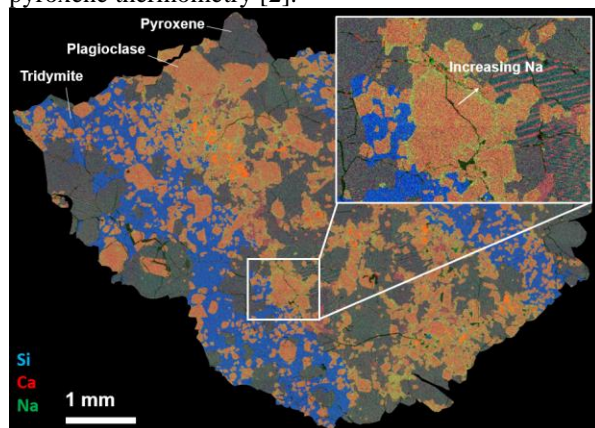


# THERMODYNAMIC AND DIFFUSION MODEL ESTIMATES ON METAMORPHIC TEMPERATURES AND TIMESCALES FOR BASALTIC EUCRITE GRA 98098

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**Introduction:** HED meteorites are thought to represent igneous rocks from Vesta's basaltic crust and preserve evidence of early crustal metamorphism. Determining the temperatures and timescales of thermal metamorphism is important for reconstructing crustal evolution in the early solar system. Here, we study basaltic eucrite Graves Nunataks (GRA) 98098, which has been identified as a highly metamorphosed eucrite [1]. We present new estimates on metamorphic temperatures determined via thermodynamic modeling as well as the initial results from diffusion models constraining timescales of thermal metamorphism.

**Sample Description:** GRA 98098 is an unbrecciated eucrite with a granoblastic plagioclase and pyroxene mineralogy. Millimeter to cm-long lathes of tridymite cross-cut and poikilitically enclose plagioclase and pyroxene [1, this work]. Pyroxene grains have exsolved into Ca-rich ( $\sim\text{Wo}_{38}\text{En}_{29}\text{Fs}_{33}$ ) and Ca-poor ( $\sim\text{Wo}_{4.5}\text{En}_{36}\text{Fs}_{59.5}$ ) lamellae. Both unzoned and zoned plagioclase grains are observed. Unzoned plagioclase grains are found solely with tridymite laths. These grains have  $\sim\text{An}_{92}$  compositions. The cores of the zoned plagioclase grains have the same composition and thin, relatively sodic rims ( $\sim\text{An}_{67}$ ), (Fig. 1). The bulk sample is unusually enriched in highly incompatible elements and has one of the most fractionated REE patterns reported [1]. Maximum metamorphic temperatures of  $985 \pm 78^\circ\text{C}$  have been estimated using two-pyroxene thermometry [2].



**Figure 1:** False colored element map of GRA 98098 with magnified zoned plagioclase indicated by the white box.

**Methods:** *Thermodynamic modeling.* Thermodynamic models were constructed using the software

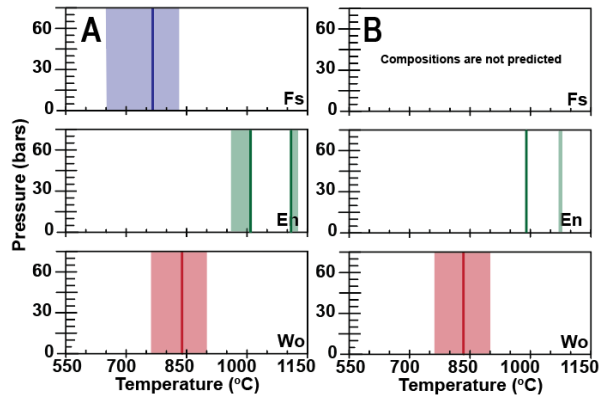
Perple\_X, which employs a Gibbs free energy minimization in order to determine the most stable phase assemblage for a given bulk rock composition [3]. Bulk composition was calculated using mineral compositions acquired via EMPA (this study) and the observed abundancies present in the thin section. Two bulk compositions were estimated; 1) includes all phases present in the thin section, (assumes that all phases are present during metamorphism), 2) excludes tridymite from the bulk calculation (assumes that tridymite was not present during metamorphism). In order to determine whether metamorphic equilibria was achieved and estimate temperatures of metamorphism, we compared measured pyroxene compositions with thermodynamically predicted compositions [4, Fig. 2].

*Diffusion Modeling.* Several time-temperature dependent diffusion profiles were calculated in order to determine the best match for  $X_{\text{An}}$  chemical profiles observed at the edges of the zoned plagioclase (Fig. 3). We assumed that the start condition was a stepwise gradient at the plagioclase/pyroxene interface. We also assumed an average diffusion coefficient ( $D$ ) and a constant temperature using the equation in [5].  $D$  was determined for two temperatures ( $T = 1060^\circ\text{C}$ ; near eucrite solidus [6] and  $T = 985^\circ\text{C}$ ; metamorphism reported in [4]) and then  $X_{\text{An}}$  was calculated as a function of distance from plagioclase core to rim using an error function solution to Fick's second law.

**Results:** Thermodynamic model results are summarized in Fig. 2. For a bulk composition that includes all phases in the thin section, pyroxene endmember compositions plot in the following temperature ranges: Fs  $\sim 660\text{--}860^\circ\text{C}$ , En  $\sim 1000^\circ\text{C}$  &  $1150^\circ\text{C}$ , and Wo  $\sim 760\text{--}900^\circ\text{C}$  (Fig. 2a). For a bulk composition that excludes tridymite from the peak metamorphic assemblage (i.e., the bulk composition minus the contribution from tridymite), a temperature range could not be determined for the Fs component of pyroxene. For Wo,  $T \sim 760\text{--}900^\circ\text{C}$  and En,  $T \sim 1000^\circ\text{C}$  &  $1150^\circ\text{C}$  (Fig. 2b).

Fig. 3 summarizes the diffusion model results. For  $T = 1060^\circ\text{C}$  &  $985^\circ\text{C}$ , the most appropriate time interval was estimated based on which diffusion curve most matched (solid lines, Fig. 3) the EMPA data. For  $T = 1060^\circ\text{C}$ , the best looking match was  $t = 500$  ka. For  $T = 985^\circ\text{C}$ , the best match was  $t = 7$  Ma.

**Discussion and future work:** Temperature estimates from thermodynamic models are not conclusive because the temperature ranges determined for pyrox-

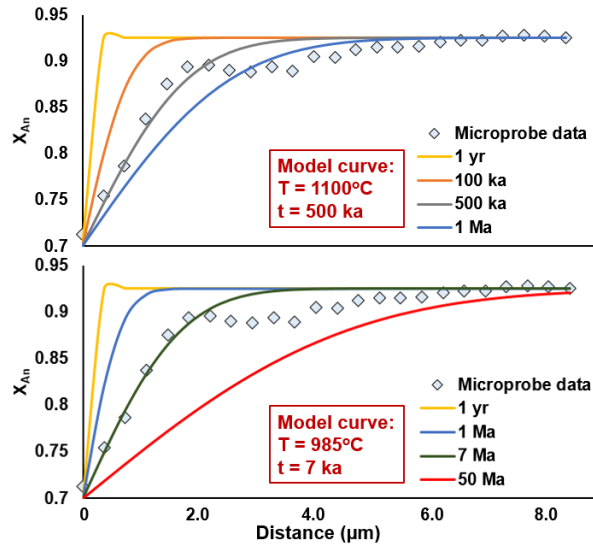


**Figure 2:**  $P$ - $T$  phase diagrams predict the thermodynamic stability fields of Wo (red), Fs (blue), and En (green) in pyroxene hosts from GRA 98098. A) Results generated using the thin section composition. B) Results generated removing tridymite from the thin section composition.

ene endmember stability do not overlap (colored fields in Fig. 2), thus implying that there is disequilibrium between pyroxene crystals and the bulk composition considered [4]. Thus, additional exploration is needed to define a metamorphically equilibrated domain that accurately records peak temperature. The utility of defining metamorphically equilibrated domains to improve the accuracy and level of detail elucidated regarding the petrogenetic history of metamorphose samples has been demonstrated previously [4,7]. We suggest that in the case of Fig. 2a, the thin section composition is not representative of the length scales over which metamorphic equilibrium was achieved and in the case of Fig. 2b, the assumption that tridymite was not present during metamorphism was incorrect.

However, results from thermodynamic models can provide insight into the relative timing of mineral and compositional textures. For example from texture alone, it is unclear whether tridymite was igneous in origin and represents the last bits of melt in a crystallizing magma chamber, or if it formed during (and possibly initiated) open system thermal metamorphism. The latter could be consistent with a partial melt hypothesis [8,9] while the former implies that simple fractional crystallization can yield the textures present in GRA 98098. The lack of coincidence between pyroxene endmember compositions in Fig. 2b suggest that the bulk composition minus tridymite was not the assemblage in equilibrium with the pyroxene, suggesting that tridymite was present during metamorphism and formed during igneous crystallization.

We conclude that the development of the Na-rich plagioclase rims likely occurred during or immediately after peak thermal metamorphism, because eucrites of similar metamorphic grade and texture have unzoned plagioclase ( $\sim\text{An}_{92}$ ) [2,4,8], and Na zoning is only ob-



**Figure 3:** Diffusion profiles (solid lines) calculated for  $X_{\text{An}}$  in plagioclase for two different temperatures and for different time intervals and superimposed on microprobe data (blue diamonds) to determine a best fit curve.

served in the plagioclase not included in the tridymite. This suggests that the zoning formed after tridymite formation, and therefore after igneous crystallization. Thus, the timescales calculated via diffusion modeling possibly represent the time interval over which thermal metamorphism occurred. Cooling rates approximated for the Vestan crust predict that the crust cooled below 300°C around 35-40 Ma after formation [10]. This is consistent with our modeling results that predict formation of the Na rich plagioclase rims occurring at higher temperatures over a period of 0.5 to 7 Ma years.

**Future work.** Additional thermodynamic modeling work will focus on selecting an equilibrated bulk rock domain in which to elucidate metamorphic conditions. Diffusion models currently provide a minimum timescale, since diffusion slows down as the system cools. Future work will focus on integrating cooling into the diffusion models and constraining the depth at which thermal metamorphism occurs because it could be used to determine whether the range of timescales calculated for thermal metamorphism are consistent with the geologic environment.

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