from the maxillary palp, likely through repulsive interaction with Plexin-A, a receptor for Sema1A (*11*). Thus, the same family of axon guidance molecules plays a role in axon-axon interactions in the fly and mouse olfactory systems, implying an evolutionally convergent strategy for olfactory circuit formation.

After the coarse olfactory map in the mouse is established by the processes described above, axon-axon interactions among those that target neighboring glomeruli further refine the map through attractive and repulsive interactions (*13*, *14*). Thus, wiring specificity of complex neural circuits is achieved through stepwise mechanisms, involving axon sorting along the path (*3*, *15*), at the targets (*11*, *13*), and pre- and postsynaptic recognitions. As well, the individual identification tags originally proposed by Sperry for pre- and postsynaptic matching can serve at multiple steps to ensure the precise wiring of the brain.

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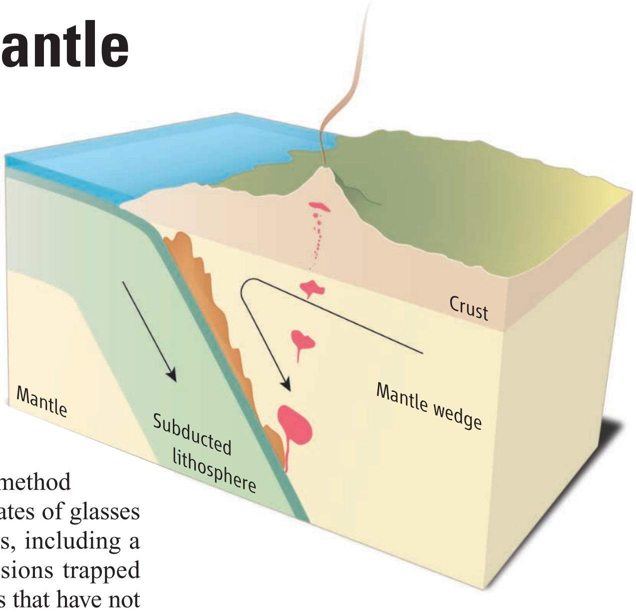
GEOCHEMISTRY

Ironing Out the Oxidation of Earth's Mantle

Subduction processes cause magmas from volcanoes in island arcs to become more oxidized and may influence the oxidation state of the entire mantle.

Marc M. Hirschmann

Lavas from island arc volcanoes form when the crust is recycled into the mantle at subduction zones (see the figure). These lavas are more oxidized than those produced at mid-ocean ridge volcanoes. On page 605 of this issue, Kelley and Cottrell (*1*) use a high–spatial resolution method to determine iron oxidation states of glasses from a suite of volcanic rocks, including a broad sampling of tiny inclusions trapped in minerals from arc volcanoes that have not undergone degassing. They correlate these measurements with dissolved water and trace element concentrations determined by other microanalytical techniques, and link the oxidation of arc volcano magmas with oxidants in the fluids that infiltrate the mantle wedge above subduction zones, as opposed to other processes, such as volcanic degassing in surface regions.



Oxidizing mantle rocks and magmas. Subduction of oceanic lithosphere carries oxidized surface rocks into Earth's interior. These rocks, including sediments and hydrothermally altered basalts, are rich in water, which is released into the overlying mantle wedge, as indicated by the region in brown. This process initiates melting in the mantle wedge, which in turn leads to formation of volcanoes in island arcs such as Japan and Indonesia. Regions where silicate melt is present are shown schematically in red. Kelley and Cottrell show that the subducted, volatile-rich geochemical component found in island arc volcanoes is also associated with oxidation, strongly suggesting that the fluids added from the subducted lithosphere to the mantle wedge are rich in an oxidizing agent such as ferric or sulfate ions. The mantle wedge is dragged into the deeper mantle by viscous coupling to the subducted lithosphere (curved arrow).

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The lavas produced at arc volcanoes—adjacent to oceanic trenches in Japan, Chile, Indonesia, and other places around the Pacific "ring of fire"—are created when cold rocks from near Earth's surface are returned to the mantle at a subduction zone (see the figure). It may seem paradoxical that cold materials lead to volcanism, but the subducted rocks release fluids that rise and induce partial melting in the overlying mantle wedge. The partial melts are buoyant, and once they segregate from the mantle, they create arc volcanoes.

The fact that arc magmas are more oxidized than mid-ocean ridge magma has been attributed to subduction processes, but recently, new methods analyzing vanadium in arc lavas have challenged this supposition (*2*). Because vanadium takes on different oxidation states depending on its environment, its geochemical behavior can be used to infer the oxidation state during partial melting. Studies based on this method suggested that the mantle wedge beneath island arcs (see the figure) is no more oxidized than is the mantle in other regions (*2*). This could indicate that the oxidized character of arc volcanic rocks derives from near-surface processes, such as fractional crystallization or volcanic degassing.

However, the results of Kelley and Cottrell suggest a different explanation. Using microscale x-ray absorption near-edge spectroscopy, they determined the iron oxidation state of the lavas and found that it correlates with water content. They argue that the oxidation state of arc magmas is affected mainly by the proportion of subduction fluid added to the source. Thus, the oxidation process must occur near where the subducted rock meets the mantle wedge. The oxidation state is also proportional to trace element indicators of subduction influence, although more data will be required before a strong correlation can be established.

The study by Kelley and Cottrell shows that the increase in oxidation state is not an arti-

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fact of unrelated processes, such as fractionation, interaction with shallow rocks below the volcano, or volcanic degassing. However, their results do not fully resolve how subduction fluids oxidize the mantle wedge. In the mantle, water itself is a poor oxidant, and so the oxidation must be effected by chemical components associated with the water-rich fluid. Kelley and Cottrell explore several possibilities, including iron-containing brines, subducted sulfates, or hydrous silicate fluids or melts. However, it is unclear whether sufficient brine or sulfate is subducted in most places, and so the most likely candidate is ferric ion (Fe^{3+}) carried as a dissolved component in a silicate melt or silicate-rich fluid. The results of Kelley and Cottrell thus lend support to the hypothesis that the fluid leaving the slab is silicate-rich.

These studies of mantle oxidation raise another unresolved question. Subduction has been occurring on Earth for much of its history, and surface rocks have been oxidized at least since the rise of an oxygenated atmosphere ~2.5 billion years ago. Shouldn't billions of years of subduction have partly oxidized the mantle? At current subduction rates, deep recycling of a mantle wedge section, with an average thickness of 70 km (see the figure), would mean that 40% of the mantle has been flushed with comparatively oxidizing melts or fluids in the past 2.5 billion years. Yet investigations to date have not found evidence for an increase over time in the oxidation state of the mantle (*3*).

Why, then, is the mantle not more oxidized? Perhaps most of the oxidant released from the slab is extracted at arcs, leaving the mantle wedges relatively unaffected, or possibly oxidation has been offset by subduction of reduced surface materials, such as organic carbon. Indeed, the rise of oxidized surface conditions has been linked to sequestration of reduced carbon in the mantle (*4*). The work of Kelley and Cottrell firmly establishes that subduction oxidizes the source regions of arc magmas, but the long-term consequences for the evolution of Earth remain poorly understood.

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ASTRONOMY

Probing the Cold Universe

Michael Rowan-Robinson

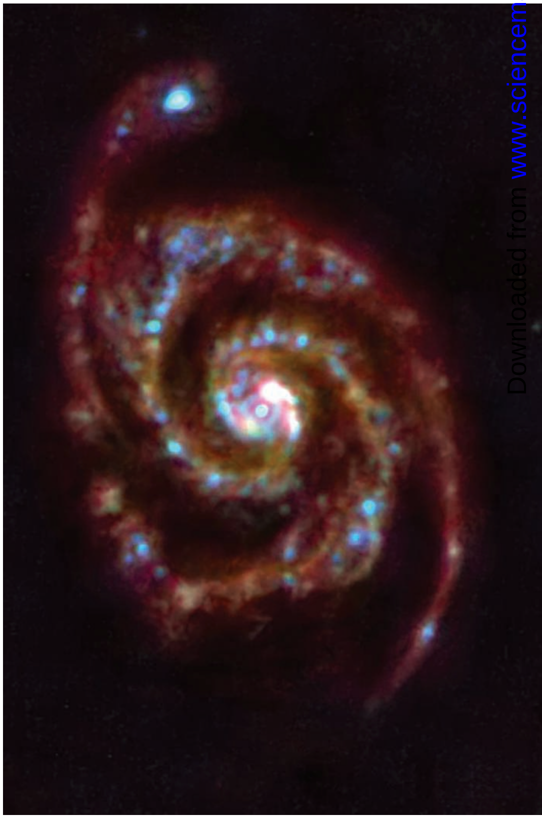
The launch of the Herschel infrared space telescope is expected to provide new vistas on the cold and dusty universe.

The successful launch of the Herschel and Planck satellites on 14 April 2009 was a great achievement of the European Space Agency. With a mirror diameter of 3.5 m, the Herschel Space Observatory is the largest space telescope ever launched. The complex dual launch went perfectly, and both missions are performing well. After removing the cover of the cryostat housing the instruments on 14 June, Herschel was pointed to the famous M51 "whirlpool" galaxy and produced an impressive first image (see the figure), with an immediate resolution improvement over previous far-infrared missions.

From its final destination at the Lagrangian point between Earth and the Sun, Herschel will view the universe in the last unobserved wavelength band; the far infrared and sub-mm range from 60 to 600 µm. These wavelengths are inaccessible from the ground except for narrow windows at 350 and 450 µm. Herschel, named after the German musician turned British astronomer, William Herschel, who discovered infrared radiation in 1800, will penetrate the clouds of dust that shroud newly forming stars and galaxies. The stars and planets that form in these dense clouds do not emit visible light. It is only at infrared wavelengths that these processes can be observed. The molecules present in the clouds act as "probes" of the physical conditions, allowing Herschel to determine the physical and chemical details of these previously mysterious places.

Infrared space astronomy began in 1983 with the Infrared Astronomical Satellite (IRAS), a 60-cm telescope. Over 10 months of operation, it produced the first map of the entire sky at far infrared wavelengths. Following up on IRAS came the Infrared Space Observatory (ISO), launched in 1995, and then the Spitzer Space Telescope, launched in 2003, both general-purpose infrared observatories. Spitzer, with its 0.85-m diameter mirror, is still in orbit, but its coolant exhausted on 15 May this year, so it now continues operations as a survey instrument at 3.6 and 4.5 µm only. With its much larger size, Herschel presents a giant leap forward in infrared technology.

Herschel carries three scientific instruments. The Heterodyne Instrument for the Far Infrared (HIFI) (*1*) takes very high-resolution spectra in thousands of wavelengths simultaneously. It covers the bands 160 to 200 and 240 to 600 µm, using superconducting mixers as detectors. The Photoconductor Array Camera and Spectrometer (PACS) (*2*) is an infrared camera and a spectrometer operating at 60 to 210 µm, with bolometer and photoconductor array detectors. The Spectral and Photometric Imaging REceiver (SPIRE) (*3*) is a camera and spectrometer, providing broadband photometry simultaneously in bands centered on 250, 350, and 500 µm.



First light. The Herschel-PACS instrument images the Messier 51 whirlpool galaxy, coded with blue for 70 µm, green for 100 µm, and red for 160 µm. The image was taken as soon as the cryostat cover was removed, while Herschel was still in transit to its final orbit at the Sun-Earth L2 Lagrangian point.

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