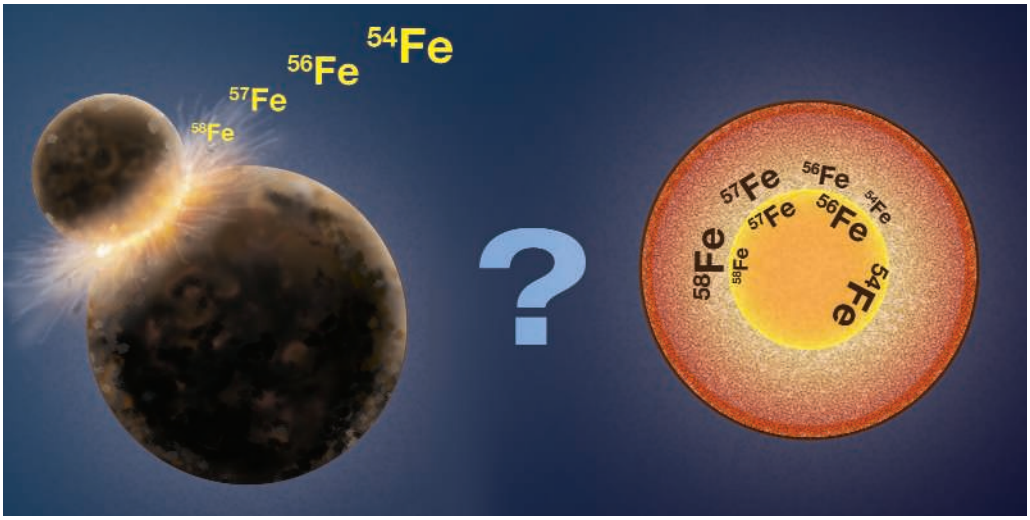
GEOCHEMISTRY

Probes of the Ancient and the Inaccessible

Iron isotopes may be witnesses of the interplanetary impact that formed the Moon or probes of processes occurring at Earth's core-mantle interface.

Franck Poitrasson

The Earth-Moon system was found to have an iron isotope composition enriched with heavier isotopes relative to meteorites, including those thought to originate from Mars (*1*). This isotopic difference was interpreted as fingerprints of a giant impact between the early Earth and a smaller planet, which resulted in the formation of the Moon. Such a high-energy event likely involved partial planet vaporization that would have led to the loss of the lighter Fe isotopes to space, resulting in Earth and the Moon being enriched in the remaining heavy Fe isotopes (see the figure, left panel). On page 912 of this issue, Polyakov (*2*) proposes an alternative interpretation for the difference in isotopic composition. Studying minerals under conditions occurring near Earth's core-mantle boundary, he considers the possible effects of pressures above 100 GPa on the Fe isotope fractionation process between minerals.



Isotope fractionation. Currently proposed explanations of the heavy Fe isotope composition of the Earth-Moon system relative to meteorites. (**Left**) Giant interplanetary impact that led to the formation of the Moon and was accompanied by the preferential loss to space of light iron isotopes. (**Right**) High-pressure core-mantle fractionation that results in the enrichment of light iron isotopes in the metallic core and heavy iron isotopes in Earth's mantle. Symbol size is proportional to isotopic relative enrichment.

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Studying the early Earth remains a challenge because of the very few remaining witnesses after 4.5 billion years of geological history. Equally challenging is the study of processes occurring at depths of 2900 km, near the core-mantle boundary. Iron isotope geochemistry may provide an approach to learn about these difficult problems.

Taking current estimates of the deep mantle mineralogical composition, Polyakov (*2*) uses computed Fe isotope fractionation factors at 130 GPa and 4000 K of postperovskite [(Fe,Mg)SiO$_3$], ferropericlase [(Fe,Mg)O], and metallic iron to propose that the Earth-Moon heavier Fe isotope composition relative to other planetary bodies may simply be explained by Earth's core-mantle equilibration at the very high pressures found at depths of 2900 km (see the figure, right panel). Although this idea has already been raised (*3*, *4*), Polyakov takes into account the effect of the very high pressures occurring in the deep mantle on the Fe isotope fractionation between minerals.

If confirmed, this finding has important implications for our understanding of Earth's early differentiation and bulk composition estimates. The current paradigm envisions a final metal-silicate equilibration in a magma ocean several hundred kilometers deep, prior to metallic core segregation from the silicate mantle (*5*). Recent experimental evidence suggests that such a process should not affect Fe isotope signatures of Earth materials (*6*), in agreement with previous conclusions reached from meteorite studies (*7*). However, if we follow Polyakov's interpretation that the heavier Fe isotope composition of the Earth-Moon system results from the equilibration of a metallic core and a silicate mantle, it implies that the early terrestrial magma ocean model cannot lead to a correct understanding of the bulk silicate Earth composition. This has ramifications for our knowledge of deep Earth interior properties and for models of Earth's origins.

However, the original finding was that whereas Earth is isotopically heavier than meteorites and other planets, the Moon bulk Fe isotope composition estimate is actually twice as heavy as that of Earth (*1*). This topic was subsequently hotly debated (*8*–*10*) and remains an open question. Part of the discussion revolves around whether certain types of lunar basalts, characterized by either their low or high content of Ti, were produced through an as yet unknown magmatic process that may affect Fe isotope signatures. If the heavier Fe isotope composition of the Moon relative to Earth is confirmed, it follows that the high-pressure metal-silicate Fe isotope fractionation process proposed by Polyakov cannot alone explain the Fe isotope systematics between planets; the Moon is only 1% of the mass of Earth, so the required high pressures in the interior could not be achieved. Depending on the level of homogenization of the whole mantle, another possible outcome of Polyakov's prediction is that basalts from volcanoes, sampling zones from the deeper mantle known as "hot spots," should be isotopically heavier than the vast majority of the basalts originating from the shallower mantle. However, the current database does not support this (*1*, *3*, *11*). Although Fe isotope variations were recently found in an evolving Hawaiian mafic lava lake, possibly linked to kinetic processes specific to this geological

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setting (*12*), this database shows that it is an uncommon feature in mafic igneous rocks. Contrary to Weyer's assertions (*13*), terrestrial bulk mafic rocks generally do not show Fe isotope variations through differentiation: They are characterized by a very homogeneous Fe isotope composition (*1*, *3*, *11*).

Further work is therefore required to understand this apparent contradiction between Polyakov's predictions and our current knowledge of the Fe isotope signatures of igneous rocks. For instance, new ab initio techniques have correctly reproduced the iron isotope fractionation observed experimentally between aqueous species (*14*). Polyakov's Fe isotope fractionation factors between minerals, based on spectroscopies (*15*), should therefore be subjected to such computations. Also, estimating the isotopic composition of the silicate portion of a planet on the basis of a few samples taken at the surface remains a challenge, and this implies that a correct understanding of iron isotope fractionation laws between minerals in magmatic systems has yet to be properly established. The work on bulk planetary stable iron isotope estimates and systematics is promising, as it may eventually lead us to see the Moon's igneous history or Earth's deep mantle processes in a new light.

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CELL BIOLOGY

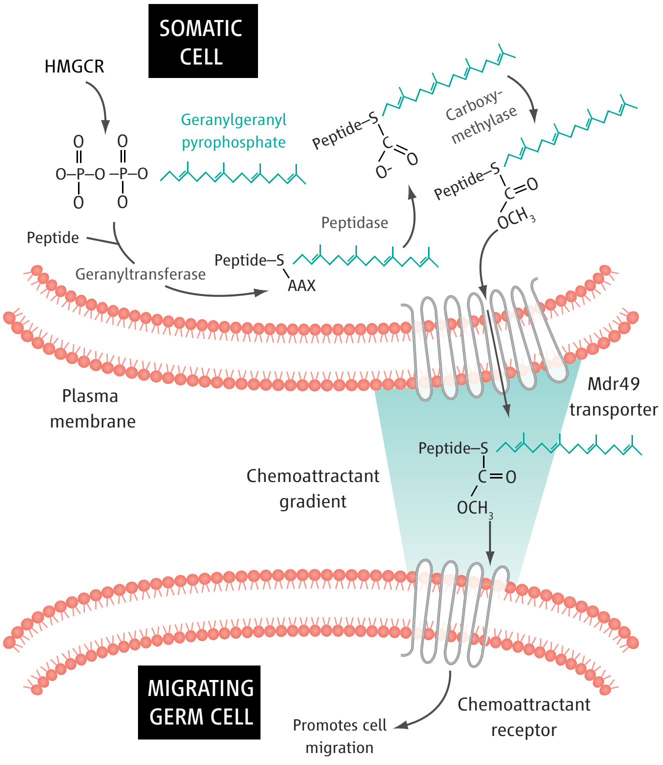
The ABCs of Lipophile Transport

Proteins pump lipophilic molecules out of cells, establishing gradients that guide cell movement during development.

Timothy Hla[1] and Dong-Soon Im[1,2]

During animal development, certain embryonic cells export lipophilic molecules into their surroundings to guide tissue and organ formation. Two proteins that function as cellular transporters for such molecules have now been identified. On page 943 of this issue, Ricardo and Lehmann characterize a transporter in the fruit fly *Drosophila melanogaster* that exports a lipophilic molecule essential for germ cell migration (*1*). In another study, Kawahara *et al.* identify a transporter in the zebrafish *Danio rerio* that exports a lipophilic molecule to direct muscle cell movement during heart development (*2*). The findings underscore the generality and importance of cellular export mechanisms for molecules that presumably establish precise gradients in space and time to control cell migration.

In *Drosophila*, germ cells migrate toward somatic gonadal precursor cells to form gonads. The process is controlled by the activity of an enzyme in the somatic gonadal precursor cells, 3-hydroxy-3-methylglutaryl coenzyme A reductase (HMGCR), which catalyzes the formation of a lipophilic geranylgeranyl moiety that is added posttranslationally to the carboxyl termini of peptides. Loss of functional HMGCR, or its misexpression in the wrong cell type, results in aberrant migration of germ cells and defective gonad formation (*3*). Ricardo and Lehmann show that an ABC-type transporter, Mdr49, acts downstream of HMGCR. It turns out that Ste6p, an ABC-type transporter in yeast cells (*Saccharomyces cerevisiae*), exports a mating factor that is also geranylgeranylated. The authors determined that Ste6p could substitute functionally in *Drosophila* cells lacking Mdr49. Remarkably, orthologs of other enzymes involved in the yeast mating factor export pathway—prenylated peptide protease and carboxymethylase—are also required for germ cell migration toward somatic gonad precursor cells (see the figure). The findings not only suggest that the lipophile export machinery is conserved in evolution, but also that the germ cell chemoattractant may be structurally similar to a yeast mating factor (a geranylgeranylated peptide). A challenge will be to elucidate the structure of the germ cell chemoattractant.



Go that way. Somatic cells in the developing fly gonad secrete a lipophilic molecule (geranylgeranylated peptide) using the transporter Mdr49. A molecular gradient is established that attracts germ cells by activating receptors for the chemoattractant. AAX (A, Ala; X, any amino acid).

The germ cell migratory system in *Drosophila* also relies on the lipid phosphate phosphatase enzymes Wunen-1 and -2, which dephos-

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