

STUDYING THE THERMAL METAMORPHISM EXPERIENCED BY THE PARENT ASTEROID OF VILLALBETO DE LA PEÑA ORDINARY CHONDRITE USING AN EQUILIBRIUM PHASE DIAGRAM MODEL. M. J. Herrero Pérez^{1,2}, J. Reche Estrada³, J.M. Trigo-Rodríguez², J. Ibáñez-Insa⁴, J. Llorca⁵. ¹Rensselaer Polytechnic Institute, New York, USA (herrem2@rpi.edu), ²Institute of Space Sciences (CSIC-IEEC), Cerdanyola del Vallés, Barcelona, Catalonia, Spain, ³Universitat Autònoma de Barcelona, Catalonia, Spain, ⁴Geociències Barcelona-CSIC, Catalonia, Spain, ⁵Universitat Politècnica de Catalunya, Catalonia, Spain.

Introduction: The study of chondritic meteorites gives us the chance to recover valuable information about the thermal and collisional evolution of undifferentiated planetesimals formed early in the history of the Solar System [1]. In particular, oxygen isotopes indicate that ordinary and enstatite chondrites were probably dominant as terrestrial building blocks [2], which makes them a clear target when studying terrestrial crust and mantle. Chondrites themselves are primarily composed of the primordial protoplanetary disk materials which constituted the original building blocks of the bigger bodies in the Solar System: planets, comets and asteroids [3]. The latter bodies are the best candidates when characterizing the early stages of the Solar System aggregates.

During the past few years, important advances have been made regarding the modeling of phase relations in terrestrial mantle rocks, leading to modeling metamorphism and partial melting of ordinary chondrites by [4] who used the recent thermodynamic database of [5] onto a specific chondritic sample. In this work, the theoretical equilibrium phase diagram for the homogeneous bulk composition (BC) of a single domain in a chondritic meteorite, the Villalbeto de la Peña (VP) L6 chondrite, is derived. The BC of the modeled domain in VP was measured previously by [6,7]. The system used in our modeling was SNCFMASHONiCr without Mn, K, Ti and P. The measured bulk composition needed to be corrected using the following assumptions: a) Mn, Ti and K, present in minor amounts in the measured BC (c. 0.3% for Mn and c. 0.10 wt% for both Ti and K); b) No FeNi phases are present in the [5] database, so we considered the following alternatives: either FeNi is in excess and in this case some Fe must be subtracted from the BC, or Ni can be left in the BC. The principal results are more consistent with observations using the latter, although a Ni oxide (NiO) is stabilized, which doesn't seem a realistic fact; c) Similarly, with troilite S can be left in the BC, as it is stabilized in the majority of assemblage fields. Finally d) all P was considered to be present as the mineral apatite in minor amounts, so a corresponding amount of Ca was also subtracted ($3.33 \cdot P_2O_5$ in mol%) from its total. The resulting modified BC was then calculated in cation % (Fig. 1 BC) as input to the phase diagram modeling software *Theriak-Domino* [7] in order to determine the P-T conditions under which the main

mineral assemblage reached equilibrium. Although the observed presence of FeNi phases implies reducing conditions, T-XFe³⁺ diagrams were calculated in order to have a glimpse of the effect of oxidation phenomena at two P conditions. Also, T-XH₂O phase diagrams were derived to test the impact of aqueous alteration on the sample. Thus, we have characterized the theoretical phase relations in a P-T-XH₂O-XFe³⁺ space with a range of 0-15000 in P (bar) and 700-1200 in T (°C). Assuming that the BC of the chosen equilibrated domain is representative, we characterized the phase relations and the P-T conditions where the assemblage observed in VP equilibrated (i.e. its metamorphic conditions). Furthermore with the T-X diagrams we can have a first approximation of the effects of interaction with intergranular or advecting volatile-rich fluids with a variety of redox conditions. As H₂O contents are known to influence the initial melting conditions (solidus is depressed until a minimum T with progressive hydration), we had to assume a mol% H₂O for our P-T modeling. The P-T diagram presented here assumes null hydration. More hydrated states have been modeled using the T-XH₂O phase diagrams and will be presented elsewhere, as will the T-XFe³⁺ diagrams. At the end of the study we also assess the value of phase equilibria modeling to set key constraints on the evolution in chondritic asteroids [8].

Discussion: A previous work [5,6] provided the bulk composition (in mol %) of the VP chondrite, having the following values: 0.89 Na₂O, 38.16% MgO, 1.24% Al₂O₃, 376.40% SiO₂, 1.41% CaO, 21.63% FeO and 0.25% Cr₂O₃. It also provided the mineral modes of the VP domain (in vol%): 51.4% olivine (OL), 25% pyroxene (OPX and CPX not distinguished), 8.8% plagioclase (PL) and 1.2% chromite spinel (SP). Also the modes of non-modelled phases: 6.1% troilite (Tro), 4.5% kamacite (Km) and 2.3% taenite (Tae). Also [6,7] provided the mean measured compositions of OL (Fa 24.2±0.2), and PL (Ab 69.2±2.1). After comparing these values with the calculated isopleths of modal abundance (vol%) in P-T space, and composition (XFa-OL) (Fig.1), the P-T range under which such minerals can coexist and be stable is estimated (see oval in Fig1). Note that the preferred conditions do not constrain P much, but imply a T very near the solidus, consistent with classification of VP as an L6 chondrite.

The PL composition isopleths of (Xab) have not been included in Fig.1 because all along the main assemblage field (PL-CPX-OL-SP-OPX-NiO-TRO, showed in bold) $X_{ab} > 0.9$, only decreasing drastically near the solidus, where the observed $X_{ab-PL} = 69.2\%$ can be attained. Similar behavior is displayed by the XFa-OL (in Fig.1e the observed XFa-OL = 0.24 is reached at c. 2500 bar). Mode values in the preferred region of CPX and OPX added together (Fig. 1 c and d) provide a value of 21-23 vol%, similar to the observed 25%. The values of vol% PL (8.8%) and OL (51.4%) can be attained in the preferred region where condensed isopleths show very quick rates of change as the solidus is crossed. We can also observe that plagioclase is unstable under high-T conditions (at c. 1000-1100 °C) depending on P, meaning that the very low contents of plagioclase in the modeled VP domain is a strong indicator of high-grade thermal metamorphism, very close to the solidus or even with melt present conditions. Comparison with the measured modes and phase compositions of the VP chondrite indicate formation conditions of c. 1000-1100 °C and c. 5000 ± 2500 bar. Notably, the mineralogical assemblage does not vary significantly by increasing the water content, which supports the initial classification of VP as a type 6 OC that has suffered very little aqueous alteration. On the other hand, the Fe^{3+} content does make an impact in the phase equilibria, where the mineral olivine decreases

its concentration as the oxidation state increases, (this could explain the difference between the observed 51.4% and the predicted 54-57% at the dry conditions of Fig.1). Remarkably, the results of the modeling point towards pressure formation regimes for OCs that are in agreement with recent studies made independently using other techniques, supporting the idea that the parent body from which OCs derive could be significantly larger than typically considered in the scientific literature [9].

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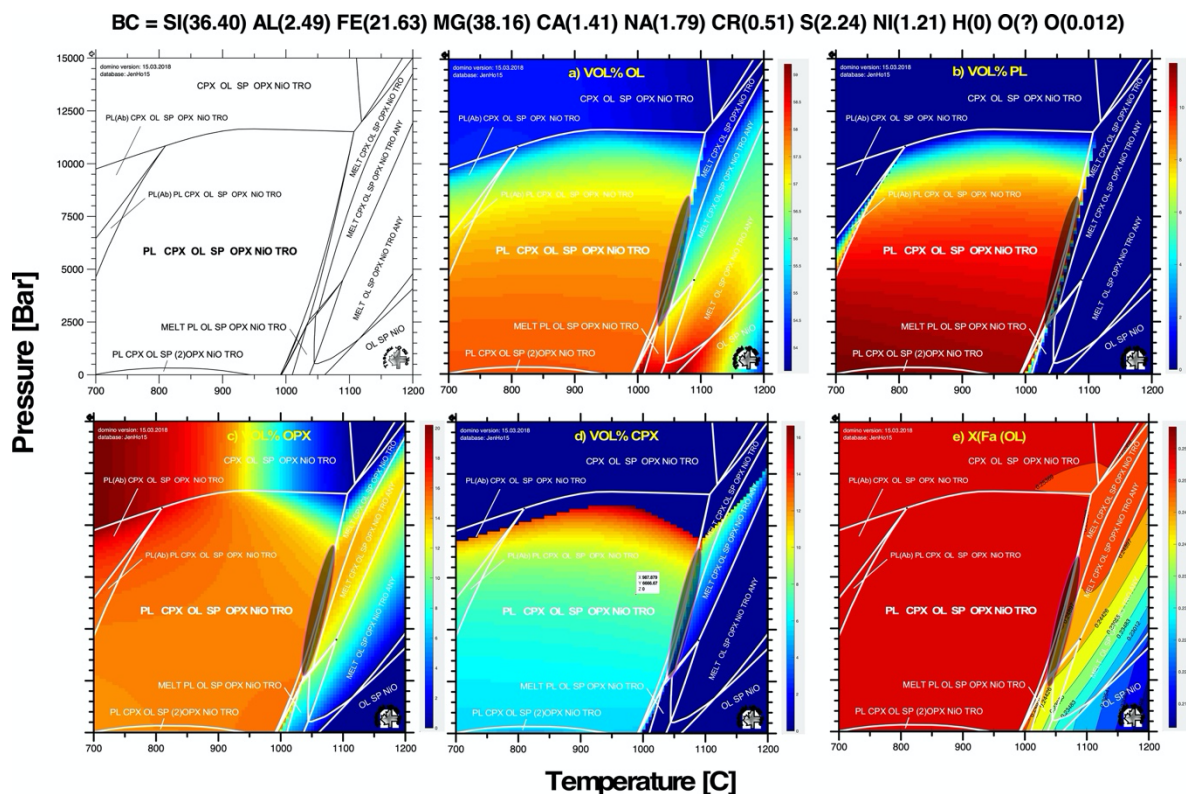


Figure 1: Calculated isochemical P-T phase diagram and selected modal and composition isopleths in the SNCFMASONiCr model system.