2S reacts with NH_3 to form highly soluble $(NH_4)_2S$ or NH_4SH. Nonpolar vola-tiles, such as CH_4, N_2, and CO, form solid clathrate hydrates and can occur in aqueous solutions of salts or NH_3 at levels of ~1% at hundreds of bars pressure.

Table I shows some chemical stability relations in simple ternary systems. The major points are that $MgSO_4$ and NH_3 are chemically unstable with respect to one another ($Mg(OH)_2$ and $(NH_4)_2SO_4$ are formed), formaldehyde and ammonia are similarly unstable (hexamethylenetetramine hexahydrate is formed), and CO_2 and NH_3 react to form any of several ammonium carbonates, bicarbonates, or carbamates, depending on the stoichiometry of the reactants. Na_2SO_4 likely would exhibit comparable reactions with NH_3, perhaps forming NaOH. If sulfates are present and widespread on Europa, it may suggest that any NH_3 would have reacted to ammonium compounds, organic salts, and hydrox-ides. Thus, ammonia-water volcanism is not too likely if Europa is uniformly $MgSO_4$-rich.

Europan chemical geodynamics

The possibility that NH_3 saturation occurs in some parts of Europa could be supported by cryovolcanological studies, which point to the existence of thick, lobate flows attributable to possible ammonia-water volcanism. If some regions are NH_3-undersaturated and enriched in magnesium sulfate, and others are NH_3-saturated (possibly also containing ammonium salts), then perhaps the ocean is not globally extensive and distinct chemical reservoirs exist. On the other hand, if Europa's compositional layering is laterally uniform (with surface variations occurring only due to differences in age or surface environment), a globally extensive ocean is possible. Constraints on these possibilities might be obtained with combined analysis of NIMS and imaging data.

An ocean containing abundant $MgSO_4$ places sharp constraints on the nature of seafloor hydrothermal processes on Europa. By analogy with Earth's ocean, hydrothermal circulation in a basaltic crust must be nil; otherwise sulfate reduction would be virtually complete. However, circulation in a sulfate-carbonate-rich suboceanic crust (as considered by Kargel 1991) might not cause the chemical reduction of sulfates that occurs in ferrous iron-rich silicate crusts such as Earth's.

References. Anderson, J.D., Lau, E.L., Sjogren, W.L., Schubert, G., and Moore, W.B., 1997, Europa's differentiated internal structure: Inferences from two Galileo encounters, Science, v. 276, p. 1236-1239. Belton, M.J.S. et al., 1996, Galileo's first images of Jupiter and the Galilean satellites, Science, v. 274, p. 377-385. Kargel, J.S., 1991, Brine volcanism and the interior structures of asteroids and icy satellites, *Icarus*, v. 94, p. 368-390. McCord, T.B., et al., 1997, Composition of the Icy Galilean satellite surfaces from the Galileo NIMS investigation, Supplement to Eos, v. 46, p. F407. Ockert, M., et al., 1987, Europa's ultraviolet absorption band (260 to 320 nm): Temporal and spatial evidence from IUE, Icarus, v. 70, p. 499-505.

TABLE I. Chemical stability of Europan volatiles and salts.

Substance	Stable in aqueous $MgSO_4$?	Stable in aqueous NH_3?	Solid compounds formed in H_2O-$MgSO_4$ or H_2O-NH_3
CH_3OH	Yes	Yes	$CH_3OH \cdot H_2O$, $2CH_3OH \cdot NH_3$, $CH_3OH \cdot NH_3$ (depends on stoichiometry); various hydrocarbons, CO_2, and/or HCHO or POM (by photolysis)
HCHO or POM	Yes?	No	POM, $(CH_2)_6N_4 \cdot 6H_2O$ (by reaction with ammonia)
CO_2	Yes	No	CO_2 (vapor condensate), $CO_2 \cdot 5.75H_2O$ precipitation in aqueous systems), $(NH_4)_2CO_3 \cdot H_2O$, $(NH_4)_2CO_3$, $(NH_3)_2CO_2$, NH_4HCO_3, $(NH_4)_2CO_3 \cdot 2NH_4HCO_3$ (compound depends on stoichiometry)
NH_3	No	Yes, by definition	NH_3 (vapor condensate), $NH_3 \cdot 2H_2O$ (normal crystallization of ammonia-water liquid), $NH_3 \cdot H_2O$ (fractional crystallization of ammonia-water eutectic liquid), $(NH_4)_2SO_4$ (reaction with $MgSO_4$)
$MgSO_4$	Yes, by definition	No	$MgSO_4.nH_2O$ (n =0, 1, 6, 7, or 12) $Mg(OH_2)$ + $(NH_4)_2SO_4$ (reaction w/NH_3), Mg-silicates such as serpentine + sulfides such as pyrite (hydrothermal reaction with rock)
SO_2	Yes, soluble gas ?		SO_2 (vapor condensate), S (by dissociation), $SO_2 \cdot 5^3/_4H_2O$, H_2SO_4 (by UV photolysis with water)