THE CHRONOLOGY OF BASALTIC METEORITES AND THE HISTORY OF THEIR PARENT BODIES.
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Basaltic meteorites probably sample at least six different asteroidal parent bodies, based on oxyen isotope [1] and geochemical signatures. They comprise two main groups (the eucrites and angrites), a suite of basaltic clasts in mesosiderites and three apparently unique examples, namely Asuka 881394, Ibitira, and Northwest Africa 011. Published ages of these meteorites, based on four high-resolution chronometers (^{207}Pb-^{206}Pb, ^{26}Al-^{26}Mg, ^{53}Mn-^{53}Cr and ^{182}Hf-^{182}W) are summarised in Fig. 1. The ages are of two types, whole-rock (W-R) and mineral isochron ages.

W-R ages include ^{53}Mn-^{53}Cr and ^{182}Hf-^{182}W bulk meteorite isochrons [2-4] and also ^{26}Al-^{26}Mg model ages which are two point isochrons passing through bulk meteorite and an inferred chondritic source [5, 6]. W-R ages, regardless of parent body, are about 3 to 4 Myr after CAIs and correspond to an idealized stage when the basalts in a given parent body were chemically heterogeneous but isotopically homogeneous. We suggest that the W-R ages may date the local extraction of melt fractions with differing degrees of partial melting from a homogeneous parent body source.

Mineral isochrons are in many cases close to, or up to 1 or 2 Myr younger than, W-R ages (4 to 5 Myr after CAIs) [e.g. 2, 7-14]. They date the last time of isotopic equilibration between minerals, and can provide good estimates of crystallization ages of rapidly cooled basalts. In the latter case, to account for the slightly younger ages, we suggest the magma may have remained trapped for a while within the parent body after it segregated but before it erupted and crystallized.

Younger ages of 9 Myr characterise a sub-set of texturally equilibrated angrites, presumably reflecting their slow cooling [e.g. 2, 7, 12]. A wide range of still younger ages in eucrites probably result from late isotopic disturbance or resetting, perhaps related to slow cooling or impact heating [2].

Sahara 99555 [6] and Asuka 881394 [8] have anomalously old ^{207}Pb-^{206}Pb ages < 1 Myr after CAIs. Sahara 99555 now has a revised younger age, close to that of D'Orbigny [9], casting doubt on a claim that CAIs were formed about 3 Myr earlier that this, at 4569.5 Myr ago [6]. Asuka 881394 remains enigmatic, and is the subject of ongoing investigation.

The tight clustering of mineral isochron ages between 4 and 5 Myr demonstrates concordance, within error, between the four chronometers, and it implies uniform distribution in the accretion disk of the parent nuclides, ^{26}Al, ^{53}Mn and ^{182}Hf. Age concordance has been reinforced by recent ^{182}Hf-^{182}W isochrons for angrites, not plotted on Fig. 1 [7]. This, along with independent evidence for the uniform distribution of ^{26}Al in the disk [15], is very significant because it implies widespread and inevitable meltdown of early-accreted bodies due to ^{26}Al heating.

Knowing that parent bodies of iron meteorites had melted within just 0.5 Myr after CAIs [14, 16] the segregation of basalt, at 3 to 4 Myr after CAIs, is a little puzzling. A solution may be found in simple thermal modelling of the parent bodies, assuming an ^{26}Al heat source. Our calculations, based on assumptions in [17] suggest that where a parent body accreted very early (< 1 Myr after CAIs) it would quickly have overheated and become a global magma ocean undergoing convection. The dense metal would evidently have segregated quickly, accounting for the highly unradiogenic tungsten in magmatic irons. By 3 to 4 Myr, after substantial crystallization of the magma ocean, basalt would, we predict, have remained as a *residual* interstitial melt, in a locked-up crystal mush. In some way, the basalt would then have been drawn off in batches and migrated upwards. On the other hand, where a parent body accreted later, at say 1.5 Myr, (Fig. 2) then *partial melting* would have yielded basaltic magma, by 3 to 4 Myr, in a straightforward way. Thus the consistent ages of basaltic meteorites may be purely a function of the decline in heating power of ^{26}Al, regardless of how early accretion occurred. After all, while tungsten anomalies imply very early core formation they tell us nothing of when continued heating and melting in the overlying silicate mantle finally ended.

Basaltic meteorites show large depletions in moderately volatile elements . We suggest that this cosmochemical signature is inherited from their parent bodies that perhaps accreted, as 'second-generation' bodies, from the volatile-depleted ejecta of early giant impacts, in the manner inferred by [18-20]. This kind of two-stage accretion model is also consistent with Hf-W isochrons of eucrites [4] and angrites [7], both of which pass above the position of primitive chondrites. These basalts could not, therefore, have a chondritic source, but require instead a source with a pre-accretion history giving inflated (supra-chondritic) Hf/W such as being in the mantle of a first generation body.

Returning to the issue of very old ^{207}Pb-^{206}Pb ages, we proposed earlier [21] that these recorded Pb loss during early impact-induce volatile depletion. This now appears doubtful since ^{207}Pb-^{206}Pb ages are strictly isochron ages that date fractionation of Pb and U between pyroxene and other minerals at the time of crystallization.

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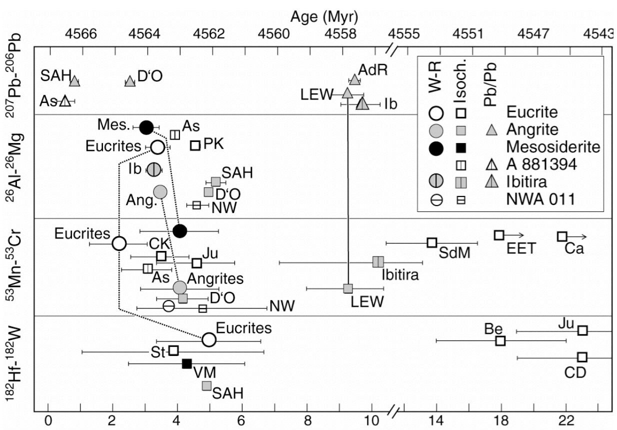

Fig. 1 Compilation of published ages of meteoritic basalts. ^{53}Mn-^{53}Cr relative ages are tied to ^{207}Pb-^{206}Pb ages using LEW 86010 [2, 12]; ^{26}Al-^{26}Mg, and ^{182}Hf-^{182}W relative ages are tied to ^{207}Pb-^{206}Pb ages using CAIs as an anchor [14, 22]. Abbreviation: SAH – Sahara 99555, D'O – D'Orbigny, AdR – Angra dos Reis, LEW – LEW 86010, As – Asuka 881394, Ib – Ibitira, Mes. – basalt clasts in mesosiderites, PK – Piplia Kalan, Ang. – angrites, NW – NWA 011, CK – Chervony Kut, Ju – Juvinas, SdM – Serra de Magé, EET – EET87520, Ca – Caldera, Be – Bereba, CD – Camel Donga, St – Stannern, VM – Vaca Muerta. Not all data sources have been cited in the reference list.

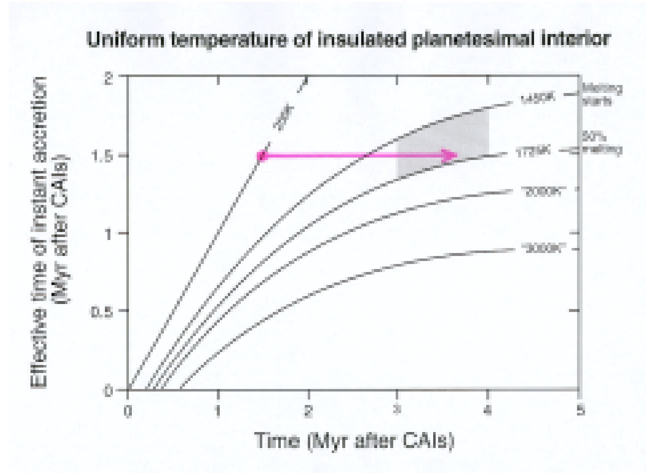

Fig. 2 . Time (in Myr after CAI formation) when a particular uniform temperature is reached throughout the insulated interior of a planetary body of dry chondritic composition, as a function of the time when accretion takes place. ^{26}Al is the only heat source, and the starting temperature is 250 K. Planetesimals up to a few hundred km across are envisaged. Thermal parameters are those used in [17] but with a decay energy of 3 MeV per atom. Partial melting and basalt production occurs in the shaded area between 1450 K (the solidus) and 1725 K (corresponding to 50% melting). Accretion at 1.5 Myr leads to partial melting between about 3 and 4 Myr, marked by an arrow. Accretion at 2 Myr will not lead to any melting. Accretion at 0.5 Myr would theoretically lead to temperatures exceeding 3000 K by 2 Myr, but in practice a global magma ocean is predicted to develop [17] and will lose heat rapidly by convection, keeping its temperature below the liquidus (1850 K). Once ^{26}Al has largely gone, the ocean will gradually freeze and basalt will remain for a while as a residual liquid between the solid silicate grains. This stage is estimated to occur, again, between about 3 and 4 Myr.