

daughter) isotope composition of the silicate Earth to be displaced from the array defined by undifferentiated meteorites. The extent of this displacement would depend on the time of fractionation. Therefore, the lead isotope composition of the bulk silicate Earth (BSE), if it were precisely known, could serve to estimate the timing of core formation²; however, it is not well known. This is because homogenization as a result of mantle stirring has not been sufficiently fast to eradicate the isotopic heterogeneities that reflect differences in time-integrated U/Pb ratios between parts of the silicate Earth. Attempts to obtain a precise mass balance of the heterogeneous mantle and crustal reservoirs are bedevilled by the unknown masses of reservoirs with characteristic lead isotope compositions.

Specifically, terrestrial lead isotope evolution models have been presented for the crust–mantle system³. In the preferred solution for these, a timescale for core segregation of 60 Myr after Solar System formation, based on the then (1997) prevailing interpretation of chondritic tungsten isotope data⁴ (later shown to be erroneous^{5,6}), was used as an imposed constraint³. This yielded the BSE lead isotope composition estimate shown as KT 97 in Fig. 3 of Wood and Halliday¹. Using this value to derive a core-formation age is therefore circular. The core-formation timescale is not a

critical parameter for terrestrial Pb modelling (Fig. 9 of ref. 3). The much faster core formation now implied by tungsten-isotope models^{5–7} is equally consistent with the lead data.

The BSE lead-isotope estimate MKC 03 (in Fig. 3 of Wood and Halliday¹) was a by-product of finding a refined solution to the first lead-isotope paradox⁸. It depends on the core-formation age preferred by Murphy *et al.*⁸, who maintain that the slope of the calculated 'geochron' corresponds to an age of 4,503 Myr and that this implies catastrophic core formation within about 65 Myr. Wood and Halliday's model¹ returns exactly that age for their proposed stage of lead loss with a late sulphide melt. Again, the argument is circular.

These examples show that it is not possible to determine the lead isotope composition of BSE directly with sufficient precision to constrain a relatively short time interval at the beginning of Earth's history. Early work on the 'U–Pb age' of Earth⁹, which required implausibly protracted core formation (200 Myr), historically influenced all estimates for the lead isotope composition of BSE. Six of the 11 estimates used by Wood and Halliday¹ were published before 1990 and yield an average time of core formation of 91 Myr. The five more recent estimates return a faster average core-formation date of 61 Myr. This demonstrates that, as we learn to appreciate the complexity of terres-

trial differentiation¹⁰, our estimates of the BSE lead isotope composition are moving closer to the meteorite isochron than was previously thought possible⁹. It may be that the true BSE lead composition is compatible with tungsten isotope constraints for very rapid (that is, ≤ 30 Myr) accretion and core formation. We therefore find no solid observational evidence for the complex core-formation process proposed by Wood and Halliday¹.

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GEOCHEMISTRY

Wood & Halliday reply

Replying to: Q.-Z. Yin & S. B. Jacobsen *Nature* **443**, doi: 10.1038/nature05358 (2006) ; B. S. Kamber & J. D. Kramers *Nature* **443**, doi: 10.1038/nature05359 (2006)

Yin and Jacobsen¹ and Kamber and Kramers² highlight several issues to do with the tungsten (W) and lead (Pb) isotopic chronometry of terrestrial accretion and core segregation, although none of these affect our model or conclusions³. Yin and Jacobsen¹ suggest that it is not clear from our analysis³ that ^{182}Hf – ^{182}W provides a reliable system of chronometry for the bulk of core formation, whereas $^{235/238}\text{U}$ – $^{207/206}\text{Pb}$ relates to the very last stage of sulphide segregation — which was exactly our point³ and is clarified here.

The concern of Yin and Jacobsen¹ that we used different versions of Fig. 1^{3,4} to illustrate scenarios for the accretion of the Earth is addressed in the respective figure captions and texts^{3,4}, which demonstrate the wide range of different kinds of accretion model that underlie the W and Pb isotope modelling. There is no inconsistency. None of the accretion curves shown is likely to represent the actual growth of the Earth, which is underconstrained. ^{182}Hf – ^{182}W chronometry does not provide a unique mass accretion and core-formation history of the Earth^{4,5}.

The difficulties both sets of authors raise^{1,2}

about the determination of the average Pb isotopic composition of the bulk silicate Earth (BSE) are correct, but these are well known and illustrated by the range of existing estimates^{4–6}. They have not prevented Pb isotope estimates being made and inferences drawn about their significance^{6,7}. Explanations for certain facets of the Pb paradox that are based on melting and recycling of material within the BSE are irrelevant; they cannot change the average composition. Either all 11 of these estimates, and the Pb isotope space between them, are incorrect, or the timing and mechanism of U/Pb and Hf/W fractionation are different, with $^{235/238}\text{U}$ – $^{207/206}\text{Pb}$ always yielding longer timescales^{3–7}. This is not a random scatter that reflects a poorer ability to determine the average Pb isotopic composition of the BSE. Rather, there is a systematic offset that provides evidence for a different fractionating process, or a systematic error, as we state^{3,4}. Yin and Jacobsen¹ agree with this¹; Kamber and Kramers² do not, but do not explain how this discrepancy can be eliminated.

The weak constraints on the μ_{TOTE} of the Earth are well known^{4–7}. We used³ an esti-

mate⁷ based on chondrite volatile depletion trends⁴. Estimates based on half-mass condensation temperature (see ref. 6, for example) are slightly higher⁸, but these increase the discrepancy between the timing deduced from $^{235/238}\text{U}$ – $^{207/206}\text{Pb}$ and ^{182}Hf – ^{182}W (ref. 4). Our arguments are, if anything, conservative.

Kamber and Kramers² point out that ^{182}Hf – ^{182}W constraints have been used to determine the average Pb isotopic composition of the BSE^{9,10}. It would have been better not to use their estimates because of the circularity involved. Based on partitioning, the approach of using ^{182}Hf – ^{182}W to predict the Pb isotopic composition of the BSE is flawed³. Our concern was mainly to demonstrate that all estimates were consistent with our model. The three most recent estimates attributable to Kamber and Kramers are similar to the average of the eight earlier, more varied, estimates (see ref. 4). The means of the two-stage model ages are 67 and 81 Myr, respectively, whereas the equivalent calculation for ^{182}Hf – ^{182}W yields about 30 Myr (ref. 11).

Although Kamber and Kramers² clarify how they made their estimates and Yin and Jacobsen¹

reiterate the importance of the ^{182}Hf – ^{182}W system, this does not change any major aspect of our paper. In closing, we point out two inaccuracies in their comments.

Yin and Jacobsen¹ claim that the age of the Moon is well constrained by ^{182}Hf – ^{182}W to about 30 Myr, citing six papers, none of which contains an analysis of a lunar sample and one of which preceded the first data. The ^{182}Hf – ^{182}W age of the Moon is 30 to 55 Myr^{12–14}. If it were earlier, the W isotopic effects would be greater; if it were later, there would be no radiogenic effects. A more precise age will not be determined until the initial and average W isotopic compositions of the Moon, which were derived from an unknown mixture of the silicate Earth and the silicate and metal reservoirs of Theia, are known. An estimate of 40–50 Myr has been used^{3,4}, based on the least radiogenic lunar tungsten to be found so far^{4,5,12–14}; a similar estimate of 30 to 50 Myr was based on the apparent radiogenic ingrowth within lunar reservoirs¹⁴. But there is no basis for stating that it is about 30 Myr.

Kamber and Kramers² claim that the time of core formation was previously constrained to about 60 Myr (ref. 9) on the basis of W isotopic data¹⁵. This is incorrect, because at that time no difference in W isotopic composition between chondrites and the BSE had been resolved. Even now that accurate chondrite data have been acquired, the meaning of the difference between chondrites and the BSE needs to be interpreted in terms of other constraints, such as Pb isotopes. If not, the W isotopic difference could be interpreted in terms of half the core forming at the start of the Solar System and the other half during the Battle of Hastings.

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