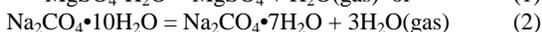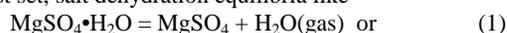# THERMODYNAMIC STABILITY OF HYDRATED SALTS ON THE SURFACE OF EUROPA.

M. Yu. Zolotov and E. L. Shock, Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130-4899. E-mails: zolotov@zonvark.wustl.edu, shock@zonvark.wustl.edu.

Introduction: *Galileo* spacecraft reflectance spectroscopy in the near infrared indicates the presence of hydrated salts in a non-H_2O ice component on the surface of Jupiter's moon Europa [1-4]. Magnesium and sodium sulfates (e.g., $MgSO_4 \cdot 7H_2O$, epsomite; $MgSO_4 \cdot Na_2SO_4 \cdot 4H_2O$, bloedite; $Na_2SO_4 \cdot 10H_2O$, mirabilite), sodium carbonate ($Na_2CO_3 \cdot 10H_2O$, natron) and mixtures of these salts provide good fits for the near infrared spectra for the non-ice material [1-2]. The vivid association of non-ice material with disrupted areas (linea, chaos) on Europa's surface can be interpreted in terms of sublimation/sputtering of salty ice and/or freezing/evaporation of water derived from a salty ocean [1,5]. The multi-component composition of oceanic water should lead to a variety of salts in the products of freezing and sublimation on Europa's surface [6-9]

The deposition of salts from an aqueous solution should lead to the initial formation of compounds with the highest degree of hydration. On the surface of Europa, those salts can desiccate in contact with space, as shown experimentally at simulated European condition [4]. The extent of salt dehydration can also be evaluated theoretically by thermodynamic calculations of dehydration equilibria. Here we apply calculations of this type to estimate the stability and relative abundance of hydrated sulfates, chlorides, and carbonates of Mg, Ca, Na, K, and Fe in ice-bearing materials and ice-free salty lag deposits on Europa.

Model: Two sets of calculations are described here. In the first set, salt dehydration equilibria like

$$MgSO_4 \cdot H_2O = MgSO_4 + H_2O(gas) \quad \text{or} \quad (1)$$
$$Na_2CO_4 \cdot 10H_2O = Na_2CO_4 \cdot 7H_2O + 3H_2O(gas) \quad (2)$$

were calculated from 80 to 140 K to cover the range of observed temperatures of Europa's surface (86-132 K [10]). The activity of solid phases was unity and water vapor is assumed to be an ideal gas. The calculated equilibrium partial pressures of water vapor (P_{H2O}) for dehydration reactions like eq. (1) and (2) are compared with equilibrium P_{H2O} values over ice.

In the second set of calculations, we applied the free energy minimization method to evaluate chemical equilibrium in the $H_2O(gas)$-C-O-S-Cl-Mg-Ca-Na-K system at 100 K. The values of P_{H2O} were varied from ice saturation condition to several log units lower to cover the range of P_{H2O} that could occur in salty lag deposits. These calculations model the degree of hydration and relative abundances of salts in a cross-section of a lag deposit. The bulk atomic composition corresponds to our working model for Europa's ocean chemistry (*K1a* in [8]) except for an arbitrarily chosen C abundance. Thermodynamic data for salts are taken from [11,12]. The P_{H2O} values over ice from [13] were extrapolated to Europa's temperatures.

Results: Fig. 1 depicts dehydration equilibria among magnesium sulfates and sodium carbonates together with the ice-water vapor phase boundary curve. The areas between the equilibrium curves represent the stability fields of salts and ice. One can see that the conditions of water vapor-ice saturation favor the stability of salts with the highest degree of
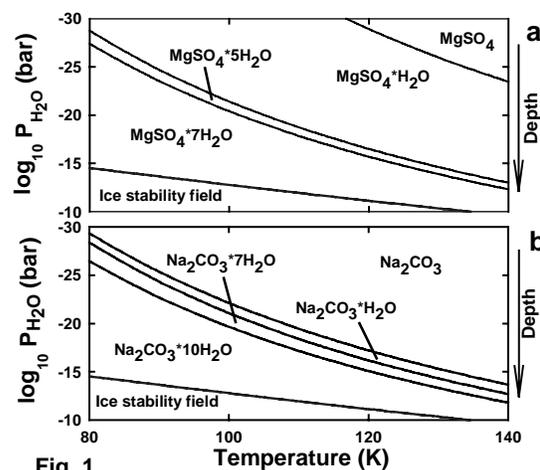

Fig. 1

hydration. An increase in temperature and/or decrease in P_{H2O} leads to the stability of sequentially less hydrated salts.

The stability fields of other salts relative to water ice at 100 K are depicted in Fig. 2. A decrease in P_{H2O}, which can occur toward the top of salt deposits, favors dehydration of salts. Relative salt abundances in a modeled lag deposit at 100 K are shown in Fig. 3. Magnesium and sodium sulfates compose more than 70% of the calculated deposit, and are less hydrated toward the uppermost layer of the lag deposit.

Discussion: Figs. 1-3 show that highly hydrated salts are thermodynamically stable in ice-bearing deposits on the surface of Europa and throughout the icy crust. This is consistent with earlier investigations [2,4,7]. Salt lag deposits formed through sublimation/sputtering of the ice can contain less hydrated salts than ice-bearing materials. This can occur because P_{H2O} values in the lag deposits should be less than those in ice-bearing materials and because the surface of salt deposits could be warmer compared to deeper layers. Both heating of the surface and a lower albedo of salt deposits compared to ice should contribute to temperature differences between ice-bearing and ice-free deposits. If salt lag deposits are thick enough, salt desiccation can lead to hydration stratification with depth, approaching highest states of hydration in ice-bearing materials in the lowest parts of the deposits, as can be seen in Figs. 2 and 3. Spatial variation in average surface temperature can also lead to differences in the degree of hydration of the surface non-ice materials. Less hydrated salts can be expected in low-albedo and, therefore, warmer areas.

The observed dominance of highly hydrated salts on Europa [1,2] can be caused by (1) the presence of ice in salt-rich deposits, (2) a shallow thickness of lag deposits, and (3) slow dehydration rates compared to the age of the surface. A high stability of hydrated Mg sulfates with respect to dehydration in vacuum [4] is consistent with these observations.
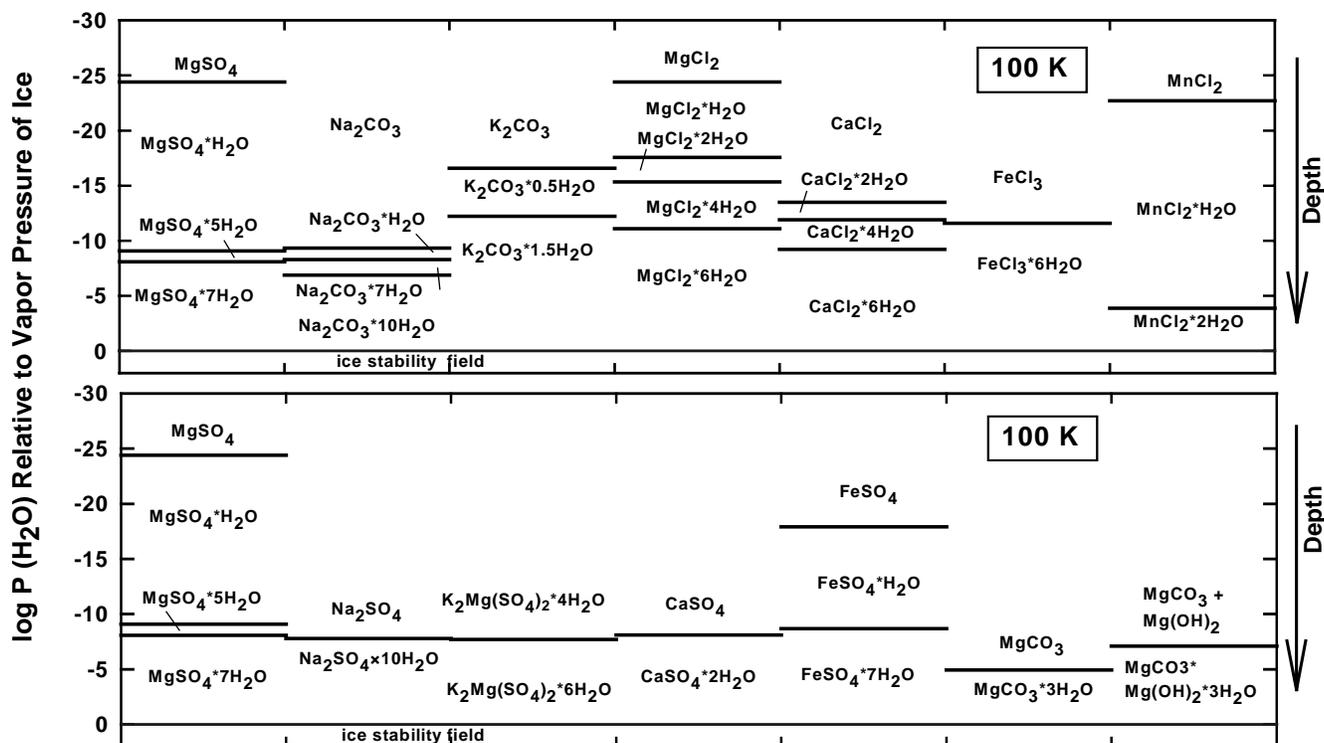
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Fig. 2

On the other hand, other salts (e.g., natron [4]) can dehydrate rapidly. It follows that upper layers of ice-free lag deposits can contain both kinetically stable highly hydrated salts (i.g., Mg-sulfates) and several dehydrated salts that desiccate more rapidly. Inside the lag deposits, the partial pressure of water vapor and salt hydration states can be buffered by dehydration equilibria among the less kinetically stable salts rather than the most abundant salts.

Conclusions: Highly hydrated salts are stable in ice-bearing surface materials and throughout the icy crust of Europa. In the ice-free salty lag deposits, predicted hydration stratification is controlled by the thermodynamic stability and dehydration kinetics of salts.

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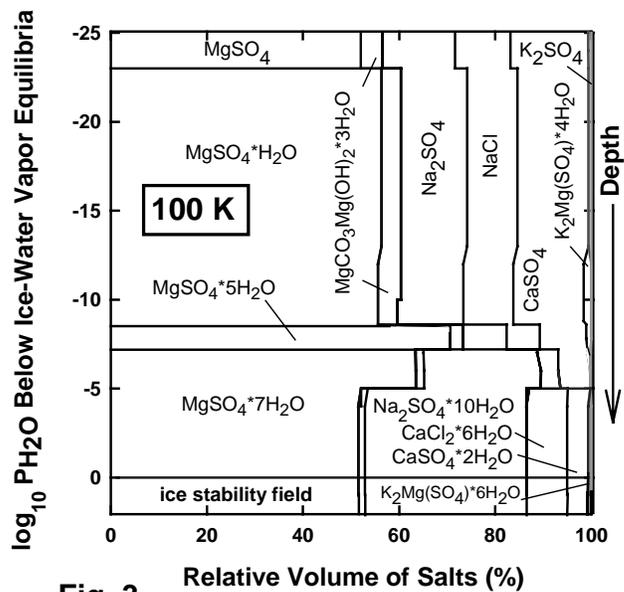
Fig. 3