

MASS BALANCE CONSTRAINTS ON THE ELEMENTAL COMPOSITION OF THE OCEAN ON 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: Data on surface morphology and reflectance spectroscopy in near-IR wavelengths, as well as magnetic measurements obtained by the *Galileo* spacecraft, indirectly indicate the existence of a salty liquid-water ocean on Jupiter's moon Europa [1-3]. On Earth, leaching of elements during water-rock interaction and degassing of the interior provide major contributions to oceanic composition [4]. The presence of aqueous components in the ocean on Europa is also probably a result of leaching and degassing of elements from the silicate part (mantle + crust) of Europa [5,6] during the satellite's accretion, differentiation, and early and/or subsequent water-rock interaction. The assumption of leaching/degassing provides an opportunity to evaluate limits for elemental composition of the ocean based on the mass of an assumed chondritic composition of the silicate part of Europa, a proposed thickness of the ocean, and terrestrial data on partitioning of elements among the mantle, ocean, and crustal geochemical reservoirs. Here we present geochemical mass balance calculations that constrain upper and lower limits for abundances of several elements in the ocean on Europa. In addition, we use data on the composition of Europa's atmosphere and charge balance constraints to get a working model for oceanic aqueous chemistry.

Model: Total and partial extraction was calculated from the mantle + crust (Bulk Silicate Europa, BSE) into the ocean for Na, K, Mg, Ca, Cl, Br, B, and I. The thickness of the solid+liquid water shell (80-150 km), and the mass of BSE ($3.5\text{-}3.9 \times 10^{25}$ g) was taken from a *Galileo*-based model for Europa's inner structure, which assumes either metallic Fe or Fe-FeS core [7]. Our nominal case was for a 100 km thick ocean and an Fe core. In addition to CM carbonaceous chondrites, considered earlier as a meteoritic analog for the silicate part of Europa [e.g., 5,8], we take into account CV and CI carbonaceous chondrites as well as H ordinary chondrites. None of these chondritic analogs for BSE contains enough water to produce the 100-km thick ocean from a BSE and, therefore, an icy component may have been added during the accretion of the satellite. Since CM chondrites may form during aqueous alteration of CV carbonaceous chondrite material [e.g., 9], our choice for a nominal BSE is CV carbonaceous chondrites. CV-type material could have accreted together with an icy material followed by radioactive/tidal heating, ice melting, igneous differentiation, water-rock interaction, and the separation of a salty ocean.

Three sets of calculations were done. In the first set, the upper limits for elemental composition of the ocean were calculated by a virtual total extraction of elements from a BSE of varied composition and mass. In the other two sets, we calculated partial extraction of elements from a chondritic BSE based on terrestrial geochemical data on element partitioning between major geochemical reservoirs. For this purpose, we calculated extraction factors $K1$ and $K2$ that represent the fraction of an element that is extracted into the ocean and other crustal reservoirs that are rich in volatiles.

The extraction factor $K1$ represents the mass (M) fraction of an element (i) that is extracted from Bulk Silicate Earth

(BSEH) to the Upper Continental Crust (UCC) and the ocean:

$$K1 = M_i(\text{UCC} + \text{ocean})/M_i(\text{BSEH}).$$

This factor includes an extraction into salty sediments (e.g., evaporites) and other continental sediments, together with granites. A limited role of evaporitic processes on Europa and a lack of knowledge about granites allow us to consider this extraction factor as a first order proxy for Europa at least for Na, Cl, and Br that, by terrestrial analogy, probably have small affinities to form chemical sediments on Europa.

Factor $K2$ represents the fraction of an element extracted to the Earth's ocean only:

$$K2 = M_i(\text{ocean})/M_i(\text{BSEH}).$$

We used this factor to set a lower limit for Europa oceanic composition because of the limited chance of evaporative sinks for elements from the Europa ocean. The mass of salts on the satellite's surface seems to be negligible compared to oceanic abundances. The calculations were made with elemental abundances in chondrites, terrestrial UCC and BSEH taken from [10,11] and [12], respectively.

Results: Mass balance calculations for the total extraction of elements from BSE's of several chondritic types are displayed in Fig. 1a and compared to the composition of Earth's ocean. All chondritic mantles considered lead to similar results. In addition, the variations proposed in the oceanic thickness and in the mass of BSE's do not lead to significant changes in the calculated upper limits for oceanic composition. Calculations for a CV carbonaceous chondrite BSE with mass = 3.9×10^{25} g, are shown in Table 1. The values obtained for abundant mantle elements like Mg, Ca, and S are greatly overestimated in a calculation of such a type. However, the calculations imply that the ocean can be saturated or supersaturated in these elements. Results obtained for Cl, Br, and B show that even total leaching of these elements from a chondritic mantle does not lead to the corresponding terrestrial values. It is interesting that complete extraction of a CV-type BSE leads to concentrations of Na and K in the Europa ocean that are only 4 and 10 times higher, respectively, than those of the terrestrial ocean.

Partial extraction calculated with the $K1$ factor indicates that in addition to Cl, Br, and B, Europa's ocean can also be depleted in Na compared to the terrestrial ocean, as shown in Table 1 and Fig. 1b. Note that calculations with this factor assume that there are no sinks of solutes into chemical sediments, hydrothermal deposits, or granites on Europa. We believe that this is not the natural case, and that real abundances can be lower than estimated by $K1$. However, we do not expect that the oceanic abundances are less than those obtained by the calculations with the $K2$ factor that lead to significantly lower concentrations for all elements.

To get a working chemical model for Europa's ocean ($K1a$), we start with our calculations with the $K1$ factor and set the oceanic Na/K atomic ratio of 25 according to the value observed in the Europa's atmosphere [13]. In addition, the calculated abundance of Mg, which seems to be in excess, is adjusted to achieve charge balance among the major

ions. The ionic composition (in molal concentrations) that corresponds to the *K1a* model is: Mg^{2+} , 0.0619; SO_4^{2-} , 0.096; Na^+ , 0.049; Cl^- , 0.021; Ca^{2+} , 0.02; K^+ , 1.96×10^{-3} (Fig. 2). The compositions of the adopted ocean model (*K1a*) are shown in Table 1 and Figs. 1b and 2.

Summary and Discussion: Mass balance calculations that model extraction of elements into the aqueous phase from chondritic material show that the concentrations of Na, Cl, Br, B, and possibly K, in an ocean ~100 km thick do not exceed the corresponding values for the Earth's ocean and could be more than one order of magnitude lower. For Na and K, this conclusion is consistent with the Na/O and K/O atomic ratios of ~1/300 and ~1/7500 observed in Europa's atmosphere [13]. If these ratios represent corresponding oceanic values, they lead to oceanic abundance of Na and K of 4.3 and 0.29 g/kg, respectively. Note that those atmospheric ratios give upper limits for oceanic abundances, because salts are probably enriched in the surface lag deposits. The inferred low abundance of chlorine in oceanic water is consistent with observations and reinforces numerically earlier investigations [5,6,14].

Sulfur, magnesium, and calcium may be the major elements in the ocean on Europa, but the concentrations of the corresponding ions are probably limited by the solubility of corresponding minerals (e.g., Ca-sulfates and Ca-Mg carbonates) that may form a chemical sediment on the oceanic floor. By analogy with the terrestrial ocean, the concentrations of K (as well as Rb, Cs, and Li) and, in part, Mg could be controlled by ion exchange between water and hydrous phyllosilicates in the ocean floor sediments. Carbon-bearing solutes (e.g., HCO_3^- , CO_3^{2-}) can be present in Europa's ocean water, but evaluations of their abundances require several additional constraints. A lack of terrestrial-type chemical weathering and formation of evaporites, a relative deficiency of oxidizing agents, and the possible absence of plate tectonics and living organisms would also be responsible for differences in abundance and speciation of several elements (especially S and C) in the ocean on Europa compared to terrestrial values.

The major fraction of terrestrial iodine is in oceanic biogenic sediments on the ocean floor [15]. By analogy, the abundance of iodine in Europa's ocean should depend on whether organic sediments exist. Detection of iodine in Europa's atmosphere or on its surface would yield insights into biological activity on Europa.

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Table 1. Chemical models for the composition of the ocean on Europa (g/kg oceanic water)^a

Element	Total extraction	<i>K1</i>	<i>K2</i>	<i>K1a</i>	Earth's Ocean
Na	44	1.1	0.055	1.1	11
Mg	1,800	0.32	0.0036	1.5 ^b	1.3
S	280	3.1	0.31	3.1	0.9
Cl	3.2	0.74	0.58	0.74	19
K	4.6	1.6	0.003	0.077 ^c	0.4
Ca	240	0.8	0.001	0.8	0.41
Br	0.021	0.016	0.013	0.016	0.067
B	0.0039	4.4×10^{-4}	1.3×10^{-5}	-	0.044
I	0.0021	7.6×10^{-4}	3.9×10^{-6}	-	6×10^{-5}

^aThe calculations were done for a 100 km thick ocean and a CV carbonaceous chondrite Bulk Silicate Europa

^bMg is adjusted to achieve charge balance for the *K1a* model

^cK is set by the Na/K ratio in Europa's atmosphere [13]

