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Metamorphism and partial melting of ordinary chondrites: Calculated phase equilibria

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ABSTRACT

Constraining the metamorphic pressures (P) and temperatures (T) recorded by meteorites is key to understanding the size and thermal history of their asteroid parent bodies. New thermodynamic models calibrated to very low P for minerals and melt in terrestrial mantle peridotite permit quantitative investigation of high-T metamorphism in ordinary chondrites using phase equilibria modelling. Isochemical P–T phase diagrams based on the average composition of H, L and LL chondrite falls and contoured for the composition and abundance of olivine, ortho- and clinopyroxene, plagioclase and chromite provide a good match with values measured in so-called equilibrated (petrologic type 4–6) samples. Some compositional variables, in particular Al in orthopyroxene and Na in clinopyroxene, exhibit a strong pressure dependence when considered over a range of several kilobars, providing a means of recognising meteorites derived from the cores of asteroids with radii of several hundred kilometres, if such bodies existed at that time. At the low pressures (<1 kbar) that typify thermal metamorphism, several compositional variables are good thermometers. Although those based on Fe–Mg exchange are likely to have been reset during slow cooling, those based on coupled substitution, in particular Ca and Al in orthopyroxene and Na in clinopyroxene, are less susceptible to retrograde diffusion and are potentially more faithful recorders of peak conditions. The intersection of isopleths of these variables may allow pressures to be quantified, even at low P, permitting constraints on the minimum size of parent asteroid bodies. The phase diagrams predict the onset of partial melting at 1050–1100 °C by incongruent reactions consuming plagioclase, clinopyroxene and orthopyroxene, whose compositions change abruptly as melting proceeds. These predictions match natural observations well and support the view that type 7 chondrites represent a suprasolidus continuation of the established petrologic types at the extremes of thermal metamorphism. The results suggest phase equilibria modelling has potential as a powerful quantitative tool in investigating, for example, progressive oxidation during metamorphism, the degree of melting and melt loss or accumulation required to produce the spectrum of differentiated meteorites, and whether the onion shell or rubble pile model best explains the metamorphic evolution of asteroid parent bodies in the early solar system.

1. Introduction

Chondritic meteorites are the oldest known rocks containing components whose age defines that of the solar system (Allegre et al., 1995; Patterson, 1956). Their study provides clues critical to understanding the formation of the sun and planets, and their arrival from outer space has had a profound impact on the evolution of life on Earth (Scott, 2007; Sleep et al., 1989; Suess, 1965; Trieloff et al., 2003; Urey, 1962). Ordinary chondrites are by far the most abundant type of meteorite, comprising 80% of all that fall to Earth. Along with composition (H, L and LL), metamorphic grade, or petrologic type, is a primary variable by which ordinary chondrites are classified (Van Schmus and Wood, 1967). More accurately constraining the metamorphic history of chondrites and their parent bodies is key to better understanding the early evolution of the solar system.

Based on the U–Pb systematics of phosphates within ordinary chondrites, the peak of thermal metamorphism is constrained to the interval 4.56–4.50 Ga (Göpel et al., 1994), in which the two viable heat sources were decay of short-lived radionuclides, mainly ^{26}Al (Hutcheon and Hutchison, 1989; Minster and Allègre, 1979), and frictional heating due to impacts (Ciesla et al., 2013;

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Rubin, 1995). Two plausible end-member hypotheses have been proposed to explain the thermal and accretionary histories of the parent asteroid bodies from which ordinary chondrites were derived (Harrison and Grimm, 2010; McSween and Patchen, 1989; Scott and Rajan, 1981). The 'onion-shell' model requires that parent bodies remained more-or-less undisturbed during metamorphism and subsequent cooling. In this model, in which the contribution from impact heating may have been small, metamorphic temperature (T and petrologic type) and pressure (P) should be positively correlated, and T and cooling rate (S) inversely correlated (Göpel et al., 1994; Harrison and Grimm, 2010; Herndon and Herndon, 1977; Minster and Allègre, 1979; Trieloff et al., 2003). The 'rubble-pile' hypothesis involves syn-metamorphic fragmentation and re-assembly of parent bodies before they had cooled (Harrison and Grimm, 2010; McSween and Patchen, 1989; Scott et al., 2014; Scott and Rajan, 1981). In this scenario T, P and S may exhibit no clear correlations and the contribution of impact heating may have been dominant.

So-called equilibrated (type 4–7) ordinary chondrites are fine-grained metamorphosed ultramafic rocks characterised by increasing grain size (from a few microns or less in type 4 to several tens of microns in types 6 and 7) and textural integration between matrix and chondrules (Dodd et al., 1967; Huss et al., 2006; Van Schmus and Wood, 1967). Equilibrated ordinary chondrites contain mineral assemblages comprising variable abundances of the silicate minerals olivine, orthopyroxene, clinopyroxene and plagioclase with Fe–Ni metal (taenite–kamacite), sulphide (troilite), chromite, phosphate (apatite and merrilite) and accessory phases (Dunn et al., 2010a; Huss et al., 2006; Tait et al., 2014). Although olivine is equilibrated (i.e. shows no compositional zoning) by type 4, pyroxene may not be compositionally equilibrated until type 5 (Dodd, 1969; Huss et al., 2006; Van Schmus and Wood, 1967). Based largely on experimentally calibrated equilibria, principally two-pyroxene thermometry, temperatures in type 4–6 ordinary chondrites are generally estimated at between 500 °C and 1000 °C (Dodd, 1981; Mare et al., 2014; McSween and Patchen, 1989; McSween et al., 1988; Slater-Reynolds and McSween, 2005). However, it is unclear to what degree these thermometers record equilibrium at peak metamorphic conditions, or rather reflect incomplete re-equilibration of primary (igneous) compositions and/or retrograde resetting of peak metamorphic compositions during cooling (McSween and Patchen, 1989). Silicate partial melting in type 7 chondrites is evidence for metamorphic temperatures in excess of ∼1050–1150 °C (Hutchison, 2004; Jurewicz et al., 1993; Keil, 2000; McSween and Patchen, 1989; Tait et al., 2014).

Metamorphic pressures are much harder to constrain, but are generally thought to be less than 1 kbar (Dodd, 1969; McSween and Patchen, 1989). Assuming a constant density of 3300–3400 kg/m^3, pressures of 1 kbar correspond to maximum depths of around 250 km and derivation from bodies similar in size to, or larger than Vesta. However, significantly higher pressures up to and in excess of 10 kbar have been suggested on the basis of structural parameters in clinopyroxene (Pletchov et al., 2005; Zinovieva et al., 2006).

Equilibrium phase diagrams calculated for specified rock compositions have become the method of choice in constraining the P–T history of metamorphic rocks on Earth, where the approach is routinely applied to both subsolidus rocks and those that partially melted (migmatites) under the most extreme metamorphic conditions (Kelsey and Hand, 2015; Korhonen et al., 2014; White et al., 2014). However, to date such studies have concentrated on crustal rocks. Building on models developed in the simple CaO–MgO–Al_2O_3–SiO_2 system (Green et al., 2012a, 2012b), thermodynamic models describing non-ideal activity–composition relations for solid solution minerals (olivine, orthopyroxene, clinopyroxene, garnet, plagioclase, spinel, chromite) and silicate melt in anhydrous peridotite have recently been calibrated in the expanded Na_2O–CaO–FeO–MgO–Al_2O_3–SiO_2–Fe_2O_3–Cr_2O_3 (NCFMASOCr) chemical system (Jennings and Holland, 2015). Although designed specifically to investigate equilibria in fertile upper mantle, including its partial melting to produce basaltic primary (oceanic) crust, the solution models are calibrated down to very low pressures (1 bar) allowing, for the first time, a quantitative investigation of phase equilibria in stony meteorites using a modern petrological approach.

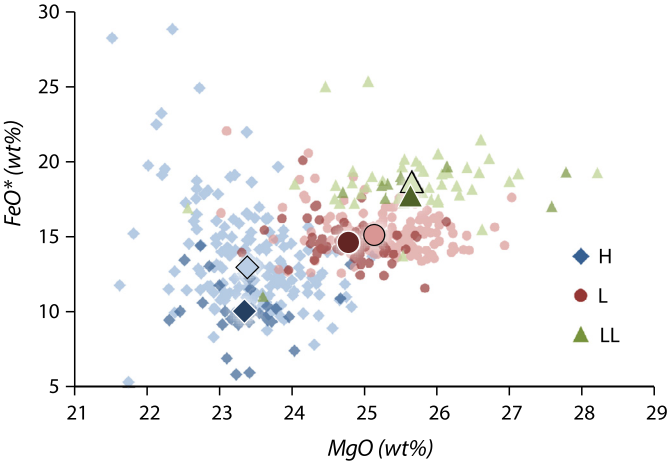

Fig. 1. Binary variation diagram showing the composition of ordinary chondrites (darker shades are falls, paler shades are finds) in terms of MgO vs FeO. The average falls from each compositional type (large symbols) define a linear relationship. Although type H chondrite have the highest bulk Fe contents, they have on average the lowest FeO contents.

Here we present subsolidus and suprasolidus P–T phase relations for ordinary chondrites, including the calculated abundance and composition of the main minerals. We compare and contrast the results with existing data to assess the viability of the phase equilibria modelling approach to extraterrestrial rocks. We discuss how the method might be used to better constrain metamorphic pressures and temperatures and in the quantitative investigation of some key processes operating during the early evolution of the solar system.

2. Samples and methods

Bulk rock data from more than 1000 meteorites compiled by Nittler et al. (2004) demonstrates that, although exhibiting considerable variability and overlap, H ($n = 195$), L ($n = 217$) and LL ($n = 53$) ordinary chondrites define distinct compositional groups for some major elements (Fig. 1; Supplementary Fig. S1). Although, by definition, class H chondrites have the highest elemental Fe abundances, they also have the highest concentrations of metallic Fe. After excluding metallic Fe and that associated with sulphides, H chondrites have the lowest FeO contents and X(Fe) (= molar FeO/FeO + MgO), and LL the highest (Nittler et al., 2004) (Fig. 1). Importantly, there is a clear distinction between meteorite finds and falls, in particular with respect to FeO. This is most pronounced for H chondrites, for which the average of falls contains significantly less FeO (∼10 wt%) than the average of all analysed H chondrites (∼13 wt%), consistent with terrestrial weathering and concomitant oxidation of metallic Fe in meteorite finds (Nittler et al., 2004).

For representative compositions for phase equilibria modelling we use the average composition of meteorite falls for H ($n = 34$), L ($n = 58$) and LL ($n = 12$) chondrites (see Table 1, in mol.%), which define a linear trend from H [FeO = 10.05 wt% FeO, X(Fe) = 0.19] through L [FeO = 14.62 wt% FeO, X(Fe) = 0.25] to LL [FeO =