Neurobiology and Cognition, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria.
e-mail: tecfitch@mac.com

1. Herodotus *The Histories* (Penguin, 1964).
2. Lenneberg, E. H. *Biological Foundations of Language* (Wiley, 1967).
3. Kuhl, P. K. *Nature Rev. Neurosci.* **5,** 831–843 (2004).
4. Fehér, O., Wang, H., Saar, S., Mitra, P. P. & Tchernichovski, O. *Nature* **459,** 564–568 (2009).
5. Goldin-Meadow, S. & Mylander, C. *Nature* **391,** 279–281 (1998).
6. Mühlhäusler, P. *Pidgin and Creole Linguistics* revised edn (Univ. Westminster Press, 1997).
7. Sandler, W., Meir, I., Padden, C. & Aronoff, M. *Proc. Natl Acad. Sci. USA* **102,** 2661–2665 (2005).
8. Senghas, A., Kita, S. & Özyürek, A. *Science* **305,** 1779–1782 (2004).
9. Darwin, C. *The Descent of Man, and Selection in Relation to Sex* 1st edn (John Murray, 1871).
10. Marler, P. & Slabbekoorn, H. *Nature's Music: The Science of Birdsong* (Academic, 2004).
11. Marler, P. in *The Epigenesis of Mind: Essays on Biology and Cognition* (eds Carey, S. & Gelman, R.) 37–66 (Lawrence Erlbaum Associates, 1991).
12. Senghas, A. & Coppola, M. *Psychol. Sci.* **12,** 323–328 (2002).
13. Jarvis, E. D. *Ann. NY Acad. Sci.* **1016,** 749–777 (2004).
14. Nottebohm, F. *Ann. NY Acad. Sci.* **280,** 643–649 (1976).
15. Haesler, S. *et al. PLoS Biol.* **5,** e321 (2007).

EARTH SCIENCE

Restoration of the noble gases

Tim Elliott

The noble gases emitted from deep inside the Earth have been sending mixed messages to those intent on deciphering them. A model that promises to help clear up the confusion is now on offer.

Geochemists have long taken a close interest in emissions from the bowels of the Earth. In particular, analyses of noble gases emanating from the mantle have been prominent in shaping models of Earth's structure. Lately, these data have seemed to be more paradoxical than illuminating, but Gonnermann and Mukhopadhyay (page 560 of this issue)[1] have revisited this puzzle and, by adding a new twist to an old concept, help us come to terms again with our planet's gassy innards.

Gas is continuously lost from Earth's interior, being carried to the surface in magmas produced by melting of the shallow mantle. The abundances and isotopic compositions of the trace amounts of noble gases thus erupted provide clues to Earth's evolution. In this field of study, the natural isotopic variability of helium has had an especially influential role. Helium has two stable isotopes, ^{3}He and ^{4}He. Earth's complement of ^{3}He was acquired during the planet's formation, whereas ^{4}He has been produced throughout Earth's history by the decay of the naturally occurring radionuclides of uranium and thorium. Thus, the ^{4}He/^{3}He ratio increases with time, with a magnitude dependent on the (U+Th)/He ratio.

It is well established that the ^{4}He/^{3}He ratios of magma from many ocean islands (such as Hawaii) are significantly lower than those of magma erupted at submarine mid-oceanic ridges. This observation has been thought to reflect 'degassing' of the upper mantle as a result of melting and crust formation at mid-ocean ridges, driven by the spreading of tectonic plates (Fig. 1a). Magma transports helium, uranium and thorium from the mantle to the surface. Although helium is ultimately lost to the atmosphere, non-volatile uranium and thorium remain in the crust to be subsequently returned to the mantle by plate subduction. Hence, the mantle involved in the plate-tectonic cycle attains a higher (U+Th)/He ratio and so evolves to higher ^{4}He/^{3}He ratios than any unmolested, 'primitive' mantle. The low ^{4}He/^{3}He ratio evident in some ocean islands was thus taken to reflect their derivation from such a primitive source that had been convectively isolated from the rest of the mantle. This meshed with the idea that ocean islands are the surface manifestation of mantle plumes that, like the wax in lava lamps, rise by thermal buoyancy from a deep, hot boundary layer (Fig. 1b).

Imagination can be allowed to run further riot within this conceptually appealing model. Early estimates of the composition of the continental crust suggested that it might have been derived from melting of the upper third of the mantle. This fraction spookily corresponds to the proportion of the mantle above a notable seismic feature at a depth of 660 kilometres. So the notion of a layered mantle was born, with the 660-km discontinuity dividing 'depleted' upper mantle from 'primitive' lower mantle (Fig. 2a). The calling card of the lower mantle was its low ^{4}He/^{3}He ratio, and this ratio acquired a mystical significance, such that it is even traditionally expressed in the opposite way to all other radiogenic isotope ratios (that is, as ^{3}He/^{4}He, with the isotope produced by radioactive decay in the denominator).

Although the layered-mantle model also helped to account for a series of other notable observations of noble gases (refs 2, 3, for example), it has proved inconsistent with geochemical constraints provided by much of the rest of the periodic table. There is little evidence for any extant primitive mantle as assessed from a wide range of non-volatile element abundance and isotope ratios (ref. 4, for example). Moreover, seismological studies convincingly demonstrated[5] that the 660-km discontinuity is not a boundary to mantle flow, and so the notion that primitive mantle can be preserved in the lower mantle became untenable (Fig. 2b). Thus, some researchers[6,7] have argued for an entirely different mechanism for creating low ^{4}He/^{3}He ratios in the mantle. Yet noble-gas mythology is deep-rooted, and others have rebranded the layered mantle with a deeper boundary[8], or suggested that we live in a unique time in which long-term layering has only just been breached[9]. So it has increasingly seemed that noble-gas

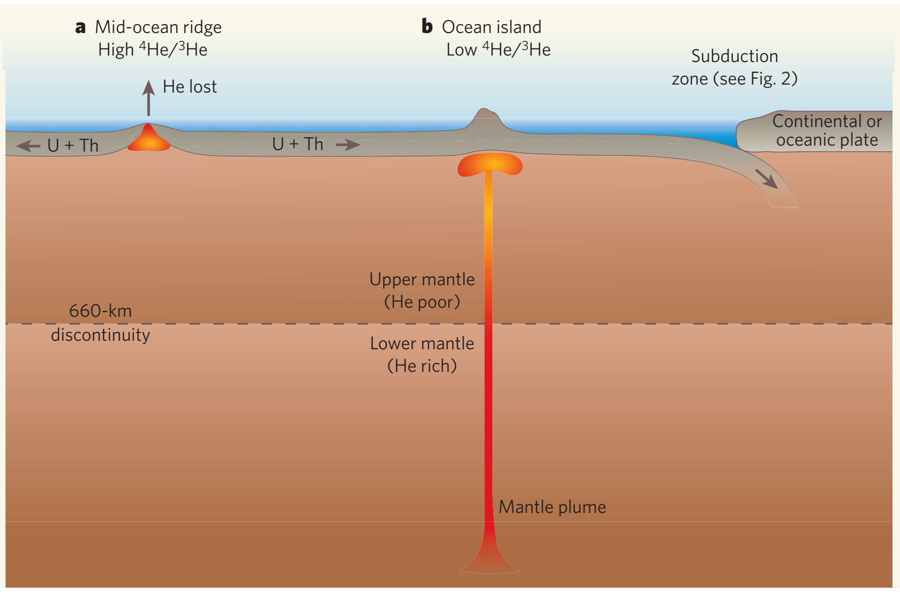

Figure 1 | Isotope ratios and Earth's mantle. a, As oceanic plates are pulled apart at mid-ocean ridges, the upper mantle rises in their place and (partially) melts. Uranium, thorium and helium in this portion of mantle are transferred to the magma, which migrates to the surface to form crust. Helium is lost during crystallization of the melts, but uranium and thorium are retained in the crust and are ultimately returned to the mantle by plate subduction (Fig. 2). Thus, the upper mantle becomes 'degassed' and the (U+Th)/He ratio increases, which with time translates into higher ^{4}He/^{3}H ratios. **b,** By contrast, ocean islands show a low ^{4}He/^{3}He ratio, thought to reflect a deep-mantle source of underlying mantle plumes. Graphic not to scale.

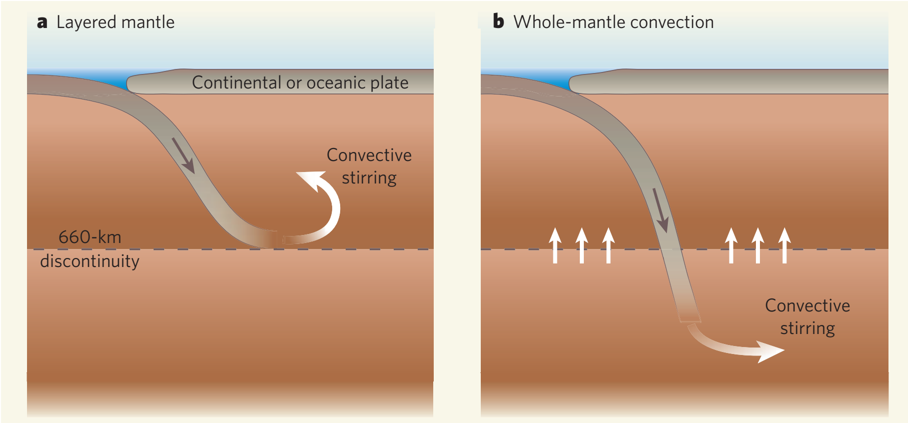

Figure 2 | The subduction connection. a, Models of noble-gas evolution have classically implied that only the upper mantle is effectively degassed[2,3], with the 660-kilometre seismic discontinuity producing a layered mantle by representing a boundary to the subduction of plates and the flow of material into the deep mantle. **b,** Seismological images[5], however, now provide strong evidence that plates can penetrate into the lower mantle, with the associated counterflow producing whole-mantle convection. The model of Gonnermann and Mukhopadhyay[1] shows that, contrary to many expectations, this mode of whole-mantle convection is quite compatible with observations of helium isotopes and other noble gases. Graphic not to scale.

measurements pose more questions than they provide answers for in our understanding of Earth's interior[10].

Gonnermann and Mukhopadhyay[1] tackle these issues with alarmingly simple finesse. They propose a solution in which the lower mantle is not isolated, but just sluggish. This is not unreasonable because mantle viscosity is believed to increase significantly with depth. The authors construct a model in which exchange between the shallow and the deep mantle is allowed, with plate subduction occurring through the 660-km discontinuity, and the associated counterflow (Fig. 2b) producing a more homogeneous, less-layered mantle. But this is not an all-or-nothing process, with the deep subduction being limited to a modest flux consistent with the seismological observations. The authors explore the parameter space in which their model can reproduce the helium isotope ratios of mid-ocean-ridge basalts and the ocean islands. The inputs to successful solutions are quite compatible with independent constraints on terrestrial gas budgets and the isotope ratios of non-volatile elements such as neodymium ($^{143}Nd/^{144}Nd$, for example).

The authors' model[1] consists of an elegant mass balance, similar to one that has been used to reproduce the natural range of isotopic compositions in other systems[11]. It is not a dynamic model, but the requirements of the successful model solutions do not seem onerous, even if they clearly need to be explored using numerical simulations of convection. The essential feature, that the mantle is not layered but not homogeneous, also seems eminently reasonable, and it is perhaps surprising that such an idea has previously not been sufficiently explored. Yet many ideas seem obvious only after they have been shown to be effective.

Before feeling too comfortable, however, it must be remembered that there are the mysteries of xenon and its nine isotopes to get to grips with[12]. And perhaps ironically, the work of Gonnermann and Mukhopadhyay[1] arrives at a time when the Earth science community is grappling with striking evidence[13] for a 'hidden reservoir' that formed at the base of the mantle within the first 30 million years of the birth of the Earth, some 4.5 billion years ago. So it seems that we now have an embarrassment of hide-outs for noble gases (see also ref. 14), and several possible solutions to our volatile dilemmas. ■

Tim Elliott is in the Department of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK.
e-mail: tim.elliott@bristol.ac.uk

1. Gonnermann, H. M. & Mukhopadhyay, S. *Nature* **459,** 560–563 (2009).
2. Porcelli, D. & Wasserburg, G. J. *Geochim. Cosmochim. Acta* **59,** 4921–4937 (1995).
3. Allègre, C. J., Hofmann, A. & O'Nions, K. *Geophys. Res. Lett.* **23,** 3555–3557 (1996).
4. Hofmann, A. W. *et al. Earth Planet. Sci. Lett.* **79,** 33–45 (1986).
5. van der Hilst, R. D., Widiyantoro, S. & Engdahl, E. R. *Nature* **386,** 578–584 (1997).
6. Class, C. & Goldstein, S. L. *Nature* **436,** 1107–1112 (2005).
7. Parman, S. W. *et al. Nature* **437,** 1140–1143 (2005).
8. Kellogg, L. H., Hager, B. H. & van der Hilst, R. D. *Science* **283,** 1881–1884 (1999).
9. Allègre, C. J. *Phil. Trans. R. Soc. Lond. A* **360,** 2411–2431 (2002).
10. Ballentine, C. J. *et al. Phil. Trans. R. Soc. Lond. A* **360,** 2611–2631 (2002).
11. Kellogg, J. B., Jacobsen, S. B. & O'Connell, R. J. *Earth Planet. Sci. Lett.* **204,** 182–202 (2002).
12. Pepin, R. O. & Porcelli, D. *Earth Planet. Sci. Lett.* **250,** 470–485 (2006).
13. Boyet, M. & Carlson, R. W. *Science* **309,** 576–581 (2005).
14. Jephcoat, A. P., Bouhifd, M. A. & Porcelli, D. *Phil. Trans. R. Soc. Lond. A* **366,** 4295–4314 (2008).

OLFACTION

Noses within noses

Steven D. Munger

The mammalian olfactory system does more than just detect food odours and pheromones. The discovery of a novel class of olfactory receptor provides evidence that mammals can also sniff out cell damage and disease.

The mammalian olfactory system recognizes diverse chemical stimuli conveying information about such things as food quality, the genetic identity or sexual status of potential mates, and even stress[1,2]. An exciting paper by Rivière *et al.*[3] (page 574 of this issue) describes the identification of a previously unrecognized type of chemosensory neuron in the rodent nose that responds to stimuli associated with cell damage, disease and inflammation. These results should help us to understand how animals identify pathogens or assess the health status of potential partners.

Not so long ago, it was believed that the olfactory system of most mammals had only two divisions: a main olfactory system that detects environmental odours, for instance those emitted by food or predators, and an accessory (vomeronasal) olfactory system that detects pheromones — intraspecies chemical signals that elicit a stereotyped behavioural or hormonal change. It is now clear that the sense of smell is much more complex. Indeed, the main and accessory olfactory systems each respond to both general odours and pheromones[4–6]. Furthermore, each olfactory division contains several types of sensory cell identified by the receptors and other proteins they express, the connections they make in the olfactory part of the brain, and the chemical stimuli to which they respond[2]. This diversity of sensory cells in the nose has given rise to the concept of olfactory subsystems, each dedicated to a particular chemosensory role[2].

There is a growing literature indicating that animals use olfaction to assess whether other organisms may be dangerous, or even to judge the health status of potential partners. For example, mice use olfactory cues to avoid potential mates that are infected with parasites[7], whereas nematode worms develop aversions to odours given off by harmful bacteria, thereby avoiding toxic food[8]. However, although such olfactory-based aversion behaviours have been documented, no olfactory subsystem that is dedicated to the assessment of health status or disease has been identified in mammals. The findings of Rivière and colleagues[3] may provide this missing link.

In mammals, most olfactory receptors are