Volatile-Bearing Phases in Carbonaceous Chondrites: Compositions, Modal Abundances, and Reaction Kinetics

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The spectral and density characteristics strongly suggest that the Phobos and Deimos (the two small natural satellites of Mars) and a significant fraction of the near-Earth asteroids are made of carbonaceous chondrites, which are quite rich in volatile components and, thus, could serve as potential resources for propellants and life-supporting systems in future planetary missions. However, in order to develop energy efficient engineering designs for the extraction of volatiles, we must have a good knowledge of the nature and modal abundances of the minerals in which the volatiles are structurally bound and appropriate kinetic data on the rates of the devolatilization reactions.

The grain size of the volatile-bearing phases in carbonaceous chondrites are often too small (100 to 1000 A) to permit identification under optical microscopes and are best observed under high-resolution transmission electron microscopy (HRTEM). We have, therefore, carried out theoretical calculations to predict the modal abundances and compositions of the *major* volatile-bearing and other mineral phases that could develop in the bulk compositions of C1 and C2 classes as functions of pressure and temperature. These are the most volatile-rich classes among carbonaceous chondrites. The results suggest that **talc** and **antigorite ± magnesite** are the major volatile-bearing phases and are stable below ~400°C at 1 bar in these chondritic compositions. The phyllosilicates are fairly iron rich, with about 25-30 mol% of Fe^{2+} end-member components in solid solution.

Simulated *equilibrium* heating of a kilogram of C2 chondrite at fixed bulk composition between 400 and 800°C at 1 bar yields about 135 gm of volatile, which is made primarily of H_2O, H_2, CH_4, CO_2, and CO. The relative abundances of these volatile species change as functions of temperature and, on a molar basis, H_2 becomes the most dominant species above 550°C. Hydrogen is a very good propellant and reducing agent, which may be preferentially extracted, according to the above results, by heating the C2 chondritic material to T > 550°C. In contrast to the C2 chondrite, the volatiles given off by C1 material under equilibrium conditions at 1 bar, T > 400°C, consist essentially of H_2O and CO_2. Per kilogram of material, the total yield of volatile is about 306 grams, of which nearly 60 wt% is H_2O.

The theoretical study summarized above has been published recently in a paper entitled "Theoretical Predictions of Volatile Bearing Phases and Volatile Abundances in

Carbonaceous Chondrites" (pages 97-105 in *Space Manufacturing 7*, American Institute of Aeronautics and Astronautics, 1989). A copy is included as Appendix D.

Having identified the most likely mineralogical source of volatiles in the carbonaceous chondrites, we have begun a program of systematic kinetic study of devolatilization reactions. The results will provide the framework for optimal engineering designs for the extraction of volatiles from the mineral phases. These will also help resolve the problems concerning the process and condition of formation of the volatile-bearing phases, especially the phyllosilicates, in the carbonaceous chondrites, which are of fundamental importance to our understanding of the planetary processes.

We have determined the rates of dehydration of talc at 585, 600, 637, and 670°C, P(total) = 1 bar, according to the reaction

$$\text{Talc} = 3 \text{ Enstatite} + \text{Quartz} + H_2O \ .$$
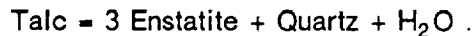
The dehydration kinetics was studied before by Greenwood (1963) at P_{H_2O} = 2 Kb. However, the available data were inadequate to permit reliable extrapolation to lower pressure. The "process condition" for the extraction of volatiles is likely to be set at a pressure of the order of 1 bar.

·The starting material talc is nearly pure Mg-end member. The weight loss of a known quantity of material was determined continuously as a function of time at the above temperatures by the thermogravimetric (TG) method. The results are illustrated in Figure 1.8 in terms of fractional weight of talc remaining versus time. The sample was suspended within the reactor in open platinum containers shaped from Pt-foils. The TG setup used in this study has the drawback that it does not permit introduction of the sample within a reactor that has been preheated to the desired run temperature. Thus, corrections have to be made for the weight loss through the induction period to the run temperature. The corrections, however, are quite straightforward. Another drawback of this particular TG setup is that the change of weight as a function of time is recorded in a strip-chart recorder, but it is not available in the form of a digitized output. Thus, the curves in the strip-chart recorder have to be visually read to compute fractional weight loss, which has led to the irregularities seen in the curves in Figure 1.8. The raw data show a very smooth relation of weight of talc versus time. We are in the process of developing a TG setup that would permit direct introduction of the sample into a preheated reactor and also provide digitized output of the data.

We have not yet carried out detailed analyses of the experimental data to obtain the kinetic parameters and to understand the mechanism of reaction. These analyses
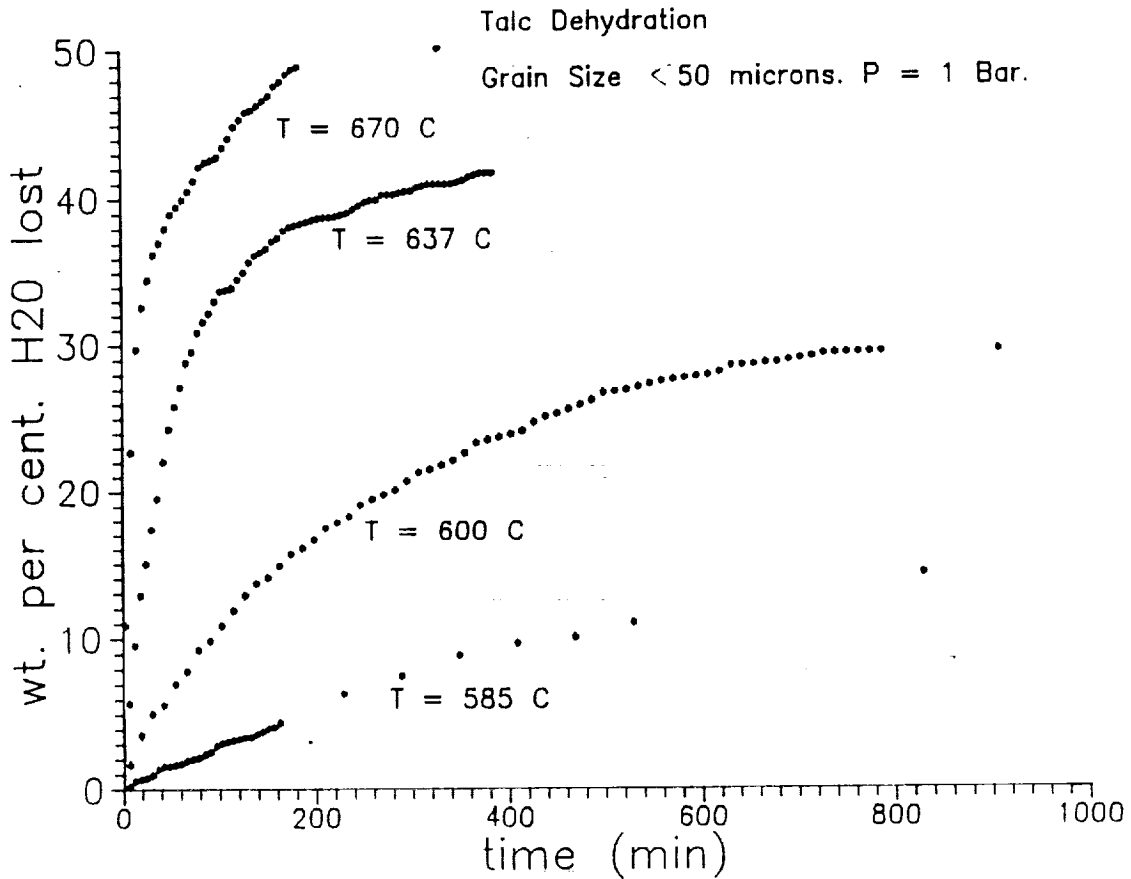
Figure 1.8   Weight fraction of talc remaining as a function of time at different temperatures.   Reaction: talc → 3 enstatite + quartz + H_2O (Talc: $Mg_3Si_4O_{10}(OH)_2$; Enstatite: $MgSiO_3$; Quartz: SiO_2)

will eventually be carried out after we gather a larger body of experimental data and refine the experimental techniques.   However, we find that the dehydration reaction does not seem to follow the first-order mechanism, which is in contrast to the high-pressure results of Greenwood (1963).

It is important for the kinetic study, especially for understanding the mechanism of reaction, to be able to determine the modal abundance of phases at various stages of reactions.   In the only work of this nature to date involving phyllosilicates, Greenwood (1963) determined the abundances of the various phases in the run products by the extremely laborious technique of petrographic modal analysis, i.e., by "point counting" the amount of phases under an optical microscope.   We have conducted a scanning electron microscopic (SEM) study to see if the relative abundance of phases can be determined on the basis of the spectral identification and X-ray mapping.   On standard samples made up of known amounts of talc, anthophyllite, and quartz, X-ray mapping

and software processing of the data resulted in the determination of quartz to talc-plus-anthophyllite combined, but the latter two could not be distinguished separately. However, once the amount of quartz is known, the proportions of talc and anthophyllite can be estimated by mass balance, assuming that no other phase is present. The latter can be checked by microprobe and X-ray analysis. In the analysis of the standard samples, we have, however, systematically overestimated the amount of talc by about 6%. With further work, we hope to be able to refine the method to yield better estimates of phases in a standard mixture.

Reference

Greenwood, H. J., 1963, "The Synthesis and Stability of Anthophyllite," *Journal of Petrology*, Vol. 4, pp. 317-351.