How to Build a Planet:

Answering Long-Standing Questions about the Formation of Diogenite Meteorites on Asteroid 4 Vesta

Jennifer T. Mitchell[1], Tim E. Johnson[2], Chris Newton[1], Andrew G. Tomkins[1]
[1]Monash University, Melbourne, Australia, [2]Curtin University, Perth, Australia
Email: Jennifer.Mitchell@monash.edu

INTRODUCTION

Diogenites are a group of meteorites from asteroid 4 Vesta, composed almost entirely of orthopyroxene with rare examples of olivine-bearing samples. Despite their mineralogical simplicity, how they form and their relationship to other Vestan meteorite groups has been debated for decades. There are two main schools of thought: a) diogenites form from a global magma ocean (40-50< % melt) [1,2], and crystallising minerals settle out into layers to create an "onion-skin" structure; b) diogenites form later in Vesta's history as magmatic intrusions into the crust [3,4,5].

Whilst NASA's Dawn mission provided a wealth of information about Vesta, there was no conclusive evidence to help answer this question. Therefore, we aim to determine the formation mechanism of diogenites so that we can better understand the behaviour of magmatism in the early solar system, over 4 billion years ago.

METHODS

Modelling of mineral crystallisation of 11 starting compositions [1,2,6,7,8] was carried out using the pMELTS software [9]. Early models found that the initial amount of melt did not change the compositions of the crystallising minerals. Instead, we varied the oxygen fugacity of the system from ΔIW -2.5 to -1.0 [5].

Later models used a restricted oxygen fugacity range of fO_2 ΔIW -1.6 and -1.2 (the best match for natural diogenites) and examined the effects of altering the starting compositions by removing 5-20% of an average eucrite component (high-Ca pyroxene-plagioclase basalts that make up Vesta's crust) to replicate diogenite compositions as if they were late-stage crustal intrusions.

The THERMOCALC 3.50 software [10] was used to generate pseudosections – graphs showing the mineral phases present at various pressures and temperatures – and additional thermal modelling explores the evolution of asteroid 4 Vesta.

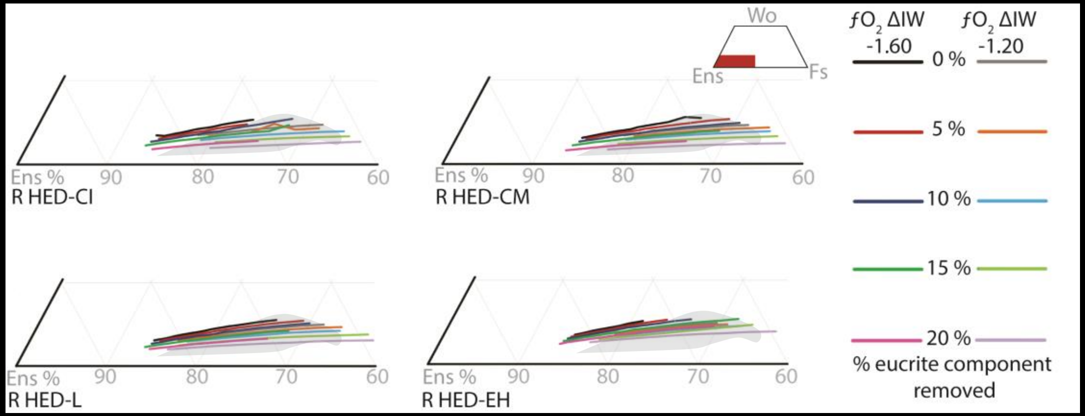

Figure 1. Examples of pyroxene compositions generated through pMELTS modelling of 4 different starting compositions [2] showing how increased eucrite removal decreases Wo content, and fO_2 controls Ens-Fs content. The shaded area reflects the compositions of 200 natural diogenites (data from the Meteoritical Society Bulletin Database. Ens = enstatite (Mg-rich); Fs = ferrosilite (Fe-rich); Wo = wollastonite (Ca-rich).

pMELTS MODELS

Early modelling established that small changes in oxygen fugacity have large changes in the enstatite (Mg-Fe) content of the crystallising pyroxenes [5]. However, all the compositions produced by these models were too high in wollastonite (Ca) compared to natural diogenites. In order to deplete the diogenite source of Ca, a Ca-rich material such as a eucrite lithology must have been removed before diogenite magmatism began.

Fig. 1 shows the effects of removing increased amounts of a eucrite component from the starting compositions. Increased eucrite removal decreases the wollastonite (Ca) content of the generated pyroxenes. We find that the removal of <20% eucrite from the diogenite source combined with variable fO_2 best matches natural diogenite compositions. This suggests that initial eucrite magmatism pre-dates diogenite formation, meaning that a magma ocean scenario is not appropriate for Vesta.

[1] Righter & Drake (1997), *MaPS*, **32**:929-940; [2] Ruzicka et al. (1997), *MaPS* **32**:825-840; [3] Beck & McSween (2010), *MaPS* **45**:850-872 ; [4] Madler & Elkins-Tanton (2013), *MaPS* **48**:2333-2349; [5] Mitchell & Tomkins (2019), *GCA* **258**:37-49; [6] Boseburg & Delaney (1997), *GCA*, **61**:3205-3225; [7] Driebus & Wänke (1980), *Z. Naturforsch*, **35a**:204-216; [8] Toplis et al., (2013), MaPS, **48**:2300-2315; [9] Ghiorso et al. (2002), G3, **3**:1-35; [10] Powell & Holland (1988), J. Metamorphic Geol., **6**:173-204

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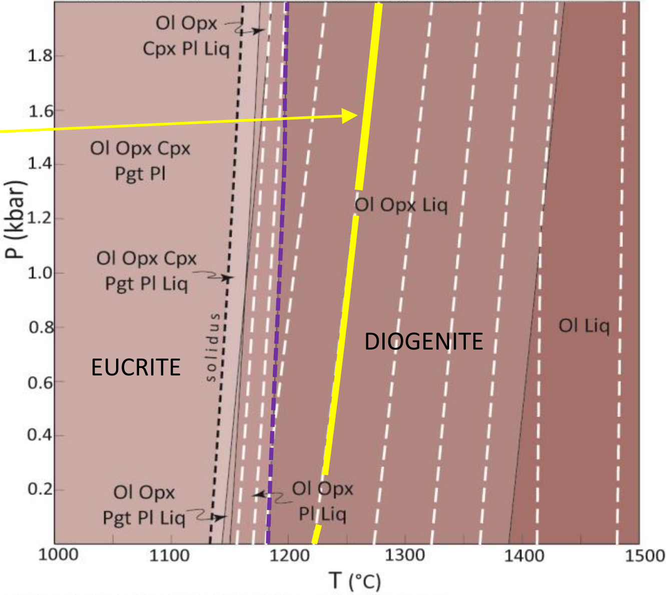
Maximum conditions required to extract melt in order to deplete the diogenite source in Ca

Figure 2. THERMOCALC pseudosection of an undepleted/primitive bulk silicate Vesta. Only low degrees of partial melting are achieved, even at high temperatures.

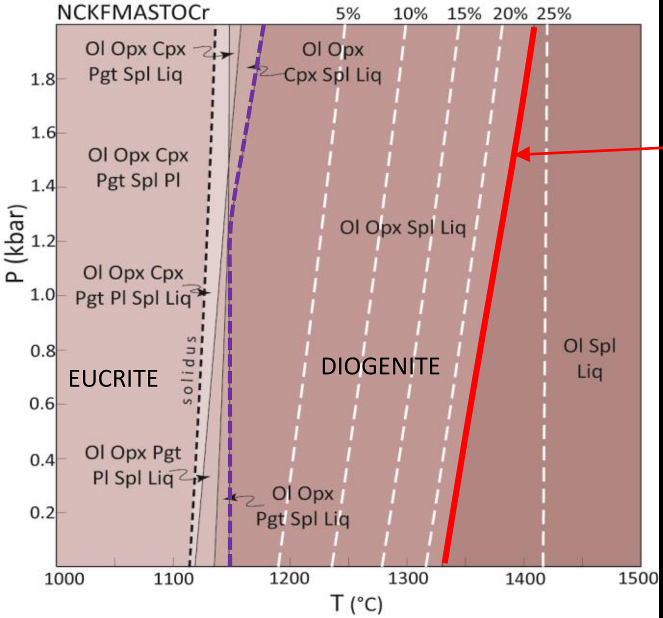
The purple dashed line marks the transition from diogenite to eucrite lithologies.

Ol = olivine; Opx = orthopyroxene; Cpx = clinopyroxene; Pgt = pigeonite; Pl = plagioclase; Liq = liquid



Undepleted/bulk silicate Vesta composition (in mol.%)

SiO_2	Al_2O_3	CaO	MgO	FeO	K_2O	Na_2O	TiO2	Cr_2O_3
40.937	1.752	2.669	43.978	10.131	0.010	0.101	0.121	0.302



Depleted/post-eucrite removal composition (in mol.%)

SiO_2	Al_2O_3	CaO	MgO	FeO	K_2O	Na_2O	TiO_2	Cr_2O_3
39.020	0.800	1.330	48.340	10.060	0.010	0.050	0.070	0.320

Minimum conditions for diogenite formation

Figure 3. THERMOCALC pseudosection of an evolved composition of Vesta, following the removal of a eucrite component which depletes the composition in Ca as established in the pMELTS model. Spinel appears in this pseudosection as the mean eucrite composition did not account for Cr2O3, and it is therefore a large component in this evolved starting composition.

The purple dashed line marks the transition from diogenite to eucrite lithologies.

Ol = olivine; Opx = orthopyroxene; Cpx = clinopyroxene; Pgt = pigeonite; Pl = plagioclase; Spl = spinel; Liq = liquid

THERMOCALC: Undepleted Vesta

The THERMOCALC model of the undepleted, primitive bulk composition of Vesta (Fig.2) finds that only low degrees of partial melt are achieved. This means that melt extraction and movement was likely very efficient in Vesta's early history [11], and that a magma ocean is not necessary to form eucrites and diogenites.

Our pMELTS models established that <20% partial melting is needed to reduce the calcium content of the diogenite source. This first stage of melt extraction (20% partial melt) occurs at approximately 1240°C. This melt would produce a stagnant lid [12] that limits the loss of heat from Vesta's interior and allows for melt compositions to evolve and diversify.

THERMOCALC: Evolved Vesta

Following the depletion of the starting composition in Ca as determined in earlier modelling, the THERMOCALC model of this evolved composition (Fig.3) finds that the temperatures required to generate diogenite compositions occur at >1340°C in order to account for the rare samples of near pure olivine (dunite) diogenites. This temperature is higher than that needed for the initial melting in the undepleted model.

This means that after the first stage of melting and the formation of a stagnant lid, the interior of Vesta continued to heat up through the decay of ^{26}Al and ^{60}Fe until high enough temperatures to create diogenites were reached, causing a delay in the start of diogenite magmatism [13]. This also supports the view that eucrite magmatism was ongoing [14].

[11] Wilson & Keil (1996), *J. Geophys. Res.*, **101**:18927-18940; [12] Gurnis et al. (1989), *Geophys. Res. Letters*, **16**:179-182; [13] Yamaguchi et al. (2015), *J. Geophys. Res.* **116**:E08009; [14] Roszjar et al. (2016), *EPSL*, **45**:216-226

MONASH University

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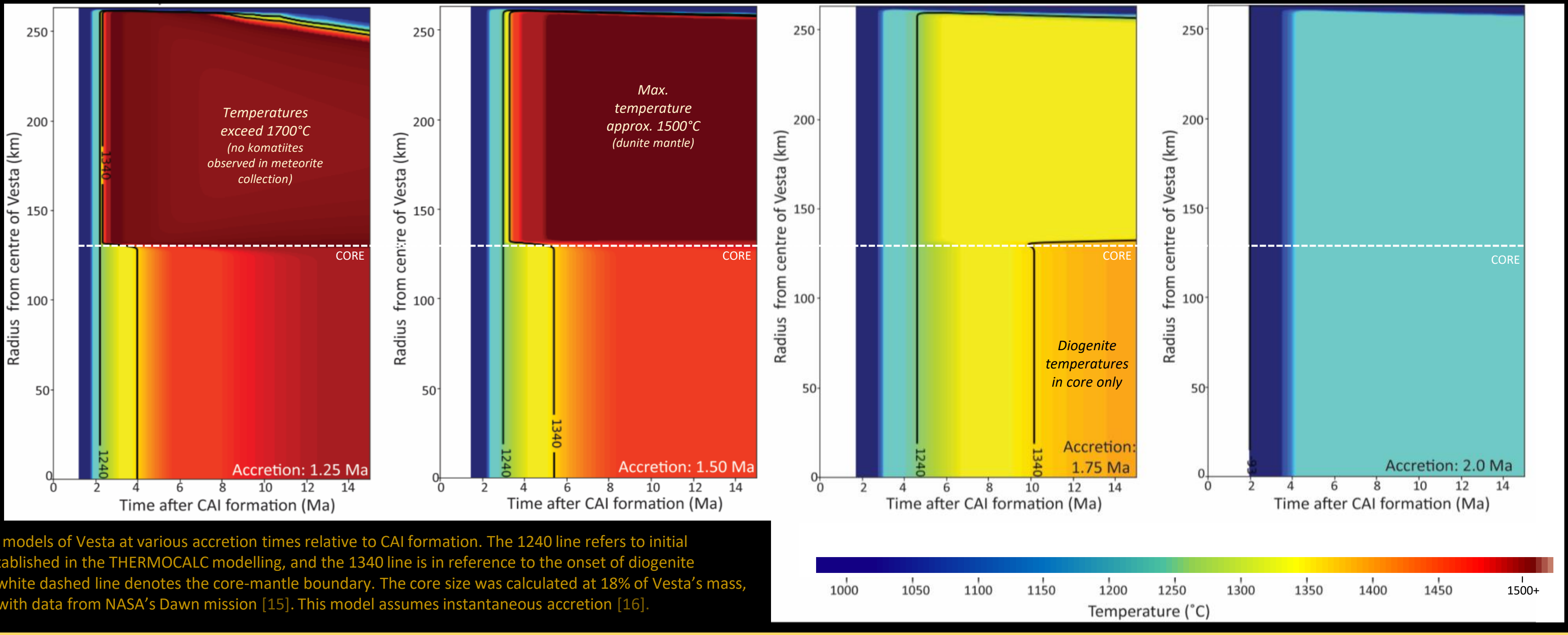

Figure 4. Thermal models of Vesta at various accretion times relative to CAI formation. The 1240 line refers to initial magmatism as established in the THERMOCALC modelling, and the 1340 line is in reference to the onset of diogenite magmatism. The white dashed line denotes the core-mantle boundary. The core size was calculated at 18% of Vesta's mass, and is in keeping with data from NASA's Dawn mission [15]. This model assumes instantaneous accretion [16].

THERMAL MODELLING

Having established the temperature requirements for each stage of magmatism from the pMELTS and THERMOCALC models, we have developed a thermal model of Vesta's interior (Fig.4). This model examines heating produced through the decay of short-lived isotopes ^{26}Al and ^{60}Fe, and the effects this has on both silicate and metal materials.

These models find that the time of Vesta's accretion is important for its thermal evolution, as this alters the amount of ^{26}Al/^{60}Fe available for decay. We find that an accretion time of approximately 1.5 Myr after CAI formation is most appropriate. If accretion occurred before this, the system is too hot to generate the lithologies observed on Vesta. After this time the system is too cold, with diogenite-forming temperatures only being reached in the core.

The first stage of magmatism, occurring at 1240°C to generate the primordial eucrite crust, takes place at approximately 3 Myr after CAI formation. This first crust of Vesta traps heat inside the body, allowing the interior to heat up over time until diogenite lithologies can be produced at 1340°C, almost 2Myr later. As such, diogenites post-date the oldest eucrites. This further supports the view that diogenites are not the result of magma ocean mineral settling, and these dates are in keeping with recent isotopic studies [17,18].

[15] Rusell et al. (2012), *Science*, **336**:684-686; [16] Henke et al. (2013), *Icarus*, 226:212-228; [17] Schiller et al. (2010), *GCA*, **74**:4844-4864; [18] Hublet et al. (2017), *GCA*, **218**:73-97

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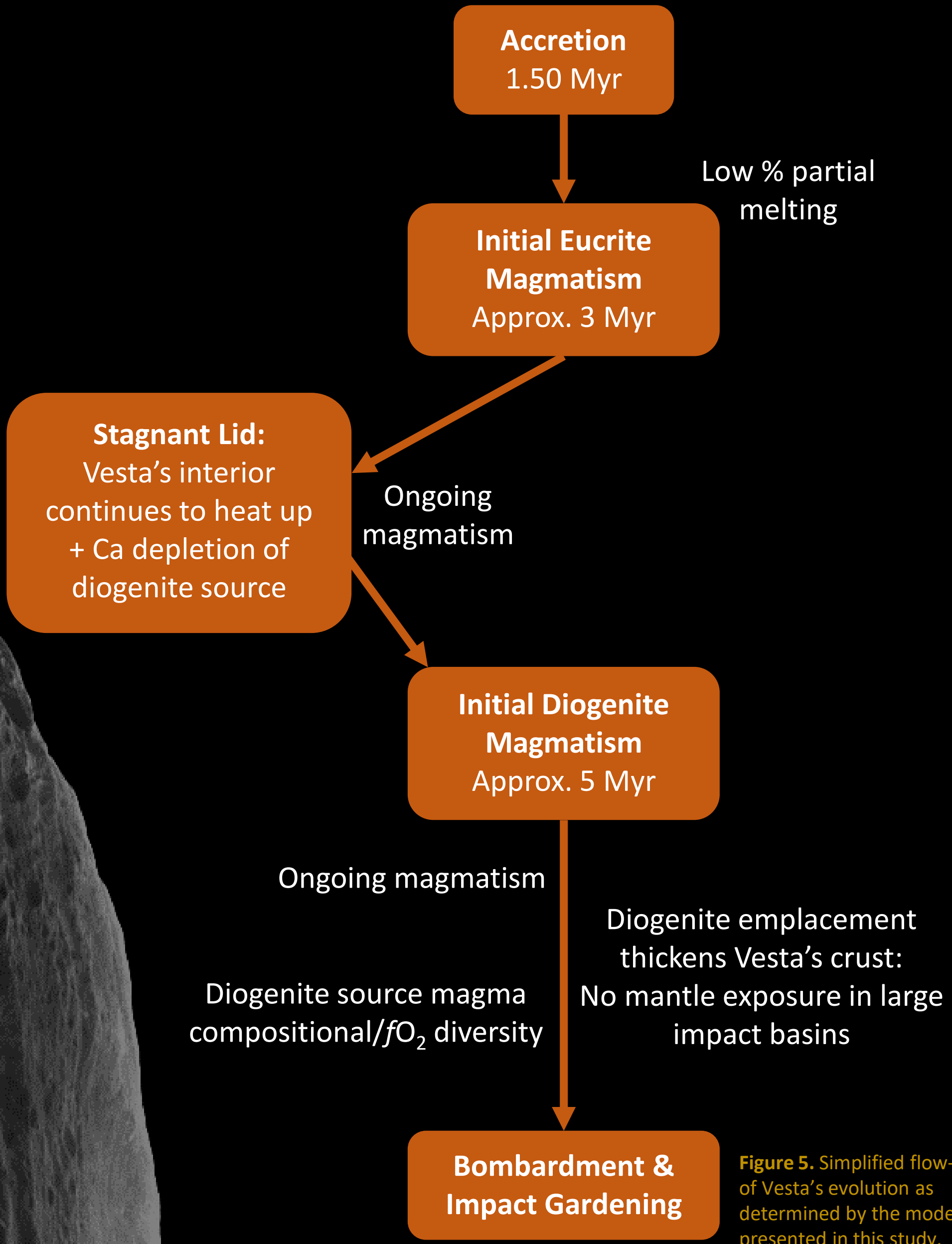
SUMMARY

Our models show that Vesta underwent a complex evolution, where multiple stages of magmatism occurred (Fig.5). Our key findings are summarised below:

- Vesta accreted early in the Solar System, allowing the decay of ^{26}Al/^{60}Fe to heat the interior of the asteroid to high enough temperatures to produce both eucrites and diogenites;
- Magmatism on Vesta functions efficiently at low % partial melt;
- Eucrite magmatism began before diogenite magmatism;
- Eucrite and diogenite magmatism are contemporaneous with other achondrite meteorite classes [18,19];
- Diogenites do not represent Vesta's mantle nor magma ocean cumulates. Instead, they are most likely late-stage crustal intrusions;
- Diogenites require compositional diversity, variable fO_2 and high temperatures in a Ca-depleted source;
- Magmatism in the early Solar System is complex.

Vesta was able to evolve with such complexity due to size and luck. Smaller parent bodies cooled too fast to generate such diverse compositions [20], and others did not survive the violent bombardment of the early Solar System [18,21]. As such, Vesta is a rare example of magmatic processes and the early stages of planetary formation occurring billions of years ago.



Accretion
1.50 Myr

Low % partial melting

Initial Eucrite Magmatism
Approx. 3 Myr

Stagnant Lid:
Vesta's interior continues to heat up + Ca depletion of diogenite source

Ongoing magmatism

Initial Diogenite Magmatism
Approx. 5 Myr

Ongoing magmatism

Diogenite source magma compositional/fO_2 diversity

Diogenite emplacement thickens Vesta's crust:
No mantle exposure in large impact basins

Bombardment & Impact Gardening

Figure 5. Simplified flow-chart of Vesta's evolution as determined by the modelling presented in this study.

[19] Lee et al. (2009), *EPSL*, **288**:611-618; [19] Budde et al. (2015), *EPSL*, 430:316-325; [20] Keil (2014), *Chemie der Erde*, **74**:311-329; [21] Downes et al. (2008), *GCA*, **72**:4825-4844

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