TOCHILINITE: A SENSITIVE INDICATOR OF ALTERATION CONDITIONS ON
THE CM ASTEROIDAL PARENT BODY Lauren B. Browning1, William L. Bourcier2, 1
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Introduction and Summary

Each CM chondrite experienced a different degree of aqueous alteration [1]. As a group, then, these meteorites preserve tangible evidence of asteroidal reactions that were interrupted at many different stages of completion. Geochemical modeling of CM reaction progress should elucidate the nature of the accreted CM materials and the specific types of asteroidal processes and conditions that subsequently influenced them. However, most of the minerals in CM chondrites are stable under a wide range of environmental conditions, which hinders efforts to capitalize on the diverse degree of CM alteration. Petrologic evidence suggests that Fe-rich tochilinite, the widespread mineralic component of CM chondrites previously referred to as "poorly characterized phase (PCP)", may be the most sensitive indicator of the conditions of CM alteration [2,3]. This possibility has not previously been explored because thermodynamic data for tochilinite are lacking. We have estimated the thermodynamic properties of tochilinite from mixing equations and then calculated its stability limits with associated non-silicate phases as a function of PS2, PO2, and PCO2. The resultant phase relations: a) are consistent with mineral association in CM chondrites, b) indicate that the CM fluids were S-depleted and extremely reducing, c) imply the possibility of H2 gas seeps on the CM parent body, and d) suggest that the alteration of CM materials occurred at significant asteroidal depths.

Procedure

The free energy of formation for Fe-endmember tochilinite (i.e. 2Fe,9S*1.67Fe(OH)2) was approximated by assuming that the sulfide and hydroxide layers in tochilinite mixed ideally [4]. All other thermodynamic data were taken from [5,6]. Mineralic phase relations were calculated at STP. An integrated form of the Virial equation was used to determine the stability limits of liquid water with increased pressure.

Results and Discussion

Meteoritic tochilinite is typically associated with calcite, pyrrhotite, ± magnetite and Fe-metal [7]. The shaded region in Figure 1 shows the approximate stability range of Fe-endmember tochilinite using a calculated free energy value of -727.02 Kcal/mol. Magnetite, pyrrhotite and Fe-metal stability fields join with tochilinite (Figure 1), while calcite and tochilinite appear together at log PCO2 values between around -22.81 and 3.45. Note that the PS2 values of tochilinite stability are too low to stabilize pyrite, which is conspicuously absent from CM chondrites. The calculated phase relations involving tochilinite are thus consistent with the mineral associations observed in CM chondrites, providing encouragement that the estimated thermodynamic data for tochilinite is reasonable.

The stability limits of tochilinite with O2 gas indicate that the CM fluids were probably extremely reducing. For example, although terrestrial serpentinization usually occurs under conditions too oxidizing to stabilize Fe-metal [8], Figure 1 suggests that the Ni-poor Fe-metal (e.g. wt. % Fe= 85) in CM chondrites may have been stable. Analogous Ni-poor Fe-metal have been reported in a few terrestrial serpentinites that experienced alteration under extremely reducing conditions [8]. However, [9] argued that any primary Ni-poor Fe-metal in CM chondrites would surely have oxidized during in situ CM alteration. These authors interpreted the coexistence-existence of Ni-poor Fe-metal and phyllosilicates in CM chondrites as evidence that the CM parent body accreted from a highly unequilibrated, and somewhat random, mixture of aqueously altered and unaltered phases.
Since isotopic and geochemical studies indicate temperatures of roughly 25°C for CM alteration \([10,11]\), it is likely that CM alteration proceeded in a liquid water-based solution. By adding the reasonable demand that liquid water be stable at the low PO\(_2\) values indicated by tochilinite stability, then, the total pressure acting on the CM fluids is constrained to be roughly 2 atm or more (Figure 1). Thus, the restrictive conditions of tochilinite stability suggest that CM alteration may have proceeded at asteroidal depths corresponding to at least 2 atmospheres of overburden pressure. Assuming an asteroidal radius of 45 km, for example, this translates into a burial depth of roughly 2 km. In addition, the equilibration of liquid water at very low PO\(_2\) requires a commensurately high partial pressure of H\(_2\) gas. The extremely reducing conditions of tochilinite stability favor the additional possibility, then, that H\(_2\) gas may have bubbled out of a relatively porous CM asteroidal parent body. Analogous hydrogen gas seeps have been detected from drill core holes that cut through incompletely serpentinized slushes \([12]\), and it has been suggested that excess hydrogen is, in some cases, generated by the serpentinization process itself \([8]\). The possibility of a H\(_2\) seepage is consistent with a previous suggestion that planetary noble gases were systematically lost from the CM asteroidal body as aqueous reactions proceeded in a partially open system \([1]\).

In conclusion, the narrow stability field for tochilinite imposes useful constraints on the asteroidal conditions during CM aqueous alteration, and urges additional consideration.


**Figure 1.** Mineralic phase relations with Fe-rich tochilinite as a function of PO\(_2\), PS\(_2\), and PCO\(_2\) at STP. Interactions between Ca and Fe were not considered. Liquid H\(_2\)O is stable above the short and long dashed lines at total pressures of 1 and 2 atm., respectively.