ultramafics), as seems to be the case at Lost City, and those that result from reaction with the basalts that are present closer to the surface? Third, what is the nature of the microbial communities that might exist at Lost City?

It has long been known that the amount of heat lost by convection on the flanks of mid-ocean ridges is much larger than that lost from the axis itself. The ratio is roughly 70:30, and the reason is that, although the axis is hotter, the flanks have a much larger area. But chemical concentrations (for instance, of iron) tend to be much higher on the axis than away from it. So debate over the relative contributions of off-axis and on-axis fluxes has centred on whether the chemical anomalies found on the axis are great enough to outweigh the greater heat (and probably water) flux on the flanks. The trouble is that off-axis venting is difficult to locate because the lower temperature of the fluids means that certain indicators in the water column (temperature, particles or salinity) or on the sea floor (large constructive features, or animal communities) are absent. Lack of knowledge of off-axis vents has also hampered attempts to estimate the overall chemical flux to the ocean through hydrothermal activity and its importance, relative to the contribution of rivers, to ocean chemistry.

The mid-ocean ridge system is huge, around 60,000 km in total length, and different ridges in the system spread at different rates. The mid-Atlantic Ridge, with which the Lost City is associated, is slow-spreading (at a full opening rate of only 2.5 cm yr⁻¹). This compares with up to 15 cm yr⁻¹ on fast-spreading ridges such as the East Pacific Rise. The previously identified sites of off-axis hydrothermal activity are all close to ridges spreading at intermediate rates, as opposed to the slow-spreading location of the Lost City. The topography of slow-spreading ridges is especially rugged, which further hampers the search for hydrothermal sites.

The spreading rate of a mid-ocean ridge is relevant to hydrothermal fluids because a determinant of the fluids' nature is the rock with which they react in passing through the ocean crust. Faster-spreading ridges are dominated by basaltic (mafic) rock types; on slower-spreading ridges, however, fluids may also react with deeper-lying peridotites (ultramafics), leading to the formation of serpentinites and thereby to different fluid compositions. Most of the known seafloor hydrothermal sites are found on basalt. But on slower-spreading ridges, the ultramafic parts of the oceanic crust are often exposed or closer to the sea floor, and venting fluids may be derived by reaction with this rock type.

This is what seems to be happening at Lost City, where the vent fluids are quite cool (40–75 °C) and alkaline (pH 9 and above).

Another example of seafloor hydrothermal fluids derived from serpentinites is the Hémi- lana trench and island arc system in the western Pacific1. Here the fluids are cooler than ambient sea water and likewise have higher pH values. A similar situation occurs on land — hot springs issuing from serpentinite substrate have extraordinarily high pH values2.

Two other places, both on the Mid-Atlantic Ridge, have been discovered where the hydrothermal fluids seem to be derived from ultramafic reactions. They are the Logatchev and Rainbow sites, at 14° 45′ N and 36° 16′ N, respectively3,4. The chemistry of the fluids at these sites is fundamentally different from those at basaltic sites (they are high in iron, calcium and transition metals, but low in silica). In contrast to the Lost City, however, Logatchev and Rainbow have high temperatures (350 °C or above) and very acidic pH values.

What about the microbial communities at seafloor hydrothermal sites? Such communities depend on chemical energy, often in the form of reduced gases such as hydrogen and hydrogen sulphide, for their existence. Anomalously high concentrations of methane, another reduced gas, have been found in the water column near the Logatchev site5, but no discrete methane source has ever been located. Another unusual aspect is the hydrogen content of the fluids issuing from ultramafic source rocks, which is greater than that of most basalt-derived hydrothermal fluids. It is not as high as the hydrogen content in vent fluids immediately after volcanic eruption, but such perturbations are only transient events. These high levels of gas led to speculation as to the importance of ultramafic sites as microbial incubators and in the evolution of life on Earth. At 40–75 °C, the hydrothermal fluids at Lost City present a much more hospitable temperature range for life than the 350 °C or so of the Rainbow and Logatchev sites. Kelley et al.6 have done some culturing work with microbes from the site. But it will take detailed DNA analyses to see whether they are unique, and if they are more like the microorganisms thought to have existed on the early Earth than are known microbial communities.

Even in the twenty-first century, unexpected discoveries in our oceans are capturing our imagination and forcing us to revise our ideas about processes on Earth. We cannot yet be sure what the chemical control on the hydrothermal fluids at Lost City may be, or how they might be affected by biological activity. However, as much of the global ridge-crest system can be characterized as slow-spreading, with ultramafic source rocks, we can be sure that Lost City will provide new ways of thinking about seafloor hydrothermal activity in general and its effect on ocean chemistry.

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Cognitive neuroscience

Bold insights

Marcus E. Raichle

Functional magnetic resonance imaging tracks changes in oxygen levels in the brain in response to different stimuli. The neural basis of these changes has, at last, been pinned down.

Over the past decade, research in the field of cognitive neuroscience has grown exponentially. To probe the mysteries of the human brain, scientists combine the experimental strategies of psychology with techniques that enable them to examine how brain activity supports mental processes. Leading the way are two techniques for imaging brain function: positron-emission tomography (PET) and magnetic resonance imaging, or functional magnetic resonance imaging (fMRI) as it is now called. fMRI is the main tool for imaging normal brain activity.

fMRI effectively measures the level of oxygen in the blood in the brain, which varies because changes in brain activity are invariably accompanied by changes in blood flow, causing the oxygen level in the blood to rise in the brain region concerned. The robust empirical relationship between changes in brain activity and blood flow has fascinated scientists for well over a century, but its neural basis has, until now, remained largely unknown. Despite this, researchers have assumed that the signals they obtain from fMRI are related to actual changes in neuronal activity. On page 150 of this issue,
Logothetis and colleagues confirm this, in an experimental tour de force that represents the first comprehensive look at the relationship between the fMRI signal and the underlying neural activity. Logothetis et al.’s results emerge from their pioneering development of fMRI, whereby both fMRI and various measures of the electrical activity of neurons are carried out simultaneously in monkeys. The experiments required monkeys to sit in an MRI scanner while viewing checkerboard patterns. The results show that a spatially restricted increase in the fMRI signal — in this instance in the brain’s visual cortex — directly reflects an increase in neural activity.

With their electrical recording techniques, the authors analysed several aspects of neuronal activity, and were able to distinguish between action potentials and local field potentials. Action potentials are the all-or-nothing firing rates of individual neurons and groups of neurons; they occur immediately after a stimulus has been presented, and reflect neural output. Local field potentials are the more slowly varying electrical potentials that arise from the input to, and integrative processes within, neurons. The major determinant of the fMRI signal turned out to be the local field potentials. So, activation of an area of the brain, as seen by fMRI, predominantly reflects the input to that area and the corresponding changes in information processing, rather than output from the area. Notably, much earlier work, using autoradiographic measurements of glucose consumption by different brain areas in rats, anticipated exactly this.

The results hold lessons for both cognitive neuroscientists and cellular neurophysiologists. Cognitive neuroscientists using fMRI must be aware that the signal-to-noise ratios for neural signals recorded directly from the brain are much greater than the accompanying fMRI signal. So the absence of an fMRI signal does not necessarily mean that no information processing is going on in a particular area of the brain. For the neurophysiologists, who seek to understand the biochemical and biophysical processes underlying neural activity, the absence of action potentials must not be interpreted as the absence of information processing. Before neurophysiologists and cognitive neuroscientists can cooperate as needed, both groups must have a working knowledge of the relationships between neuronal activities and fMRI signals.

More fundamentally, Logothetis et al.’s work comes at a time of increasing interest in the general cell biology underlying the fMRI signal. The nature of the signal and the physiological research preceding its discovery have forced us to reconsider how changes in energy production support increases in neuronal activity. At rest the human brain uses up 20% of the oxygen needed by the body, although the brain accounts for less than 2% of the body’s mass. The oxygen is used in breaking down glucose to supply the brain with energy.

Surprisingly, however, brief increases in the activity (and energy requirements) of particular brain regions are accompanied by increases in blood flow and glucose consumption that far exceed the increase in oxygen consumption. This is because glucose is being broken down anaerobically, by the rapid process of glycolysis, to supply energy. As a result there is an increase in the amount of oxygen in the blood nearby — supply exceeds demand (Fig. 1a). fMRI is sensitive to changes in the oxygen content in blood, and so detects the ‘blood-oxygen-level-dependent’ (BOLD) signal.

Recent work has offered a tentative explanation for the local increase in glycolysis (Fig. 1b, c). The communication between neurons occurs at synapses, and requires the release of neurotransmitters from a presynaptic neuron and their detection by a postsynaptic nerve cell. The amino acid glutamate is the main excitatory neurotransmitter in the brain. After it is released, glutamate needs to be removed promptly from the synapse, and this occurs by uptake into an adjacent non-neuronal cell — an astrocyte. There, glutamate is converted to glutamine before it is returned to the neuron. Glycolysis consumes glucose to produce energy, but does not require oxygen.

...
the brain's main inhibitory neurotransmitter.

After a century of research, we still do not know how or why blood flow increases during neuronal activation. It does not seem to reflect an increased need for either oxygen or glucose. But, thanks to the work of Logothetis et al., cognitive neuroscience can move forward with greater confidence in the knowledge that changes in blood flow and oxygen levels do represent definable alterations in neuronal activity.

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High-energy physics

Disappearing dimensions
Joseph D. Lykken

Some theories of high-energy physics require extra spatial dimensions, beyond the three we know. A radical proposal turns this idea on its head, and suggests that dimensions may disappear at higher energies.

What is space? Where did the dimensions of our physical world come from? Philosophers since Aristotle have been flummoxed by these ancient questions. Now the particle physicists are having a go — turning philosophy into scientific hypotheses with testable consequences. Two groups of theorists, one based at Harvard University and the other at the Fermi National Accelerator Laboratory in Illinois, have suggested a concrete mechanism for how dimensions of space can come into being, and even disappear.

Aristotle got the first step right: to understand what a spatial dimension is, you need to think about motion. The convincing evidence that we live in three spatial dimensions is that we can move in three independent ways. Objects look three-dimensional because light (composed of particles called photons) moves in three dimensions, obeying three-dimensional laws of optics, and thus of perspective. Any question about dimensionality always boils down to a question about particles and their motion.

In a solid material like a crystal, atoms are held rigidly together, forming a regular lattice of point-like locations in three-dimensional space. Most of the electrons in that material are tied to one particular atom — they effectively live in a world of zero spatial dimensions, because their motion is completely constrained. But in some materials, such as metals, there are residual forces that allow some electrons to hop from one atom to another. Depending on the material, these ‘hopping interactions’ may allow motion only along a line, or only in a planar surface, or through the full three dimensions of the solid. So, for electrons in a solid, dimensionality effectively depends on forces.

The provocative models of Arkani-Hamed et al.1 and Hill et al.2 extend this analogy to elementary particles in a vacuum. Put the Universe under a powerful enough microscope, they say, and you will find that space itself is a lattice, an array of discrete points. Elementary particles, such as electrons, quarks or photons, fundamentally inhabit only a single point. To move, there must be a force — a hopping interaction — that destroys the particle at one point in space and creates a copy of it at a neighbouring point. No force, no motion; no motion, no dimension.

The Harvard and Fermilab theorists have created this microscopic picture of discrete space and hopping particles using simple models in which ‘gauge’ forces similar to three of the fundamental forces seen in nature — electromagnetic, weak and strong interactions — induce the hopping. Now comes the tricky part. Gauge forces vary in strength according to the energy involved in the physical process. Electromagnetic forces, for example, get stronger at higher energies, whereas the strong nuclear force between quarks gets weaker at higher energies. In the models created by the two groups of theorists, the hopping interactions actually turn off at high energies, thereby reducing the number of spatial dimensions. Arkani-Hamed et al.1, with postmodernist tongue-in-cheek, call this ‘deconstructing dimensions’.

The punchline is that, in the high-energy environment of the early Universe, there may have been no spatial dimensions at all. Dimensionality itself may be a low-energy phenomenon.