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GEOCHEMISTRY

A dash of deep nebula on the rocks

The cocktail of noble-gas isotopes in an Icelandic rock suggests that the upper mantle does not, and never did, receive gas from a deeper mantle reservoir. This challenges ideas of deep Earth's behaviour and formation. SEE LETTER P.101

CHRIS J. BALLENTINE

The pattern of isotopic abundances of inert and rare noble gases, trapped in small bubbles in volcanic rock, act as a 'fingerprint' of how and where our planet first acquired its gas. Furthermore, the type of volcanic setting, and the way that parts of the fingerprint change with time, offer insight into the workings of deep Earth. Squeezing out this information from lava derived from the deepest parts of our planet — possibly some 2,900 kilometres beneath our feet — is a challenge. Yet this is precisely what S. Mukhopadhyay[1] has done, and in spectacular fashion. On page 101 of this issue, he reports the long-awaited detailed secrets of the planet's deepest gases, based on an isotope analysis performed using a new-generation mass spectrometer.

Helium is light enough to be lost from the atmosphere to space, and so its atmospheric concentration is very low. Its isotopic composition in mantle rocks (measured as the ratio of the gas's two isotopes, ^4He and ^3He) is therefore the easiest to ascertain of all the noble gases, because measurements are not swamped by background 'noise' from contaminating atmospheric helium. The $^4He/^3He$ ratios at mid-ocean ridges — the 65,000 km of interconnected underwater volcanic systems that spew magma from the uppermost mantle to build new ocean crust — are almost constant around the globe. But lower ratios have been measured in rocks produced by certain 'hotspot' volcanoes, such as those in Hawaii and Iceland, which are thought to tap the deepest mantle.

The existence of different $^4He/^3He$ ratios underpins the idea that there are at least two geochemical reservoirs in the mantle[2]: a deep reservoir rich in gases and volatile compounds feeds material into an upper reservoir, which is the convecting part of the mantle that supplies magma to mid-ocean ridges (Fig. 1). Although ideas about the depth, size and nature of the deepest reservoir have changed substantially, the two-reservoir model has dominated attempts to explain observations of mantle geochemistry for the past 30 years.

Obtaining robust information about the isotopic composition of the heavy noble gases in the mantle (neon, argon, krypton and xenon) has been far harder to do than it was for helium. This is because the atmospheric concentrations of these gases are much higher than that of helium, greatly increasing the background noise caused by air contamination of mantle samples. (No magma can erupt into the ocean or the atmosphere without the resulting basalt rock becoming contaminated by air — it would be like jumping into a swimming pool and expecting to stay dry.) Our detailed understanding of the upper mantle's heavy noble gases has therefore come almost entirely from only two rare samples in which such contamination is minimized: a single gas-rich basalt dredged from the mid-Atlantic ridge[3]; and volcanic gas trapped in a deep carbon dioxide gas field[4,5] in New Mexico.

Even fewer traces of noble gases are found in basalts produced by hotspot volcanism than in those produced at mid-ocean ridges[6], making hotspot rocks highly susceptible to air contamination. However, in one area of Iceland, a basalt has been found[7] in which more mantle gas is known to have been preserved than in most basalts, in part because it erupted under an ice cap. Mukhopadhyay[1] has now re-examined this basalt by applying a technique that allows large samples of the rock to be crushed under vacuum (to protect the isotopic fingerprint of gases in the rock from air contamination), and then analysing the released gases using one of a new generation of mass spectrometers that greatly increases the precision with which isotope ratios are measured[5]. In this way, he has teased out a veritable cornucopia of fresh information.

The isotopic composition of neon in the basalt suggests that the deep Iceland mantle gases originated from the solar nebula — the cloud of dust and gas from which the planets of the Solar System formed. Such gas was around only for the first few tens of millions of years

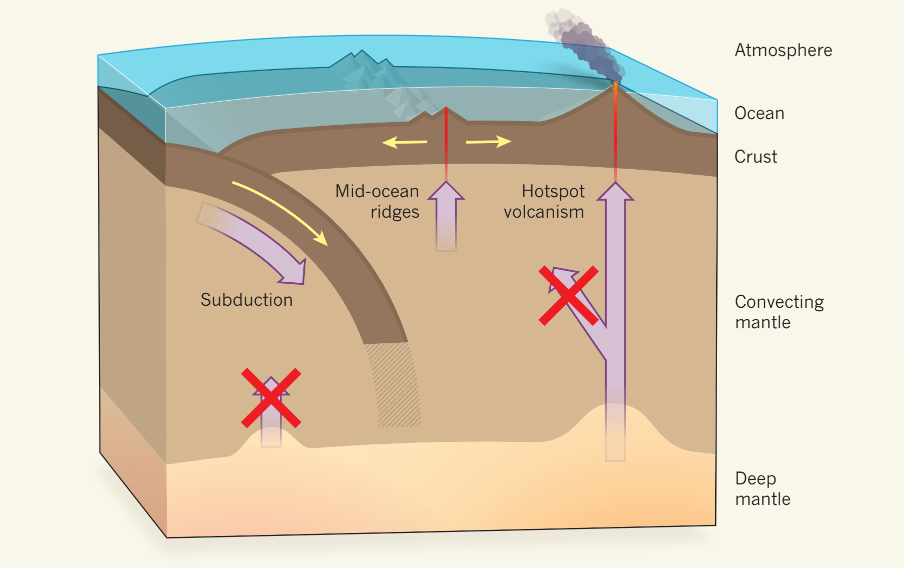

Figure 1 | Mantle movement. Magma from the upper part of the convecting mantle erupts at mid-ocean ridges, whereas that from a deep reservoir is thought to erupt at 'hotspot' volcanoes. Subduction processes transfer material from the ocean crust back into the convecting mantle, and possibly also into the deep mantle. The isotopic composition and amount of helium in the upper mantle suggest a flux of ^3He through this region[13], entering from the deep reservoir and exiting to the oceans and atmosphere. Mukhopadhyay reports[1] that the isotopic and elemental compositions of noble gases from an Iceland mantle plume that is thought to originate from the deep mantle are fundamentally different from those in the convecting mantle. If the Iceland plume is representative of the deep-mantle reservoir, this rules out the possibility of a large transfer of noble gases from the deep to the convecting mantle (red crosses), overturning a long-standing model of mantle-gas geochemistry. Yellow arrows, crust movement; pink arrows, gas transport.

of the Solar System's formation, after which it was either pulled into the Sun or blasted out of the Solar System when the Sun ignited. By contrast, the noble gases in the upper mantle came from meteorites[4,5]. Mukhopadhyay's findings, together with those of others, allow us to appreciate the true complexity of gas delivery to our planet from different sources at different stages of Earth's infancy[1,4,5,8].

But the questions of how gas from the solar nebula was trapped in the solid parts of growing planets, and how the gas was preserved through early accretionary events, will certainly test our models of accretion. Some of the noble-gas isotopes from the Icelandic deep mantle came from long-dead radioactive isotopes of iodine and plutonium that were present in the early Solar System. Mukhopadhyay[1] compared these noble-gas isotopes with those in the convecting mantle[9], and concluded that the Iceland deep mantle formed in a drier environment, and preserved a higher proportion of its plutonium-decay gases, than did the convecting mantle. This chimes with the idea of a process or location in the deep mantle that has preserved the earliest geochemical signals of accretion exceptionally well. Mukhopadyay's findings may also help to connect theories of how a planet starts to obtain its gas with evidence[10] from other isotope systems that also points to the very early formation of reservoirs hidden in the deep mantle.

Although many geochemists have argued that Earth contains a deep, gas-rich reservoir, they have struggled to pinpoint where it should be. Ever since it became apparent from seismic tomography that Earth's mantle was not nicely layered[11], the location or processes that could prevent such a deep reservoir from mixing into the convecting mantle and disappearing completely have remained enigmatic. Wherever this reservoir might be, it has survived the cataclysmic Moon-forming event (in which Earth was struck by a Mars-sized body)[12]; avoided mixing with volatile compounds brought to Earth by meteorites; and withstood continual removal of material by mantle plumes.

One result from Mukhopadhyay's work is touched on only lightly by the author, but might have the greatest impact on how we think the mantle behaves. If the isotopic composition of the basalt analysed by Mukhopadhyay — and therefore of the Iceland plume from which this hotspot rock is derived — is indeed representative of a deep mantle reservoir, then this reservoir cannot also be the source of ^{3}He needed to explain the ^{4}He/^{3}He ratio in the upper mantle, because the heavy noble gases in the basalt don't match those in the upper mantle. The two-reservoir mantle model must therefore be modified. Mukhopadhyay's data about the cocktail of mantle noble gases, however, will endure. ■

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NEUROSCIENCE

Sibling neurons bond to share sensations

Two studies show how electrical coupling between sister neurons in the developing cerebral cortex might help them to link up into columnar microcircuits that process related sensory information. SEE LETTERS P.113 & P.118

THOMAS D. MRSIC-FLOGEL & TOBIAS BONHOEFFER

A pioneering set of experiments in the 1950s and 1960s inspired generations of neuroscientists to explore how the anatomy of the brain gives rise to its function[1–3]. When researchers lowered electrodes into the cerebral cortices of cats and monkeys, they found that neurons lying above and below each other form functional columns — that is, they respond in a similar way to certain stimuli, such as touch on specific areas of the skin or the orientation of an elongated visual stimulus.

Even though such cortical columns have long been considered to be exemplars of basic computational units of cortical organization, the precise relationship between their anatomy and function has been difficult to define and remains the subject of debate[4–5]. This is particularly true in rodents, in which the cortex seems to lack functional columns almost entirely. What is common to rodents and other mammals, however, is a highly specific organization of cortical connections that link neurons across layers in the cortex to relay and process related sensory information[6–8]. Reporting in this issue, Yu *et al.*[9] (page 113) and Li *et al.*[10] (page 118) reveal some of the developmental events that could give rise to such precisely arranged functional circuits.

It has long been known that, during embryonic development of the cortex, neuronal progenitor cells give birth to daughter cells that migrate towards the brain surface to form strings of 'sibling' neurons that span the cortical layers (Fig. 1a). These radially aligned clones, referred to as radial units or ontogenetic columns, have been proposed to constitute the basis of the functional columns in the mature brain[11]. However, a direct link between cellular lineage, microcircuit development and the sensory preference of neurons had not been demonstrated.

Yu and colleagues[9] used viruses to label sibling neurons in the developing cortex of mouse embryos with a fluorescent protein, and then recorded the cells' electrical activity in brain slices prepared shortly after birth. The authors showed that gap junctions — small pores that couple adjacent cells electrically by bridging their membranes — formed transiently between sibling neurons in the same radial unit, very early in development (Fig. 1b). Gap junctions had previously been observed between clusters of excitatory neurons in the developing cortex and had been proposed to contribute to the establishment of neuronal assemblies[12], but the ancestry and significance of such cell clusters were unknown. Moreover, other work had revealed that, later in development, neurons in radial clones mostly connect to one another through chemical synapses[13] mediated by neurotransmitter molecules (Fig. 1c). Yu *et al.* showed that gap-junction inactivation abolished the formation of such synapses, and report that transient electrical coupling is thus essential for the establishment of chemical synapses between sibling neurons.

Li and colleagues[10] used the same method to label radial clones, and then used a microscopy technique known as two-photon calcium imaging[14] to monitor the activity of sibling neurons in the cortex of live mice in response to visual stimuli. The authors observed that clonally related neurons, when compared with a random subset of neighbouring cells,