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The thermal history of the Acapulco meteorite and its parent body deduced from U/Pb systematics in mineral separates and bulk rock fragments

Évolution thermique de la météorite Acapulco et de son corps parent, déduite de la systématique U/Pb dans des séparats minéraux et des fractions de roche

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ABSTRACT

U/Pb systematics of the Acapulco meteorite have been determined on phosphate and feldspar separates and on grain size fractions of bulk material. The latter show an enrichment of U and Th with respect to CI chondrites and a low (∼1) Th/U ratio. This is consistent with the model that the majority of U and Th was added early by a low temperature melt to the Acapulco precursor. The feldspar exhibits a Pb isotope composition that is close to the primordial Pb composition. Mineral separates and bulk fractions define a $^{207}Pb/^{206}Pb$ isochron. The age corresponds to 4555.9 ± 0.6 Ma. This age anchors the thermal evolution of the Acapulco parent body into an absolute time scale. Evaluation of the Hf/W and U/Pb records with the cooling rates deduced from mineralogical investigations confirms the idea that the Acapulco parent body was fragmented during its cooling. The U/Pb system precisely dates this break-up at 4556 ± 1 Ma.

RÉSUMÉ

La systématique U–Pb a été déterminée sur des séparats de phosphates et feldspath et sur des fractions tamisées de matériau global. Celui-ci est enrichi en U et en Th par rapport aux chondrites C1, avec un rapport Th/U : ∼1. Nous confirmons l'idée que l'essentiel de ces éléments a été introduit dans le précurseur d'Acapulco, par du matériau fondu de basse température. Le feldspath montre une composition isotopique de Pb proche de la composition primordiale. Les minéraux et les fractions de roche définissent une isochrone $^{207}Pb/^{206}Pb$ correspondant à un âge de $4555{,}9 \pm 0{,}6$ Ma. Cet âge permet de placer l'évolution thermique du corps-parent d'Acapulco dans une échelle de temps absolue. La confrontation des enregistrements des systèmes Hf–W et U–Pb, avec les vitesses de refroidissement déduites des études minéralogiques, confirme que ce corps parent a été fragmenté durant son refroidissement. Le système U–Pb permet de définir précisément la date de cette fragmentation à 4556 ± 1 Ma.

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1. Introduction

The inner planets of the solar system are considered to have formed from a swarm of planetesimals; meteorite parent bodies are witnesses of these early planetesimals. One of the major goals in studying meteorites is to define the accretion time scale and thermal history of their parent bodies and thus to elucidate the processes of planet formation.

Acapulcoites belong to the group of primitive achondrites and are believed to originate jointly with the closely related lodranites from a common parent body (McCoy et al., 1993). These meteorites experienced high temperatures and are highly metamorphosed and/or were partially molten. The temperature peak, ~1150 °C, is significantly higher than that estimated for the most highly equilibrated chondrites but lower than that estimated for differentiated meteorites. Acapulco is the only fall of this class. Its bulk chemical composition is similar to that of H chondrites, but it lacks chondrules and exhibits a coarsely granoblastic texture (Christophe Michel-Levy et al., 1978, 1979; Palme et al., 1981). The meteorite is unshocked and does not show evidence for disturbance after crystallization (McCoy et al., 1996). Although Acapulco experienced partial melting, it exhibits high abundances of volatiles and trapped noble gases (Palme et al., 1981). Indications for non-equilibrium, e.g. different nitrogen isotope compositions between metal and silicates and LREE- and U-excesses in phosphates with respect to silicates have been described (Kim and Marti, 1992, 1993; Zipfel et al., 1995).

The thermal history of the Acapulco parent body is heavily debated in the literature. Its cooling rate has been studied with a variety of mineralogical tools: Ca zoning in olivine (Köhler and Brey, 1990; Zipfel et al., 1995), Fe/Mg ordering in orthopyroxene (Zema et al., 1996), metallographic observations and Ni content in taenite (McCoy et al., 1996). Based on these investigations, the cooling of Acapulco was rapid, at least 10^3 °C/Ma in the temperature range between 650–350 °C (Min et al., 2003) and this fast cooling has been interpreted as being the consequence of the break-up of the Acapulco parent body (Zema et al., 1996).

In contrast, no consensus exists concerning the cooling rate below 350 °C. Low cooling rates, ~1–20 °C/Ma, have been deduced from ^{244}Pu fission track density and metallographic studies (Marti et al., 1994; Pellas and Fieni, 1992; Pellas et al., 1997). Also long-lived chronometers, U/Pb, K/Ar, and Sm/Nd, have been applied in order to constrain the thermal evolution (Amelin, 2005; Göpel et al., 1992; McCoy et al., 1996; Pellas et al., 1997; Prinzhofer et al., 1992; Renne, 2000). The ^{39}Ar/^{40}Ar age, 4514 ± 16 Ma, calculated with the ^{40}K decay constant recommended by Steiger and Jäger (1977), is ~50 Ma younger than the ^{207}Pb/^{206}Pb age of the phosphate (Pellas et al., 1997). This age difference defines a slow cooling rate corresponding to ~5 °C/Ma for the temperature interval 550–300 °C. However, Renne (2000) argued that the ^{39}Ar/^{40}Ar age becomes 4554 Ma, ~50 Ma older when the ^{40}K decay constant from Endt and van der Leun (1973) is used. This older age translates into a faster cooling rate and better agrees with the petrologic observations that support a rapid cooling. Trieloff et al. (2001) contested this approach, whereas Renne (2001) in response reiterated his arguments. Recently, new Hf/W data were published for two acapulcoites (Touboul et al., 2009). Touboul et al. (2009) estimate the Hf/W closure temperature at ~975 °C for cooling rates ~10^2 °C/Ma. These authors translate the relative Hf/W age into an absolute age, 4563.1 ± 0.8 Ma, using the U/Pb and Hf/W anchor of angrites. This age corresponds to the end of Hf/W reequilibration between metal and pyroxene.

The goal of this study is to evaluate the chemical history of the Acapulco meteorite with U/Th/Pb systematics and to better constrain the thermal history of its parent body at high temperatures, between ~1000–350 °C. The ^{207}Pb/^{206}Pb dating method is of particular interest since it permits age determinations with an uncertainty of ~1 Ma, allowing us to anchor this cooling history into an absolute time scale. This study is part of a collaborative work organized by K. Marti.

2. Sample preparation and analytical procedure

Two chips of Acapulco (1.67 and 0.89 g) were broken in a boron carbide mortar, metal was eliminated and the crushed fraction was sieved. This procedure was repeated until most of the sieved material was in the 100–200 and 200–400 mesh grain size ranges. The ground material was composed of a magnetic fraction (29.3 wt %), 100–200 mesh fraction (49.3 wt %), 200–400 mesh fraction (21.5 wt %) and a < 400 mesh fraction (0.3 wt %). Two aliquots from the 100–200 and one from the 200–400 mesh fraction were reserved for "bulk" U/Pb analysis. The rest of the material was processed on a Frantz magnetic separator and mineral separates were prepared from this aliquot.

The feldspar separate was washed prior to dissolution with acetone and leached with 0.5 M HBr. We used a mixed ^{205}Pb/^{233}U tracer for all samples, the U/Pb chemistry that was applied is described in Göpel et al. (1985) and Manhès et al. (1984). Total chemistry blanks correspond to 6.2×10^{-12} g Pb and 0.5×10^{-12} g U. Isotope measurements were performed on a Thomson CSF thermal ionization mass spectrometer (Birck and Allègre, 1973).

The Th content is not directly determined by isotopic dilution, it is derived from the measured Pb isotope composition, the measured U content and the ^{207}Pb/^{206}Pb age, assuming a Pb evolution in a closed system:

$$\left(\frac{^{232}\mathrm{Th}}{^{238}\mathrm{U}}\right) = \left(\frac{e^{\lambda t}-1}{e^{\lambda'' t}-1}\right) \times \left(\left(\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{\mathrm{meas}} - \left(\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{\mathrm{ini}}\right) / \left(\left(\frac{^{208}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{\mathrm{meas}} - \left(\frac{^{208}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{\mathrm{ini}}\right) \quad (1)$$

λ and λ" are the decay constants of ^{238}U and ^{232}Th, respectively, "meas" corresponds to the measured Pb isotopic ratio, "ini" to the initial composition of Acapulco. This initial isotopic composition is defined in this study and will be discussed in more detail in Section 3.2.

3. Results

U and Pb concentrations, Pb isotopic compositions as well as ^{207}Pb/^{206}Pb model ages, ^{238}U/^{204}Pb and ^{232}Th/^{238}U ratios of all analyzed samples are reported in Table 1.

Table 1
U–Pb systematics of Acapulco samples.

Tableau 1
Systématique U–Pb des échantillons d'Acapulco.

Sample	U	Pb	$^{238}U/^{204}Pb$	$^{232}Th/^{238}U$	$^{206}Pb/^{204}Pb$	$^{204}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	Pb/Pb age	ρ 4/6–7/6	ρ 4/6–8/6
Weight	(ppb) +	(ppb) +	+,†	*,†	$	+	+	+	(Ma) #		
feldspar 6.2 mg	0.05	2407.1	0.0009 ± 0.0007		9.346 ± 0.006	0.107070 ± 0.000079	1.10839 ± 0.00051	3.1536 ± 0.0023	6030 ± 120	−0.378	−0.521
fr 100 a 15.1 mg	82.3	440.4	12.761 ± 0.218	1.03	24.759 ± 0.019	0.040362 ± 0.000033	0.80431 ± 0.00029	1.3474 ± 0.0011	4562.0 ± 1.5	−0.506	−0.263
fr 100 b 11.5 mg	63.8	466.4	9.19 ± 0.07	1.55	23.125 ± 0.018	0.043231 ± 0.000034	0.81767 ± 0.00030	1.5029 ± 0.0010	4563.8 ± 1.6	−0.535	−0.613
fr 200 7.5 mg	157.2	786.5	13.32 ± 0.15	0.84	24.092 ± 0.025	0.041496 ± 0.000043	0.80934 ± 0.00045	1.3507 ± 0.0012	4561.8 ± 1.9	−0.079	−0.171
phosphate 1 6.1 mg	2760.9	5106.2	137.11 ± 1.13	0.56	148.02 ± 0.18	0.006751 ± 0.000008	0.65106 ± 0.00067	0.32864 ± 0.00037	4556.9 ± 1.7	0.200	0.068
phosphate 2 6.1 mg	2317.2	4362.2	127.38 ± 0.72	0.58	138.63 ± 0.41	0.007208 ± 0.000022	0.6525 ± 0.0020	0.3457 ± 0.0010	4555.3 ± 5.0	0.581	0.746
troilite 5.6 mg	3.7	108.9	1.72								
leachate feldspar 6.2 mg	0.03	2.9	0.44 ± 0.70	1.35	13.779 ± 0.051	0.0794 ± 0.0048	0.979 ± 0.023	2.426 ± 0.065	4556 ± 30	0.991	0.994

Experimental uncertainties correspond to 2 σ errors. +: all values are corrected for blank chemistry, mass fractionation and spike contribution; $: isotope ratio is corrected for mass discrimination and spike contribution; #: Pb/Pb age is calculated applying the primordial Pb isotopic composition from Tatsumoto et al. (1973); *: Th/U ratio is calculated applying the primordial Pb isotopic composition from Tatsumoto et al. (1973) and assuming an evolution in a closed system since 4556 Ma; †: atomic ratio; ρ is the correlation factor between the uncertainties of the corresponding isotope ratios.

3.1. Budget of U, Th and Pb in Acapulco

The phosphate separate was dissolved in two steps. Therefore, the successive dissolution steps, "Phos 1" and "Phos 2", each one representing roughly half of the total sample, should be combined. The abundances for the combined phosphate are: 9.5 ppm Pb, 2.8 ppm Th and 5.1 ppm U; the $^{238}U/^{204}Pb$ ratio and the $^{232}Th/^{238}U$ ratio correspond to 132.5 and 0.57, respectively. The Th/U ratio allows us to discriminate between the two phosphates that are present in meteorites. Apatite exhibits low ratios (< 1) whereas whitlockite is characterized by high ($\sim$10) values (Crozaz, 1974; Göpel et al., 1994). Based on this record we deduce that the mineral separate studied here consists mainly of apatite, which is in agreement with Zipfel et al. (1995).

The feldspar is characterized by a high Pb and a low U abundance, translating into a low $^{238}U/^{204}Pb$ ratio.

Because of an abnormally high procedural blank, the Pb isotope composition of the troilite separate is not well determined and will not be considered in the following. U and Pb abundances determined for this mineral, however, allow us to use them as upper limits in the budget calculation of the bulk meteorite presented below.

The grain size fractions display variable Pb, U, Th concentrations but similar Pb isotope compositions; this can be explained by slight variations in their modal mineralogy. In order to minimize this mineralogical effect, we calculate a more representative bulk sample for Acapulco. It is calculated based on the distribution of the different grain size fractions taking their weight proportion into account (details in section "sample preparation"). We assumed that the metal that was eliminated during the grinding step, contains negligible amounts of U, Th and Pb. Then this reconstituted bulk Acapulco material exhibits the following concentrations: 0.39 ppm Pb, 70.1 ppb U and 72.8 ppb Th. The atomic $^{238}U/^{204}Pb$ and $^{232}Th/^{238}U$ ratios correspond to 12.1 and 1.07, respectively. These U and Th concentrations are in agreement with the "Acapulco average" defined by Palme et al. (1981) and Zipfel et al. (1995). Compared to CI carbonaceous chondrites (Tatsumoto et al., 1976), the reconstituted bulk material of Acapulco is enriched in U and Th by a factor of 8.5 and 2.6, respectively, whereas ^{204}Pb is depleted by a factor of 10.5. The $^{232}Th/^{238}U$ ratio, $\sim$1, is unusual for undifferentiated meteorites, in that their Th/U ratios range between 3.5 and 4.

Understanding the distribution of U, Th and nonradiogenic Pb among the different mineral phases is essential in interpreting the chronometric information. Two groups published the modal mineralogy of this meteorite (Palme et al., 1981; Zipfel et al., 1995). For our budget calculation, the following U, Th, Pb values are applied: bulk sample: 4.9 ppb ^{204}Pb, 70.1 ppb U, 72.8 ppb Th; phosphate: 33 ppb ^{204}Pb, 5.1 ppm U, 2.8 ppm Th; feldspar: 47 ppb ^{204}Pb, 0.05 ppb U; troilite: $<$ 1.8 ppb ^{204}Pb, 3.7 ppb U.

Based on the mineral composition published by Palme et al. (1981) phosphates account for $\sim$100% U, 54% Th and 9.3% ^{204}Pb. Feldspar contains 84% of ^{204}Pb and $<$ 0.01% U, troilite $<$ 1% ^{204}Pb and $<$ 0.2% U. Using the modal mineral composition defined by Zipfel et al. (1995), we find that phosphate contains 73% U, 39% Th and 6.6% ^{204}Pb, feldspar accounts for 90% of ^{204}Pb and $<$ 0.01 % U, troilite holds less than 2.9% ^{204}Pb and less than 0.4% U.

Both evaluations show that phosphate and feldspar jointly represent the major hosts for U, nonradiogenic Pb and for a significant part of Th in the Acapulco meteorite. Therefore, the interpretation of the U/Pb chronology can be based on the U/Pb systematics measured in the bulk material, the feldspar and phosphate.

3.2. U/Pb isotope systematics

The Pb isotope composition of the feldspar lies very close to the primordial Pb composition that was measured in the Canyon Diablo iron meteorite (Göpel et al., 1985; Tatsumoto et al., 1973) (Table 1). This is the first time that such an unradiogenic composition is directly measured in undifferentiated high temperature material. The Pb isotope evolution of the solar system is almost linear during the first hundred million years. The composition of the Acapulco feldspar falls close to this "instantaneous" Pb evolution

$$\frac{d^{207}\mathrm{Pb}}{d^{206}\mathrm{Pb}} = \left[\left(\frac{1}{137}\right) \times \left(\frac{\lambda'}{\lambda}\right) \times \left(\frac{e^{\lambda' 4.57}}{e^{\lambda 4.57}}\right)\right]$$

that is issued from the primordial Pb composition and may be the result from a short (~10 Ma) evolution of the primordial Pb composition. The nominal value of the initial Acapulco Pb composition, representing the Pb composition between minerals when the internal U/Pb equilibration occurred, is defined as the intersection between the ~4.57 Ga Pb evolution line starting from the primordial Pb isotope composition with the internal Acapulco isochron: $^{206}Pb/^{204}Pb = 9.3336$, $^{207}Pb/^{204}Pb = 10.3483$, $^{208}Pb/^{204}Pb = 29.4533$.

The Pb isotope compositions of the phosphate samples are radiogenic with $^{206}Pb/^{204}Pb$ values > 138. The $^{207}Pb/^{206}Pb$ model ages, assuming a primordial Pb composition (Tatsumoto et al., 1973) for the initial Pb, are similar: 4556.9 ± 1.7 Ma for Phos 1, 4555.3 ± 5.0 Ma for Phos 2. The $^{207}Pb/^{206}Pb$ model ages are slightly higher than the corresponding single stage $^{238}U/^{206}Pb$ and $^{235}U/^{207}Pb$ model ages indicating a discordance of 1.4% (Phos 1) and 1.0% (Phos 2). Two phosphates out of six published by Amelin (2005) also show a discordant behavior, that lies in the same order of magnitude.

The bulk material shows slightly radiogenic Pb compositions. Its $^{207}Pb/^{206}Pb$ model age is calculated assuming a single stage evolution starting from the primordial Pb composition. The $^{207}Pb/^{206}Pb$ age of the reconstituted Acapulco bulk material corresponds to 4562.0 ± 1.6 Ma and dates the closure of the U/Pb system at the whole rock scale. The $^{238}U/^{206}Pb$ ages (4815–5917 Ma) and $^{235}U/^{207}Pb$ model ages (4638–4945 Ma) are higher than the corresponding $^{207}Pb/^{206}Pb$ model ages, indicating an excess of radiogenic Pb. It corresponds in the reconstituated bulk Acapulco to 18%.

3.3. Internal $^{207}Pb/^{206}Pb$ age of Acapulco

The Pb isotope compositions of all samples define a line in the $^{207}Pb/^{206}Pb$ versus $^{204}Pb/^{206}Pb$ space (Fig. 1 and Table 2). The bulk sieved fraction plot on the isochron that is defined by the phosphate and feldspar. This shows that all minerals in Acapulco, beside the feldspar and phosphate, exhibit an identical $^{207}Pb/^{206}Pb$ age and that the addition of radiogenic Pb, present in excess in the bulk material, must have occurred recently, most probably during the excavation of the meteorite from its parent body (Manhès et al., 1984).

Different linear regressions, including or not including the grain size fractions into the calculation, are reported in Table 2. The similarity between the different ages confirms the isotopic consistency between bulk material and mineral separates. The $^{207}Pb/^{206}Pb$ age based on all samples analyzed in this study corresponds to 4556.4 ± 1.1 Ma; the age calculated only with phosphate data from Amelin (2005) corresponds to 4556.5 ± 1.3 Ma. When the phosphate

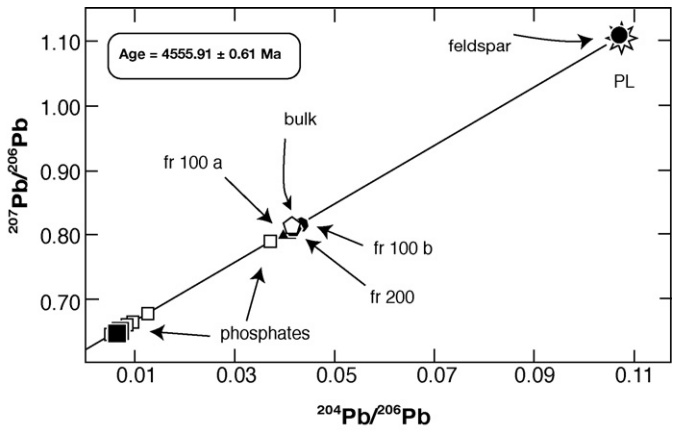

Fig. 1. $^{207}Pb/^{206}Pb$ versus $^{204}Pb/^{206}Pb$ isotope diagram for Acapulco samples. Phosphates analyzed in this study (solid squares), phosphate data published by Amelin (2005) (open squares), grain size fractions (solid symbols), and feldspar separate (circle) define a linear array in this diagram. "Bulk Acapulco" (defined in section 3.1) is represented by a pentagon. The primordial Pb isotope composition (PL) measured by Tatsumoto et al. (1973) is symbolized as a star. The size of all symbols is larger than the analytical uncertainties.

Fig. 1. Diagramme isotopique $^{204}Pb/^{206}Pb$ versus $^{207}Pb/^{206}Pb$ pour les échantillons d'Acapulco. Le phosphate analysé durant cette étude (carrés pleins), les phosphates publiées par Amelin (2005) (carrés vides), les fractions de matériau global (lozanges) et le feldspath (cercle plein) définissent un alignement. Le matériau « bulk» Acapulco (défini dans la partie 3.1) est représenté par un pentagone vide. La composition isotopique primordiale de Pb (PL), mesurée par Tatsumoto et al. (1973) est illustrée par une étoile. La taille des symboles est plus grande que l'incertitude analytique.

Table 2
Isochron regressions based on Acapulco mineral separates and grain size fractions.

Tableau 2
Isochrones définies par régression linéaire des analyses d'Acapulco.

Samples used for regression calculation	Slope	Intercept	MSWD	Probability	Age [Ma]
fr100 a, fr200, fr100 b, phos1, phos2, feldspar	4.5593 ± 0.0093	0.62033 ± 0.00046	0.65	0.63	4556.4 ± 1.1
fr100 a, fr200, fr100 b, phos1, phos2, feldspar, 6 phoshates*	4.5622 ± 0.0067	0.62014 ± 0.00026	0.85	0.58	4555.9 ± 0.6
phos1, phos2, feldspar	4.5594 ± 0.0094	0.62022 ± 0.00066	0.39	0.53	4556.1 ± 1.5

Linear regressions are calculated with Isoplot/Ex vs3.41 from Ludwig (2003); *6 phosphate data from Amelin (2005).

data from Amelin (2005) and our analyses are used together in this regression, the $^{207}Pb/^{206}Pb$ age is defined with a smaller uncertainty, 4555.9 ± 0.6 Ma. This age records the end of the U/Pb re-equilibration between the minerals of Acapulco and more specifically it indicates the end of the Pb diffusion outside of the phosphate.

4. Discussion

The Pb isotope systematics of Acapulco bulk material, phosphate and feldspar are consistent: U/Pb closure at the whole rock scale occurred at ~4562 Ma, whereas the internal U/Pb re-equilibration occurred or ended at 4556 Ma, 6 Ma later. In the following, we discuss the different events that are registered by the U/Pb system.

4.1. Enrichment of U and Th in bulk Acapulco

Zipfel et al. (1995) point out that the Acapulco bulk exhibits large excesses of LREEs and U and show that phosphates are the main carriers for these elements. However, these authors explicitly rule out a direct addition of phosphate. Such an addition would have concomitantly induced major gains in Ca and P, but the Ca/Mg and P/Mg ratios of bulk Acapulco are approximately chondritic. Therefore, they propose that a melt, rich in incompatible elements, infiltrated Acapulco at such low temperature (~800 °C) that equilibrium among different minerals could not be reached. LREEs and U were extracted by phosphates from this melt while the remaining melt, that was rich in all other incompatible elements, subsequently drained away and left Acapulco (Zipfel et al., 1995). Using Zipfel's model, we estimate the amount of U and Th that were added to the bulk sample. Compatible refractory elements (Sc, Al, Y) are enriched in Acapulco by a factor of 1.43 with respect to CI material. We assume that Acapulco prior to the melt intrusion is equally enriched in Th and U and characterized by a Th/U of 3.5 similar to CI. The calculated abundances of the Acapulco precursor correspond to 11.7 ppb U and 40.9 ppb Th. The amount of U and Th that had been added by the melt is calculated by subtracting these abundances from the measured U (70.1 ppb) and calculated Th abundances (72.8 ppb) and corresponds to 58.4 ppb U and 31.9 ppb Th. Both elements, U and Th, have been added to the bulk rock with a low Th/U ratio (0.55); this ratio is similar to that found in the Acapulco phosphates. Therefore, we propose that the melt selectively mobilized U, Th and LREEs out of the phosphates from the Acapulco parent body, these elements migrated and were incorporated during the formation of apatite. No other incompatible elements have migrated into Acapulco.

4.2. $^{207}Pb/^{206}Pb$ age of Acapulco

Two questions arise when one tries to elucidate the early events that led to the Pb depletion of the Acapulco bulk material:

- Did the melt that infiltrated Acapulco add Pb together with U, Th and LREEs? No experimental data are available that allow us to denote the behavior of Pb.
- Is the Pb depletion related to nebular processes and/or to Pb loss during the high temperature regime in the Acapulco parent body?

Based on the U/Pb record alone, we cannot answer this question. The age of 4562 Ma of bulk Acapulco may be related to nebular processes (partial condensation or partial evaporation of solar dust), or to planetary processes (thermal closure during the high temperature regime of Acapulco, incorporation of U and eventually Pb by melt percolation). If the melt did not incorporate Pb at all, the $^{207}Pb/^{206}Pb$ age of Acapulco bulk material dates the melt percolation, because the majority of U was added by this melt. On the other hand, if the melt mobilized Pb as well as U and if Acapulco incorporated Pb and U in similar proportions, this $^{207}Pb/^{206}Pb$ age does not register the melt percolation but the age is related to a U/Pb fractionation that occurred previously.

The comparison between U/Pb and $^{182}Hf/^{182}W$ data obtained on two acapulcoites partially resolves the ambiguity concerning the meaning of $^{207}Pb/^{206}Pb$ age of the Acapulco bulk (Touboul et al., 2009). The "absolute" Hf/W age of these samples corresponds to 4563.1 ± 0.8 Ma, this age indicates the end of the Hf/W equilibration between metal and silicate (Touboul et al., 2009). Consequently, the younger $^{207}Pb/^{206}Pb$ age of the Acapulco bulk is not related to the end of equilibration with the nebular gas but it dates the U/Pb closure at the whole rock scale or it dates the melt intrusion during the cooling of the Acapulco parent body.

4.3. Cooling history of the Acapulco parent body

Comparing the Hf/W and U/Pb thermochronometries with mineralogical cooling rates allows us to better

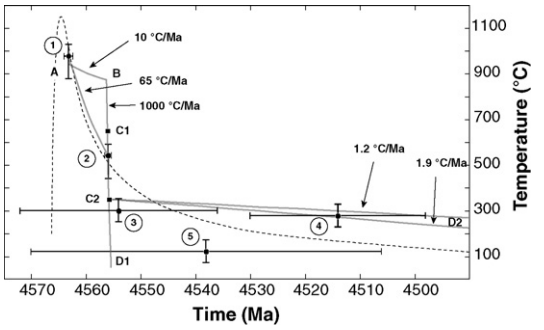

Fig. 2. Cooling history of the Acapulco parent body. Age data from acapulcoites and the Acapulco meteorite are plotted versus the closure temperature of the respective isotopic system. The values (1–5) used in this figure are taken from Touboul et al. (2009) for the Hf/W (1), this study for U/Pb (2), from Renne (2000) for old K/Ar (3), from Pellas et al. (1997) for young K/Ar (4), and from Min et al. (2003) for the U–Th/He ages (5). The segment C1–C2 represents the rapid cooling corresponding to 1000 °C/Ma in the temperature range of 650–350 °C and is based on mineralogical tools: it necessarily crosses point (2) (U/Pb). The two distinct cooling regimes of Acapulco, between ~1000 and 350 °C, are illustrated by two different paths (A-B-C2) and (1-2-C2). They depend on the initial size of the parent body and the position of Acapulco within this parent body. For temperatures < 350 °C, two different paths are indicated. •) The cooling rate stays rapid (segment C2-D1) crossing the K/Ar closure (3) as suggested by Renne (2000) and the U–Th/He closure (5) according to Min et al. (2003) or •) the cooling rate decreases < 2 °C/Ma (segment C2-D2) crossing the K/Ar point (4) from Pellas et al. (1997) and the closure indicated by the ^{244}Pu fission tracks record at 4.41 Ga according to Pellas et al. (1997) (not shown). For comparison the thermal evolution of Acapulco in a preserved body proposed by (Touboul et al., 2009: Fig. 5e) and which relies on radiometric records only, is shown as a dashed line.

Fig. 2. Refroidissement du corps-parent d'Acapulco. Les points (entourés d'un cercle) (1 à 5) représentent les fermetures thermiques des systèmes Hf/W (1) (Touboul et al., 2009), U/Pb (2) [cette étude], K/Ar (3) selon Renne (2000), K/Ar (4) selon Pellas et al. (1997), U–Th/He (5) (Min et al., 2003). Le segment C1-C2 illustre le refroidissement rapide, à 1000 °C/Ma, entre 650 et 350 °C, déduit des études minéralogiques : il passe nécessairement par le point 2 (U/Pb). Le refroidissement d'Acapulco entre ~1000 et 350 °C comprend deux régimes ; il est illustré par deux chemins (A-B-C2) et (1-2-C2), selon la taille initiale du corps parent et l'emplacement d'Acapulco dans ce corps-parent. Dans le domaine de températures inférieures à 350 °C : ou le refroidissement continue rapidement (segment C2-D1) passant par les fermetures K-Ar (4) (Renne, 2000) et U–Th/He (5) (Min et al., 2003)), ou le refroidissement est ralenti à une température inférieure à 2 °C/Ma (segment C2-D2) passant par la fermeture du K-Ar (Pellas et al., 1997) et la fermeture indiquée par l'enregistrement des traces de fission de ^{244}Pu à 4,41 Ga (Pellas et al., 1997), non reportée ici). Pour comparaison, la courbe en pointillé illustre une évolution thermique d'Acapulco dans un corps-parent préservé, proposée par Touboul et al. (2009) (Fig. 5e) sur la base des enregistrements radiométriques seulement.

constrain the thermal history of the Acapulco parent for the temperature range ~1000–350 °C. This is shown in Fig. 2.

The internal ^{207}Pb/^{206}Pb age of Acapulco corresponds to the end of Pb diffusion out of the apatite. This closure temperature is deduced from Pb diffusion experiments on terrestrial apatites (Cherniak et al., 1991) taking the crystal size of the phosphates (~200 μm) into account. For cooling rates of 1, 10, 10^2 and 10^3 °C/Ma the closure temperature corresponds to ~445, 490, 540 and 585 °C, respectively. The closure temperature of the U/Pb system lies between 650 °C and 350 °C, where high cooling rates, at least 10^3 °C/Ma, are recorded by mineralogical investigations. Therefore, the internal ^{207}Pb/^{206}Pb age precisely dates when Acapulco cooled rapidly. This is not the case for the other chronologies (Hf/W, K/Ar and U/Th–He) whose closure temperatures lie outside the temperature range 650–350 °C where mineralogical tools record the fast cooling. The mean cooling rate between the closure of the Hf/W system at 4563.1 ± 0.8 Ma and the U/Pb system at 4555.9 ± 0.6 Ma can be calculated. This time interval (7.2 ± 1.0 Ma) and the closure temperatures of the Hf/W system (985 ± 50 °C) and U/Pb system (525 ± 50 °C) define a mean cooling rate of ~ 65 ± 15 °C/Ma. This cooling rate is more than one order of magnitude slower than the minimum cooling rate of 10^3 °C/Ma suggested by Min et al. (2003). Such distinct cooling rates in an overlapping temperature range (650–520 °C) are incompatible with a model of a continuously cooling and undisrupted parent body. Combining the information derived from the U/Pb and Hf/W system with mineralogically determined cooling rates requires the break-up of the Acapulco parent body, as proposed by Min et al. (2003) and Renne (2000). Therefore, the cooling rate of Acapulco before the disrupture of the parent body is not constrained and may vary from a few up to ~10^2 °C/Ma. The size of the Acapulco parent body and the position of Acapulco inside this parent body (i.e. near the surface or deeply embedded) is less constrained than suggested by Touboul et al. (2009) whose model is only based on radiochronometric records.

The time when the parent body broke up can be precisely established from the U/Pb closure age (4555.9 ± 0.6 Ma) and the cooling rate (10^3 °C/Ma). This event may have occurred 0.4 Ma before the closure of the U/Pb (if Acapulco's cooling rate corresponded to ~10 °C/Ma) or at the time of the U–Pb closure. Therefore the break-up of the Acapulco parent body is dated at 4555.9 $^{+0.8}/_{-0.6}$ Ma.

Acapulco may have continued to cool rapidly until 120 °C inside a small fragment as supported by Min et al. (2003) and Renne (2000). On the other hand, when the ages obtained from ^{244}Pu fission track studies and Ar ages calculated with the decay constant from Steiger and Jäger (1977) are taken into account, then Acapulco must have been buried in a re-agglomarated large body in order to explain the low cooling rate, < 2 °C/Ma, between 350 °C and the retention of ^{244}Pu fission tracks at ~120 °C.

5. Conclusion

The U–Th–Pb systematics of separated minerals and in bulk fractions of Acapulco define major events of the chemical and thermal history of its parent body.

For an undifferentiated meteorite, Acapulco exhibits high U and Th abundances with an unusual Th/U ratio of ~1. It was proposed that the main part of these elements was added early to the Acapulco precursor by a low temperature melt. We support this idea and suggest that this melt selectively extracted U, Th and LREEs from phosphates. Subsequently, these elements migrated into Acapulco and were incorporated by phosphates when they crystallized. The low Th/U ratio determined for the Acapulco bulk, is the result of this melting event. It occurred between 4562 Ma and 4556 Ma.

The feldspar contains the frozen Pb composition of Acapulco at 4556 Ma, it lies close to the primordial Pb

composition (Göpel et al., 1985; Tatsumoto et al., 1973). The small difference with this primordial composition can be explained by the decay of U and Th during ~10 Ma, before 4556 Ma, the end of U/Pb re-equilibration in Acapulco.

The comparison between Hf/W ages determined in acapulcoites and the U/Pb age in Acapulco as well as cooling rates determined with mineralogical tools for Acapulco support the idea that the break-up of the parent body occurred during the cooling period. This event is precisely dated with the U/Pb system at 4556 ± 1 Ma. The initial size of the parent body and/or the position of Acapulco inside this parent body are poorly constrained.

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