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Petrology, Geochemistry (Cosmochemistry)

## Timing of metal–silicate differentiation in the Eagle Station pallasite parent body

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## ARTICLE INFO

## Article history:

Received 10 March 2014

Accepted after revision 12 March 2014

Available online 30 April 2014

## Keywords:

Eagle Station pallasite

<sup>26</sup>Al–<sup>26</sup>Mg short-lived chronometer

Metal–silicate differentiation age

## ABSTRACT

The time of the metal–silicate differentiation of the Eagle Station pallasite (ESP) parent body was investigated using the <sup>26</sup>Al–<sup>26</sup>Mg short-lived chronometer (half-life of 0.72 Myr). The Mg isotope ratios were measured in ESP olivines by both MC–SIMS and HR–MC–ICPMS, allowing us to check the consistency between the results given by two different analytical protocols and data reduction processes. Results show that the two datasets are consistent, with a  $(\delta^{26}\text{Mg}^*)_{\text{av}}$  value of  $-0.003 (\pm 0.005)\%$  (2 s.e.,  $n = 89$ ). Such a value, associated with data from the <sup>182</sup>Hf–<sup>182</sup>W short-lived systematics (half-life of 8.9 Myr), indicates an ESP parent body metal–silicate differentiation occurring most likely at least at  $\sim 2$  Ma, but possibly 4 Ma, after CAI formation. From the <sup>27</sup>Al/<sup>24</sup>Mg ratios measured in ESP olivines using MC–SIMS, the duration of the olivine crystallization process was inferred to have lasted over  $\sim 275$  kyr if the core has differentiated as early as 2 Ma after CAIs, while in the case of a core differentiation occurring 4 Ma after CAIs, the silicate–silicate differentiation should have lasted for another 4 Myr.

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## 1. Introduction

A major recent advance in our understanding of the formation of planetary bodies in the Solar System is the recognition that some of them accreted very early and differentiated into a metallic core surrounded by a silicate mantle within the first or the first 2 Myr of Solar System history, when the Sun was still a T-Tauri forming star. The “time zero” of the Solar System is generally taken as that of the formation of the oldest known solids, the so-called CAIs (Ca-, Al-rich inclusions). However, there is no consensus about the absolute Pb–Pb age of CAIs, with a range of up to 1 Myr between the ages reported by Amelin et al. (2010), Bouvier and Wadhwa (2010), and Connelly et al. (2012),

possibly reflecting disturbances of the U–Pb system, analytical bias, or variations in the U isotopic ratio. The combination of Pb–Pb dating and <sup>26</sup>Al–<sup>26</sup>Mg systematics (half-life of 0.72 Myr) on the same objects seems to indicate an age of  $\sim 4568$  Ma for CAIs [e.g., Bouvier et al. (2011), Wadhwa et al. (2014)]. The existence of a single <sup>26</sup>Al bulk CAI isochron (for CV3 chondrites) shows that these CAIs formed over a very short time interval, within less than  $\sim 40,000$  years (Jacobsen et al., 2008; Thrane et al., 2006) or even less than  $\sim 4000$  years (Larsen et al., 2011).

The <sup>182</sup>Hf–<sup>182</sup>W systematics, short-lived <sup>182</sup>Hf decays to <sup>182</sup>W, with a half-life of 8.9 Myr, of magmatic iron meteorites, allows us to date metallic core formation in their parent bodies at less than  $\sim 1.5$  Myr after CAI formation (Burkhardt et al., 2008; Kleine et al., 2005, 2009; Kruijer et al., 2012, 2013; Markowski et al., 2006, 2007; Qin et al., 2008). The differentiation of a silicate crust

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from the mantle of such early differentiated bodies probably occurred shortly after core formation, between 2 and 5 Myr after CAI formation, as suggested by the  $^{26}\text{Al}$ – $^{26}\text{Mg}$  systematics of achondritic meteorites (Baker et al., 2005; Bizzarro et al., 2005; Bouvier et al., 2011; Schiller et al., 2010; Spivak-Birndorf et al., 2009). These early differentiation processes are consistent with the rapid accretion timescales recently proposed in models, taking into account turbulence to create regions in the accretion disk of high particle/gas ratio (Cuzzi et al., 2008; Johansen et al., 2007; Morbidelli et al., 2012).

Despite these recent advances, very few data exist to constrain the timing of silicate differentiation relative to that of metal differentiation in an early accreted planetesimal. Stony-iron meteorites, named pallasites [65 vol% olivine, 30 vol% Fe–Ni metal, 5 vol% chromite, troilite and phosphate (Buseck, 1977)] are of particular interest, since they contain fragments of the metal and silicate phases produced upon differentiation. Because the metal is devoid of Hf and the olivine is devoid of Al, the W and Mg isotopic compositions of the two phases were frozen at the time of differentiation, thus, giving access, theoretically, to the  $^{26}\text{Al}$  model age of silicate differentiation and to the  $^{182}\text{Hf}$  model age of metal differentiation. Recent analytical developments for Mg isotope measurements by MC–SIMS (Luu et al., 2013; Villeneuve et al., 2009, 2011) or HR–MC–ICPMS (Bizzarro et al., 2011) allow  $^{26}\text{Al}$  model ages to be as precise (or even more precise) than  $^{182}\text{Hf}$  model ages.

The present study is focused on the Eagle Station pallasite (ESP), this pallasite being of particular interest as it is chemically anomalous compared to other pallasites (e.g., high Ni, Ge and Ir contents in the metal, and high fayalite content in olivines, Scott (1977)). It is also enriched in  $^{16}\text{O}$  [ $(\Delta^{17}\text{O})_{\text{ESP}} = -4.51\text{‰}$ , Clayton and Mayeda (1996)] compared to Main Group pallasites [ $(\Delta^{17}\text{O})_{\text{MGP}} = -0.28 (\pm 0.06)\text{‰}$ , Clayton and Mayeda (1996)], indicating possibly that this pallasite formed either in a more inner region of the disk or earlier than others. We report here Mg isotope analyses by MC–SIMS (multi-collection secondary ion mass spectrometry) and HR–MC–ICPMS (high-resolution multi-collector inductively coupled plasma source mass spectrometry) of olivines from ESP. This is the first study that associates bulk (HR–MC–ICPMS) and in situ (MC–SIMS) analyses conducted on the same samples in order to be able to look for any isotopic variations in  $^{26}\text{Mg}$  at different scales and thus to determine precisely the range of variation of the  $^{26}\text{Mg}$  excesses due to  $^{26}\text{Al}$  decay in the parent melts of the olivines. Assuming a homogeneous distribution of Mg and Al isotopes in the protoplanetary disk, these results are combined with previous W isotope data (Quitté et al., 2005) to constrain the timing of metal and silicate differentiation on the parent body of ESP.

## 2. Material and analytical procedures

The olivines from ESP selected for MC–SIMS measurements belong to two different mounts, the first one being a polished section of this meteorite (hereafter ESP-M), and the second one containing two separated olivine grains (hereafter ESP 1 and ESP 2) as well as the standard minerals (San Carlos olivine, Burma spinel, pyroxene) used in this study.

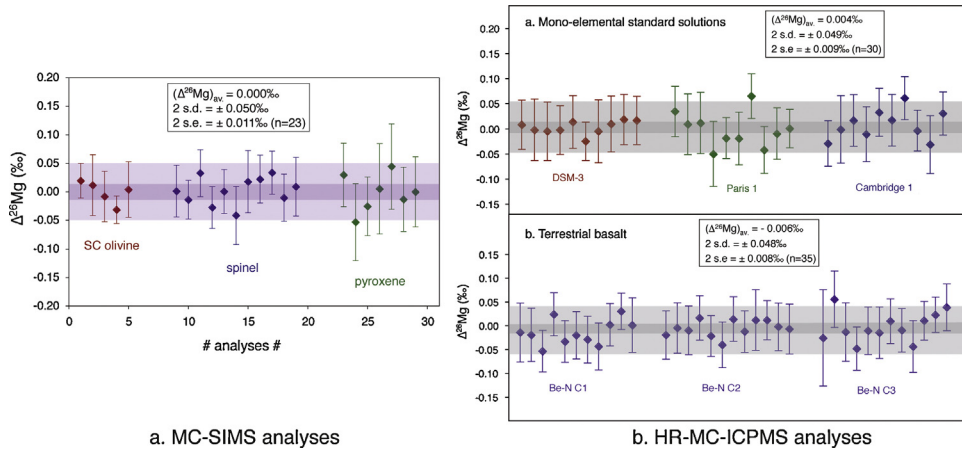
Mg isotopic compositions and Al/Mg concentration ratios were measured on both the polished section and the two individual grains, with the CRPG–CNRS (Nancy) ims 1280HR2, using procedures previously developed and described elsewhere (Luu et al., 2013; Villeneuve et al., 2009, 2011). For HR–MC–ICPMS measurements, a set (5.15 mg) of hand-picked separated olivines from ESP was digested in a 1:1 mixture of concentrated HF + HNO<sub>3</sub> acids at 100° C. The Mg chemical separation was performed according to Tipper et al. (2008), with 4 aliquots (hereafter ESP C2 to ESP C5) processed through 4 different sets of columns to also test the reproducibility of the chemical separation procedure. Mg isotopic compositions were measured using the IPG Paris Neptune HR–MC–ICPMS, via an Apex desolvating system, at a mass resolution  $M/\Delta M = 4500$ . Under these conditions, a Mg solution of 300 ppb produced a signal of  $\sim 10\text{V}$  on mass 24. A standard-sample-standard bracketing procedure was utilized to monitor the instrumental fractionation drift, with the DSM-3 pure Mg metal as an international standard (Galy et al., 2003).

Note that the Mg isotopic compositions of ESP olivines are expressed with the  $\delta^{26}\text{Mg}^*$  notation, classically used when the non-mass-dependent  $^{26}\text{Mg}$  excesses are considered to be due to  $^{26}\text{Al}$  decay. A  $\beta$  value of 0.521 was used to calculate the  $\delta^{26}\text{Mg}^*$  values according to  $\delta^{26}\text{Mg}^* = \delta^{26}\text{Mg} - \delta^{25}\text{Mg}/\beta$ . This value of  $\beta$  corresponds to equilibrium Mg isotopic fractionations akin to those taking place during the differentiation of the mantle of the Earth. No hint for kinetic Mg isotopic fractionations, as evaporation (see Discussion), exists in the present ESP data set. Reproducibility of  $\delta^{26}\text{Mg}^*$  for standards is  $\pm 0.050\text{‰}$  (2 s.d.) or  $\pm 0.011\text{‰}$  (2 s.e.,  $n = 23$ ) by MC–SIMS, and better than  $\pm 0.050\text{‰}$  (2 s.d.) or  $\pm 0.010\text{‰}$  (2 s.e.,  $n \sim 30$ ) by HR–MC–ICPMS (Fig. 1).

## 3. Results

The Mg isotope data for olivines from the Eagle Station pallasite are given in Table 1 and plotted in Fig. 2. Taking into account the whole MC–SIMS dataset, the ESP olivines display  $\delta^{26}\text{Mg}^*$  values ranging from  $-0.024 (\pm 0.029)\text{‰}$  to  $-0.002 (\pm 0.018)\text{‰}$ , with an average  $(\delta^{26}\text{Mg}^*)_{\text{av.}}^{\text{MC-SIMS}}$  value of  $-0.011 (\pm 0.009)\text{‰}$  (2 s.e.,  $n = 26$ ). The HR–MC–ICPMS analyses show data consistent within errors between the different aliquots, ranging from  $-0.004 (\pm 0.012)\text{‰}$  to  $+0.009 (\pm 0.012)$ , with an average  $(\delta^{26}\text{Mg}^*)_{\text{av.}}^{\text{HR-MC-ICPMS}}$  value of  $0.000 (\pm 0.006)\text{‰}$  (2 s.e.,  $n = 63$ ). The average MC–SIMS and HR–MC–ICPMS  $\delta^{26}\text{Mg}^*$  values are not statistically different. The average of all the measurements gives a  $(\delta^{26}\text{Mg}^*)_{\text{av.}}^{\text{SIMS+ICP}}$  value of  $-0.003 (\pm 0.005)\text{‰}$  (2 s.e.,  $n = 89$ ).

This  $(\delta^{26}\text{Mg}^*)_{\text{av.}}^{\text{SIMS+ICP}}$  value is higher than the  $\delta^{26}\text{Mg}^*$  value of  $-0.033 (\pm 0.008)\text{‰}$  previously reported by Villeneuve et al. (2011). This discrepancy is probably partly due to an under correction by Villeneuve et al. (2011) of the matrix effect on the instrumental fractionation in MC–SIMS, the olivines from ESP being more enriched in Fe (Fo#79) compared to the San Carlos olivine standard (Fo#88) used

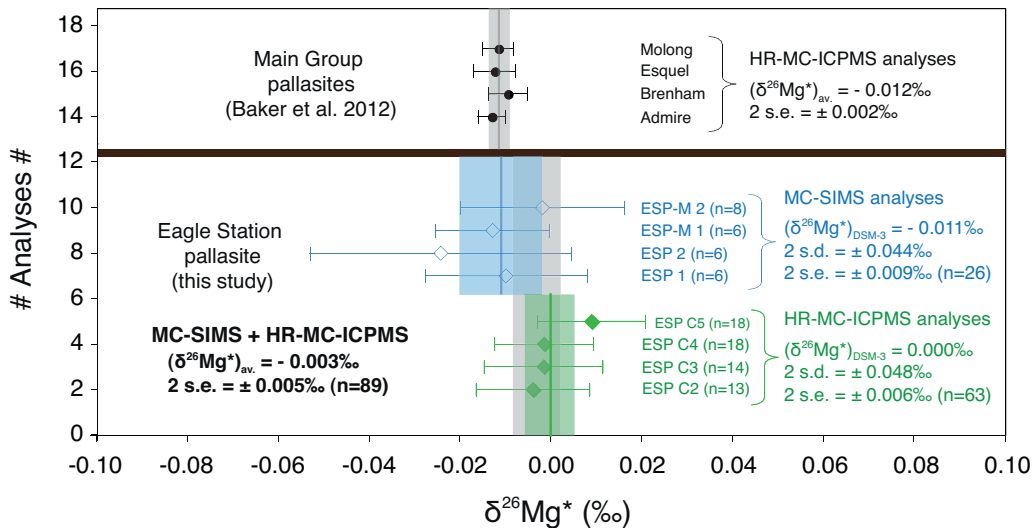


**Fig. 1.** (Colour online.) Standards show no significant excess in  $^{26}\text{Mg}$  ( $\Delta^{26}\text{Mg}$  notation used here as there is no expected contribution of radiogenic  $^{26}\text{Mg}$ ), the external reproducibility on standards measured using MC-SIMS (a) or HR-MC-ICPMS (b) being better than 0.05 (2 s.d.). The standards measured by MC-SIMS include terrestrial (San Carlos olivine and Burma spinel) and synthetic (pyroxenic glass) standards, while the standards measured by HR-MC-ICPMS include pure Mg standard solutions (DSM-3, Paris 1, Cambridge 1) not processed through chemistry and a geostandard (Be-N basalt) processed through chemistry (Be-N C1, Be-N C2 and Be-N C3 correspond to three different aliquots processed through three different sets of ion-exchange columns).

**Table 1**  
Al-Mg isotope systematics of the Eagle Station Pallasite olivines.

Name	Description	$^{27}\text{Al}/^{24}\text{Mg}$ (2 s.e.)	$\delta^{25}\text{Mg}$ (‰)	2 s.e.	$\delta^{26}\text{Mg}$ (‰)	2 s.e.	$\delta^{26}\text{Mg}^*$ (‰)	2 s.e.	n
MC-SIMS	ESP 1 Separated grain n <sup>o</sup> 1	$7.07 (\pm 1.12) \times 10^{-4}$	-0.178	0.136	-0.352	0.273	-0.010	0.018	6
	ESP 2 Separated grain n <sup>o</sup> 2	$7.63 (\pm 1.57) \times 10^{-4}$	0.007	0.054	-0.011	0.107	-0.024	0.029	6
	ESP-M 1 Section-zone n <sup>o</sup> 1	$1.22 (\pm 0.38) \times 10^{-4}$	-0.119	0.109	-0.241	0.202	-0.013	0.013	6
	ESP-M 2 Section-zone n <sup>o</sup> 2	$1.19 (\pm 0.08) \times 10^{-4}$	-0.190	0.074	-0.367	0.127	-0.002	0.018	8
	Average		-0.125	0.054	-0.251	0.103	-0.011	0.009	26
HR-MC-ICPMS	ESP C2 Aliquot n <sup>o</sup> 2		-0.165	0.012	-0.321	0.021	-0.004	0.012	13
	ESP C3 Aliquot n <sup>o</sup> 3		-0.161	0.014	-0.311	0.021	-0.002	0.013	14
	ESP C4 Aliquot n <sup>o</sup> 4		-0.181	0.010	-0.349	0.022	-0.002	0.011	18
	ESP C5 Aliquot n <sup>o</sup> 5		-0.184	0.009	-0.344	0.012	0.009	0.012	18
	Average		-0.174	0.006	-0.334	0.010	0.000	0.006	63
<b>MC-SIMS+HR-MC-ICPMS</b>							<b>-0.003</b>	<b>0.005</b>	<b>89</b>

$$\delta^{26}\text{Mg}^* = \delta^{26}\text{Mg} - \delta^{25}\text{Mg}/0.521.$$



**Fig. 2.** (Colour online.) Magnesium isotope data for olivines from the Eagle Station pallasite (this study) and from Main Group pallasites (Baker et al., 2012). Olivines from ESP display a  $\delta^{26}\text{Mg}^*$  value consistent between MC-SIMS ( $-0.011 (\pm 0.009)\%$ , 2 s.e.,  $n = 26$ , blue open diamonds) and HR-MC-ICPMS analyses ( $0.000 (\pm 0.006)$ , 2 s.e.,  $n = 63$ , green diamonds). The average of both datasets gives a  $(\delta^{26}\text{Mg}^*)_{\text{av}}$  value of  $-0.003 (\pm 0.005)\%$  (2 s.e.,  $n = 89$ ), which is slightly more positive than the  $\delta^{26}\text{Mg}^*$  value of  $-0.012 (-0.002)$  reported by Baker et al. (2012) for olivines from four different Main Group pallasites (black dots).

to calibrate the instrumental fractionation (Luu et al., 2013). The correction of matrix effect using appropriate standards gives, in this study, an average  $\delta^{25}\text{Mg}$  value measured by MC-SIMS of  $-0.125 (\pm 0.054)\text{‰}$ , consistent within errors with the value of  $-0.174 (\pm 0.006)\text{‰}$  measured by HR-MC-ICPMS, and also consistent with the  $\delta^{25}\text{Mg}$  determined for silicate Earth from analyses of oceanic basalts and mantle peridotites ( $\delta^{25}\text{Mg} = -0.13 (\pm 0.04)\text{‰}$ , Teng et al. (2010)).

The  $(\delta^{26}\text{Mg}^*)_{\text{av.}}^{\text{SIMS+ICP}}$  value reported in the present study is also slightly higher than the one reported by Baker et al. (2012) for bulk olivines from four meteorites (Molong, Esquel, Brenham, Admire) belonging to the Main Group pallasites (MGP), measured by HR-MC-ICPMS. They reported a smaller  $\delta^{26}\text{Mg}^*$  value of  $-0.012 (\pm 0.002)\text{‰}$  in average, indicative of a metal–silicate differentiation process occurring  $\sim 1.24_{-0.28}^{+0.40}$  Ma after CAIs. However, if the different groups of pallasites really originated on different parent bodies (as suggested by their respective  $\Delta^{17}\text{O}$  value), then, the metal–silicate differentiation processes could have occurred at different times, leading to different  $\delta^{26}\text{Mg}^*$  values depending on which pallasite is considered.

#### 4. Implication: timing of metal–silicate differentiation on the Eagle Station pallasite parent body

Planetary differentiation can be modeled at first order considering a two-stage evolution in which:

- (i) the planetesimal keeps its original chondritic composition between the time of its accretion  $t_0$  and the time of differentiation of its metallic core  $t_c$ ;
- (ii) core differentiation is considered to be instantaneous;
- (iii) the mantle residue produced by the extraction of the metallic core undergoes silicate–silicate differentiation by extraction of silicate liquids from time  $t_c$  until the mantle has cooled to a point where it is fully crystallized (Labrosse et al., 2007; Ricard et al., 2009).

The first major geochemical fractionation occurs for the Hf–W system at  $t_c$  when siderophile W is partitioned into the core, so that the W isotope composition of the metal reflects the timing of metal–silicate differentiation. The second one occurs after  $t_c$ , during silicate–silicate differentiation when Mg is partitioned into the olivine crystallizing from the mantle, so that the Mg isotopic composition of the olivines reflects the timing of silicate–silicate differentiation. The theoretical evolution of radiogenic  $^{26}\text{Mg}$  and  $^{182}\text{W}$  excesses as a function of the time of differentiation can be expressed in the mantle and in the core of a differentiated body using the two following equations, respectively:

$$(\delta^{26}\text{Mg}^*)_{t_c}^{\text{mantle}} = (\delta^{26}\text{Mg}^*)_{\text{SSI}} + \left(\frac{^{26}\text{Al}}{^{27}\text{Al}}\right)_{\text{SSI}} \times \left(\frac{^{27}\text{Al}}{^{26}\text{Mg}}\right)^{\text{CHUR}} \times (1 - e^{-\lambda_{26}t_c}) \times 10^3 \quad (1)$$

where  $t_c$  stands for the metal differentiation time, SSI for the Solar System Initial inferred from bulk CAIs

$[(^{26}\text{Al}/^{27}\text{Al})_{\text{SSI}} = 5.23 (\pm 0.13) \times 10^{-5}$  and  $(\delta^{26}\text{Mg}^*)_{\text{SSI}} = -0.038 (\pm 0.004)\text{‰}$ , from data by Jacobsen et al., (2008)], CHUR for CHondritic Unfractionated Reservoir (whose  $^{27}\text{Al}/^{26}\text{Mg}$  ratio = 0.725, Lodders (2003)), and  $\lambda_{26}$  for the decay constant of  $^{26}\text{Al}$ , and:

$$(\varepsilon^{182}\text{W})_{t_c}^{\text{core}} \approx (\varepsilon^{182}\text{W})^{\text{Allende}} - \left(\frac{^{180}\text{Hf}}{^{182}\text{W}}\right)^{\text{Allende}} \times \left(\frac{^{182}\text{Hf}}{^{180}\text{Hf}}\right)_{\text{SSI}} \times e^{-\lambda_{182}t_c} \times 10^4 \quad (2)$$

where  $(^{180}\text{Hf}/^{182}\text{W})^{\text{Allende}} \approx 1.4734$  (Kleine et al., 2004),  $(^{182}\text{Hf}/^{180}\text{Hf})_{\text{SSI}} = 9.72 (\pm 0.44) \times 10^{-5}$  (inferred from CAIs by Burkhardt et al., (2008)),  $\lambda_{182}$  standing for the decay constant of  $^{182}\text{Hf}$ , and  $(\varepsilon^{182}\text{W})^{\text{Allende}} = -2.08$ . The last parameter, in good agreement with the value of  $-2.0 (\pm 0.3)$  reported by Kleine et al. (2004), was recalculated using the following equation at the present day:

$$(\varepsilon^{182}\text{W})^{\text{Allende}} = (\varepsilon^{182}\text{W})_{\text{SSI}} + \left(\frac{^{180}\text{Hf}}{^{182}\text{W}}\right)^{\text{Allende}} \times \left(\frac{^{182}\text{Hf}}{^{180}\text{Hf}}\right)_{\text{SSI}} \times 10^4 \quad (3)$$

where  $(\varepsilon^{182}\text{W})_{\text{SSI}} = -3.51 (\pm 0.1)$  (Burkhardt et al., 2012). We consider a bulk composition of ESP similar to that of CV chondrites, based on the O (Clayton and Mayeda, 1996, 1999) and Cr (Shukolyukov and Lugmair, 2006) isotopic affinities of ESP to the CV3 chondrites. These theoretical evolutions of radiogenic  $^{26}\text{Mg}$  and  $^{182}\text{W}$  excesses are represented in Fig. 3, in which ESP is also plotted using the  $(\delta^{26}\text{Mg}^*)_{\text{av.}}^{\text{SIMS+ICP}}$  of  $-0.003 (\pm 0.005)\text{‰}$  of the present study and a  $\varepsilon^{182}\text{W}$  of  $\sim -3.1$  (the value of  $-3.4 (\pm 0.2)$  reported in Quitté et al., (2005) was recalculated with respect to the terrestrial value of 0.864680, to be consistent with the  $(\varepsilon^{182}\text{W})_{\text{SSI}}$  of  $-3.51 (\pm 0.1)$  reported by Burkhardt et al. (2012)). This is the only  $\varepsilon^{182}\text{W}$  value available in the literature for the Eagle Station pallasite. However, this is a minimum value, as it has not been corrected for cosmogenic effects. Indeed during cosmic ray exposure, a burnout of W isotopes caused by the interaction with thermal neutrons tends to decrease the  $\varepsilon^{182}\text{W}$  values (Leya et al., 2000, 2003; Masarik, 1997), of for instance 0.086‰ per 100 Myr of exposure for IAB irons (Schulz et al., 2009), leading to virtually older Hf–W ages if this effect is not corrected. ESP exposure age had already been measured (Megrué, 1968) using cosmogenic noble gases ( $^3\text{He}$ ,  $^{21}\text{Ne}$ ,  $^{38}\text{Ar}$ ), and giving an average value of  $\sim 40$  Myr. Such a short exposure age would keep the  $\varepsilon^{182}\text{W}$  corrected for thermal neutron capture reactions within the error bars of the raw  $\varepsilon^{182}\text{W}$  value. Recently, Kruijer et al. (2013) have shown that Pt isotopes should be used to quantify at best the cosmic ray-induced shifts on W isotope compositions because both Pt and W isotopes are affected by neutron capture reactions in the (epi)thermal energy range at large depths. Such data are lacking for ESP. The differentiation age of ESP parent body inferred from a non-corrected  $\varepsilon^{182}\text{W}$  value can be considered as a minimum age, most likely at least  $\sim 2$  Ma, but possibly 4 Ma, after CAI formation.

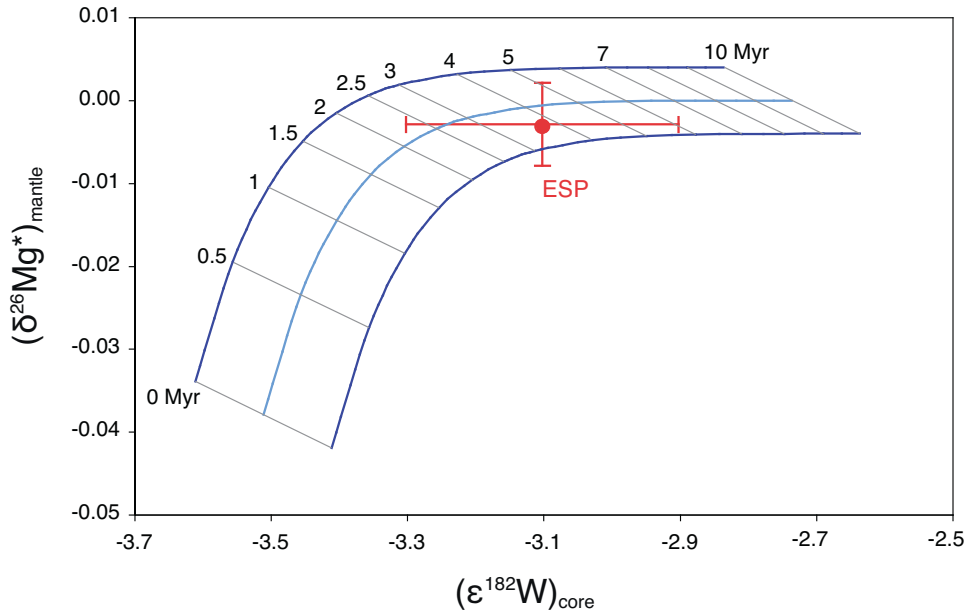


Fig. 3. (Colour online.) Theoretical evolution curves of radiogenic  $^{26}\text{Mg}^*$  in the mantle and  $^{182}\text{W}$  in the core of a chondritic parent body that underwent metal–silicate differentiation (light blue curve) as a function of the differentiation time (see text for details). Combining  $^{26}\text{Al}$ – $^{26}\text{Mg}$  and  $^{182}\text{Hf}$ – $^{182}\text{W}$  systematics allows us to constrain the metal–silicate differentiation age of the Eagle Station pallasite parent body. Metal segregation most likely occurred not earlier than  $\sim 2$  Ma, but possibly 4 Ma, after CAI formation. The error envelope (dark blue curves) is calculated from the 0.004 error on the  $(\delta^{26}\text{Mg}^*)_{\text{SSI}}$  value from data by Jacobsen et al. (2008) and the 0.1  $\epsilon$  error on the  $(\epsilon^{182}\text{W})_{\text{SSI}}$  value reported by Burkhardt et al. (2012).

The duration of olivine crystallization in the mantle of the ESP parent body can be further constrained from the observed range of  $\delta^{26}\text{Mg}^*$  values in olivine, assuming that olivine and metal in ESP originate from the same parent body. Olivine crystallization should progressively decrease the Mg/Al ratio of the remaining mantle. This is because Mg is compatible in olivine while Al is incompatible, with olivine–liquid partition coefficients ( $D_{\text{O1-Liq}}$ ) of  $\sim 8.5$  (Floss et al., 1996) and of  $0.006 (\pm 0.0005)$  (Grant and Wood, 2010), respectively. The present MC–SIMS measurements do show a significant range of variation for the  $^{27}\text{Al}/^{24}\text{Mg}$  ratio, from  $1.20 (\pm 0.16) \times 10^{-4}$  (in the polished section,  $n = 14$ ) to  $7.35 (\pm 0.94) \times 10^{-4}$  (average of analyses in the separated olivine grains ESP 1 ( $n = 6$ ) and ESP 2 ( $n = 6$ )), i.e. a factor-6 variation (Table 1). This range is best interpreted as reflecting magmatic differentiation due to progressive crystallization of olivines. Though evaporation loss of  $\sim 80\%$  of Mg from a magma ocean covering the ESP parent body could theoretically be responsible for this factor-6 variation, this is not consistent with the lack of significant  $\delta^{25}\text{Mg}$  variations in the olivines (Table 1). In order to change by this factor of 6 the  $^{27}\text{Al}/^{24}\text{Mg}$  ratio of the parent melts of the olivines, while keeping the  $(\delta^{26}\text{Mg}^*)_{\text{MC-SIMS}}$  value homogenous, at  $-0.011 (\pm 0.009)\%$ , the crystallization sequence has to be fast enough. Considering a core that could have differentiated as early as 2 Ma after CAIs (as shown by Fig. 3), this  $\sim 10$  ppm range indicates that olivine crystallization should have lasted no more than  $\sim 275$  kyr (Fig. 4); otherwise, the  $\delta^{26}\text{Mg}^*$  range in the olivines would have been larger than observed. However, the exact origin of MGP and of ESP, as well as the size of their parent bodies, remains

unknown (Boesenberg et al. (2012) and references therein). Models predict very different thermal histories for asteroids depending on their size (Bouvier et al., 2007; Hevey and Sanders, 2006; La Tourrette and Wasserburg, 1998), with mantles of objects of radii less than 10 km above the melting point of olivines for timescales  $< \sim 5$  Myr, while for asteroids of radii 25–50 km the silicate–silicate differentiation

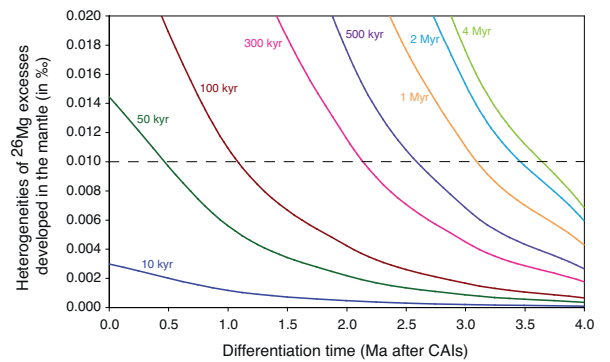


Fig. 4. (Colour online.) Difference  $((\delta^{26}\text{Mg}^*)_1 - \delta^{26}\text{Mg}^*)_{0.17}$  between the  $^{26}\text{Mg}^*$  excesses developed by a liquid with  $^{27}\text{Al}/^{24}\text{Mg} \sim 1$  (named  $(\delta^{26}\text{Mg}^*)_1$ ) and those developed by a liquid with  $^{27}\text{Al}/^{24}\text{Mg} = 0.17$  (named  $(\delta^{26}\text{Mg}^*)_{0.17}$ ), as a function of the differentiation time of the parent body and the duration of the olivine crystallization process (colored lines). The  $\sim 10$  ppm range (dashed line) on the  $(\delta^{26}\text{Mg}^*)_{\text{MC-SIMS}}$ , combined with a differentiation time for the ESP parent body occurring not earlier than  $\sim 2$  Ma after CAIs, indicates that the olivine crystallization process should have lasted over  $\sim 275$  kyr. At variance, if the core has differentiated 4 Ma after CAIs, then the silicate–silicate differentiation should have lasted for another 4 Myr.



could extend to 5–10 Ma (metallographic cooling rates of pallasites suggesting that the latter formed within bodies of radii less than 50 km (McSween, 1999)). The present Mg isotopic data (Fig. 4) implies that if core differentiation on the ESP parent body took place 4 Ma after CAIs, then olivine differentiation in the remaining mantle should have lasted for another 4 Myr. Such timescales have previously been proposed (Dauphas et al., 2005). We note, however, that an early disruption (at ~2 Ma after CAIs) of the ESP parent body would also be compatible with the present data.

At magmatic temperatures above 1200 °C (high enough for differentiation to take place), the diffusion coefficient of Mg in olivines is  $\sim 10^{-17}$  m<sup>2</sup>/s (Dohmen and Becker, 2007). This implies that Mg isotopic heterogeneities would have been erased in ~3 kyr over a distance of 1 mm and ~300 kyr over 1 cm. Thus, to preserve the 10-ppm Mg isotopic heterogeneities in olivines over the timescales predicted by Fig. 3, the present olivines should have been at least 10 cm distant one from the other. This is difficult to ascertain, but seems unlikely, considering that the olivines studied included one thin section and two separated grains for MC–SIMS analyses, and a part of another piece of the meteorite for HR–MC–ICPMS analyses. However, angular-olivine pallasites, such as the Eagle Station pallasite, are considered to have formed by mixing of fragments of mantle olivines with molten core metal during impacts (Scott and Taylor, 1990). It is thus quite possible that during the impact (Morbidelli, 2007), several meters distant olivines were mixed together with the metal.

## Acknowledgement

The authors would like to thank A. Bouvier and J. Aléon, whose contributions significantly improved the manuscript. This work was supported by a grant from the European Research Council (ERC grant FP7/2007–2013 Grant Agreement No. [226846] Cosmochemical Exploration of the first two Million Years of the Solar System Ñ CEMYSS). This is CRPG–CNRS contribution No. 2309.

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