Metamorphism on Ordinary Chondrite Parent Bodies: The Role of Fluids.

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Introduction:

The three groups of ordinary chondrites (OCs), H, L and LL, all show a range of metamorphic grades. However, metamorphic conditions on OC parent bodies are poorly constrained because of a lack of mineralogical indicators of peak temperatures [e.g. 1]. The current classification scheme for metamorphosed ordinary chondrites (petrologic types 3 to 6) relies on qualitative observations of petrographic properties [1,2]: there are few quantitative constraints that provide robust estimates of peak temperatures or that delineate the divisions between petrologic types. In addition, although it is known that there is evidence for fluids in type 3 chondrites, the role of fluids in petrologic type 4-6 chondrites is poorly understood and has not been addressed in a systematic manner. Because fluids can potentially play a significant role in mobilizing elements and can help to facilitate equilibrium during metamorphic heating, it is important to understand the nature and behavior of fluids on OC parent bodies in order to be able to interpret their metamorphic histories.

Here we synthesize our recent studies of metamorphosed ordinary chondrites. We have been conducting detailed studies of feldspar and phosphate minerals, which can provide an important record of fluid interactions, and can also potentially provide quantitative constraints on metamorphic conditions. Our data enable us to make comparisons between conditions that prevailed on the H, L and LL parent bodies. In addition, since several important geothermometers and geochronometers are based on feldspar and phosphate minerals, an understanding of their petrogenesis and the processes they record is essential for understanding the early geologic history of ordinary chondrite asteroids. Studies of metamorphosed ordinary chondrites are very topical at present because they are highly relevant to the interpretation of samples returned by the Hyabusa mission from asteroid Itokawa, which consists of metamorphosed LL chondrite material [3].

Analytical Methods:

We have made detailed observations of feldspar and phosphate minerals from petrologic types 4, 5 and 6 chondrites of each group of OCs (H, L and LL). We have studied the mineral associations, petrologic context and reaction textures of these two minerals using scanning electron microscopy (SEM) and focused ion beam / transmission electron microscopy (FIB/TEM), and analyzed mineral grains using electron probe microanalysis (EPMA). We have also conducted SIMS analyses of light elements (H and S) using the Cameca 8f Geo ion microprobe at Caltech. Analytical details can be found in the references given below.

Observations and Data, Feldspar:

It has been understood for a long time that feldspar develops during metamorphism as a result of recrystallization of chondrule mesostasis, and that feldspar grains coarsen with increasing petrologic type [2]. Our observations show that although feldspar coarsening clearly takes place, feldspar in the interior of relict chondrules shows a range of grain sizes, and that some large grains, up to 100 μm, are present even in petrologic type 4 chondrites [4]. Thus, development of sizeable feldspar grains does not necessarily require high peak metamorphic temperatures, contrary to previous assumptions.

Feldspar in relict chondrules from both L and LL chondrites shows a sequence of progressive equilibration with increasing petrologic type [4,5]. For type 4 chondrites in both groups, plagioclase in relict chondrules shows a wide range of compositions, from An_{90} to An_{10}, mostly with very low Or content (<1 mole%), and individual chondrules have well-defined compositions. In petrologic type 5 chondrites, there is a narrower compositional range: most compositions are Ab-rich, as well as containing significant Or (~5 mole%). In petrologic type 6, all feldspar is albitic and compositions are homogeneous. Average compositions of feldspar in type 6 L and LL chondrites are very similar, $An_{10}Ab_{84}Or_6$ [4,5].

Feldspar grains in both the L and LL groups also underwent similar secondary reactions. In petrologic type 4 chondrites of both groups, albitization of anorthitic feldspar is observed, as well as a lamellar reaction texture that shows evidence for leaching of anorthitic feldspar along crystallographically oriented planes [4-7]. In petrologic type 5 chondrites of both groups, albitic feldspar shows exsolution of K-feldspar [5,8]. These highly specific similarities between the L and LL groups indicate that the L and LL chondrite parent bodies experienced very similar metamorphic conditions.

In contrast to the L and LL groups, feldspar in H chondrites is homogeneous, and albitic, in petrologic types 4, 5 and 6 [4]. The average composition of feldspar in type 6 H chondrites is $An_{12}Ab_{82}Or_6$ [4]. For type 4 H chondrites, we have not observed development of anorthitic feldspar in relict chondrule mesostases, and consequently do not observe albitization reactions or lamellar reaction textures. Also, we have not observed exsolution of K-feldspar in albitic grains in any petrologic type. Mesostases of relict chondrules in H chondrites recrystallize predominantly into feldspar, instead of the mixture of feldspar and Ca-pyroxene present in L and LL chondrites [4]. In all these respects, feldspar records very different metamorphic conditions in the H chondrite parent body compared with the L and LL parent bodies. It appears that complete albitization of chondrule mesostases occurs in petrologic type 3 in H chondrites, early in the metamorphic sequence.

Observations and Data, Phosphate Minerals: It is well known that ordinary chondrites contain two phosphate minerals, merrillite and apatite [9]. We have carried out an extensive study in order to understand development of both minerals through the metamorphic sequence [10-13]. In all three OC groups, the same general sequence of phosphate mineral growth takes place. In petrologic type 4 chondrites, merrillite occurs as inclusions in metal grains, most likely as a result of oxidation of primary P that was incorporated in metal. Merrillite is also present as individual grains in the matrix and within relict chondrules. Apatite occurs in fine-grained assemblages and veins: in both occurrences it is in a reaction relationship with merrillite, olivine and albite. In petrologic types 5 and 6, both merrillite and apatite are mostly present as large (up to 300 μm) isolated grains. Some apatite grains contain remnant islands of merrillite and pore spaces indicating that they are the products of dissolution – reprecipitation reactions in the presence of fluids [14].

In all three OC groups, apatite is predominantly chlorine-rich. The high Cl/F ratio, coupled with textural observations, suggests that chlor-apatite (Cl-Ap) developed as a result of reaction of merrillite with halogen-rich fluids. These fluids appear to have been very dry [11,12]. There is no clear distinction between the L and LL chondrites and H chondrites, based on the textural development of phosphate minerals and their compositions. Cl-Ap compositions are variable within individual chondrites, and we have not observed a sequence of progressive changes in Cl-Ap compositions with increasing petrologic type in any of the three OC groups [13].

Overview of Metamorphism: Our work on secondary feldspar and phosphate minerals in type 4-6 OCs shows some important features of the metamorphic environments on OC parent bodies that have not been clearly recognized previously. In particular, we argue that there is clear evidence for the presence of fluids during metamorphism through petrologic types 4 to 6. Formation of ubiquitous albitic feldspar throughout H, L and LL chondrites is the result of extensive albitization reactions, and development of apatite is the result of reactions of host material with pervasive halogen-rich fluids.

In L and LL chondrites, initial recrystallization of chondrule mesostases resulted in formation of anorthitic feldspar, with compositions controlled by the mesostasis compositions of individual chondrules. We suggest that this crystallization took place during prograde metamorphic heating. Anorthitic feldspar then underwent albitization, which indicates the presence of a Na-rich fluid. Albitic feldspar grains within matrix likely also grew during this episode. Since progressive changes in plagioclase compositions are observed through the metamorphic sequence, the extent of the albitization reaction was apparently related to the peak temperature and / or duration of metamorphic heating. However, the extent of such a reaction may also have been controlled by the availability of fluids.

In contrast, in H chondrites, recrystallization of chondrule mesostases appears to have taken place at the same time as, or even as a result of, albitization. Metasomatism resulting from introduction of a Na-rich fluid thus occurred early in the history of the H chondrite parent body.

For all three OC groups, halogen-rich fluids infiltrated the host chondrite at a later stage, most likely during cooling of the parent body. In type 4 L and LL chondrites, this fluid reacted with anorthitic plagioclase that had not undergone complete albitization. The fluid also controlled formation of the final phosphate mineral assemblage that is now observed. Heterogeneous Cl-Ap compositions indicate that fluid compositions were variable on a localized scale and that Cl-Ap formed at a late stage.

Models for metamorphism of the OC parent bodies should take into account the complex presence of fluids of different compositions at different times in their thermal histories. A possible source of fluids is degassing from partial melts produced during impact heating. However, it would be necessary for this process to have acted uniformly in all regions of all three parent bodies, which seems unlikely. A more plausible source of fluids is from degassing of a silicate partial melt produced in the interior of the parent body. If this is the case, models for OC parent bodies need to include interior temperatures high enough for at least partial melting of silicates – significantly higher temperatures than conditions that are usually considered.

References:
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