ergy in the gap. These occur, for example, in the band gaps of semiconductors like silicon and are at the heart of semiconductor electronic technology. It turns out, however, that in superconductors, nonmagnetic impurities do not normally lead to states in the gap (see top panel in the figure). The crucial difference is that in semiconductors, the gap results from the crystal structure, which is altered by disorder, whereas the gap in superconductors results from the pairing of electrons by some attractive interaction. This pairing survives disorder and bound states do not occur, a property closely connected with Anderson's famous theorem (*6*) concerning the influence of disorder on superconductivity.

The situation changes in the case of high-T_c materials such as BSCCO, which are believed to be unconventional "*d*-wave" superconductors (*7*). The term "*d*-wave" refers to the gap Δ_k, which depends strongly on the wave vector $\boldsymbol{k}$ of the electrons in the Cooper pairs. In *d*-wave superconductors, impurities do create states in the energy gap, much like in semiconductors and quite unlike in conventional superconductors (middle and bottom panels in the figure). One difference between semiconductors and *d*-wave superconductors is that in the superconductors, the new states (called "resonances") are not bound to the impurity but are actually predicted to have extended "tails" away from the impurity (middle panel of the figure). It is these resonances that have been seen by Hudson *et al.* (*2*).

Studies of the detailed structure of the resonances are likely to lead to an improved understanding of the superconducting state. Even within BCS theory, the dependence of the density of states on the underlying band structure (bottom panel of the figure) and the local structure of the impurities has not been fully explored. The possibility that BCS theory might break down is also an exciting prospect. The experiments reported in (*2*) are for "optimally doped" BSCCO, for which the notion of quasi-particle bands still appears to hold. By reducing the oxygen content, BSCCO can be shifted into the "underdoped" regime in which the quasi-particle band picture becomes questionable. Detailed studies of the quasi-particles in this regime have the potential to illuminate new physics relating to strongly interacting quasi-particles.

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PERSPECTIVES: GEOLOGY

Sediments Reveal Their Age

Martin J. Whitehouse

Sedimentary rocks made up of coarse crystals or rock fragments (siliciclastic rocks, such as sandstones) are ubiquitous throughout the geological record, often forming spectacular sequences many thousands of meters thick that may be the sole remaining record of long since eroded mountain belts (see the figure). Determining when these rocks were deposited remains one of the most challenging problems for geologists. As reported in this issue on page 78, McNaughton *et al.* (*1*) used a large ion microprobe to measure lead isotopes in microscopic crystals of a rare-earth element phosphate mineral, xenotime, which commonly grows during diagenesis (the modification of sedimented material shortly after sedimentation). Its lead content is entirely determined by the decay of uranium incorporated into the mineral at the time of its crystallization, and the lead isotopic composition is thus a direct chronometer for the diagenetic process.

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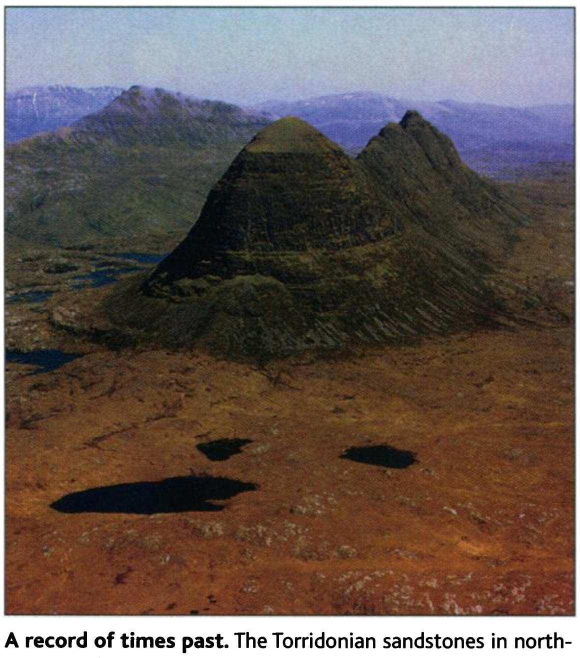
Since the discovery of radioactivity in the late 19th century and the development of modern mass spectrometers in the early 1950s, geologists have increasingly used radioactive decay sequences of elements as natural clocks to refine our understanding of the evolution of Earth. Much of this development has taken place against the backdrop of plate tectonics, the revolution in geological thinking in the 1960s that explains how continents have formed, amalgamated, and broken apart. Reconstructing plate movements through time requires correlation of the ages of rock units across both present and ancient oceans, formed when continents break apart. Such correlations clearly require accurate geochronology. Isotopic dating provides an increasingly precise, and largely unambiguous, way to date events such as the crystallization of a granite, the metamorphism of a gneiss or schist, or the eruption of an ancient volcano, ages that provide invaluable constraints. However, much of the exposed geology of the continents is made up of sediments, some of which—particularly siliciclastic rocks—are notoriously difficult to date. In the Phanerozoic era (that is, the past 540 million years), fine-grained sediments and limestones have preserved body fossils that can be used to erect a detailed "biostratigraphy." When this is calibrated by isotopic dating of, for example, interbedded volcanic rocks, it is precise and accurate. In contrast, in



A record of times past. The Torridonian sandstones in northwest Scotland were deposited after about 1.2 Ga, but accurate dating is difficult.

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the preceding Precambrian era, which represents about 90% of the geological record, biostratigraphy is generally precluded by the absence of large organisms with preservable body parts, which appeared in spectacular diversity and abundance only at the end of this era. Throughout geological time, coarser grained siliciclastic rocks (rocks such as sandstones that are mostly made up of silicate rock fragments) present a particular problem because fossils are not preserved under the more destructive conditions of their deposition.

Dating of siliciclastic sedimentary sequences has, to date, been achieved mostly by the well-established stratigraphic tool of age bracketing (*2, 3*), which involves the dating of those units within a sedimentary sequence that are amenable to direct isotopic age determination (such as volcanic units, carbonate sequences, or fine-grained shales containing datable diagenetic clay minerals) or, in the Phanerozoic only, biostratigraphy. Others have studied the ages of individual detrital zircons, another uranium-rich mineral in which lead isotopes provide a chronometer (*4*). This resistant mineral survives high-energy depositional environments and is common in coarse clastic sediments. However, it can only provide a maximum date for sedimentation because the age determined from the zircon simply reflects the age of the rock from which it crystallized. For example, the Torridonian sandstones of northwest Scotland shown in the figure contain zircons that are predominantly late Archaean [about 2.7 billion years ago (Ga)] and Mesoproterozoic (about 1.8 to 1.6 Ga) (*5*), although we know that the sediment was deposited after about 1.2 Ga (*6*). Clearly, all of these methods have limitations that restrict their applicability and accuracy for dating sedimentary sequences.

McNaughton *et al.* have now dated xenotime overgrowths on zircon crystals in sandstone. They present morphological evidence from electron microscopy that the xenotimes were formed after sedimentation, because the fine, angular crystals that they observe would have been destroyed during sediment transport. They suggest that the xenotimes were formed immediately below the sediment-water interface by circulating pore fluids and are therefore truly diagenetic in origin. Xenotime is very amenable to dating with the uranium-lead radioactive decay system. It preferentially incorporates uranium in high concentrations during crystallization under exclusion of lead, and therefore all of the measured lead is radiogenic, formed from in situ decay of the uranium, greatly facilitating the dating of the xenotime formation.

McNaughton *et al.* report finding xenotime overgrowths in about half of the 25 siliciclastic sediments of all ages that they have investigated. They suggest that their method will enable diagenesis of siliciclastic sediment to be dated with reasonable accuracy throughout the geological record, although it is likely that the youngest sediments will require further development of the method to include dates based on ratios of uranium to lead because those based on lead isotopes alone become unacceptably imprecise in young rocks.

The primary application of this powerful new method will undoubtedly be the dating of major Precambrian siliciclastic sediments that have previously eluded direct dating and application of these dates to understanding the timing of local and global tectonic processes. Given the potential of this method, the limiting factor is likely to be the availability of analytical capacity on the small number of large ion microprobes, which are required for these measurement, rather than the availability of suitable rocks for dating.

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PERSPECTIVES: NEUROSCIENCE

For the Latest Information, Tune to Channel KcsA

Bojan Zagrovic and Richard Aldrich

Potassium ion (K^+) channels are transmembrane proteins that regulate K^+ ion flux across the cell membrane with remarkable selectivity and efficiency. Their activity underlies fundamental biological processes such as electrical signaling, osmotic balance, and signal transduction (*1*). Last year, MacKinnon and colleagues published the crystal structure of KcsA, the K^+ channel of the bacterium *Streptomyces lividans* (*2*), ushering the field into a new era. Building on this landmark study, Roux and MacKinnon now report on page 100 a computational analysis of the electrostatic forces that stabilize K^+ ions inside the central cavity of the KcsA ion channel (*3*). Further, Perozo *et al.* (*4*) on page 73 describe the conformational changes that take place in KcsA as it opens and closes, a process called gating that can be followed by electron paramagnetic resonance (EPR).

Although the crystal structure of the KcsA channel has yielded valuable information about permeation (that is, how the channel selectively translocates K^+ ions across the membrane), it has not offered definitive answers about how the channel opens and closes (gates), arguably the most important question in ion channel physiology. Different ion channels gate in different ways: Some are activated by changes in cell membrane voltage, others by binding of ligand. KcsA is activated by changes in extracellular pH.

In their study, Perozo *et al.* trapped the KcsA channel in both the open and closed conformations and then analyzed the difference in the EPR signal (*5*). They introduced cysteine residues at select locations in each of the four identical subunits of KcsA—in transmembrane helices 1 and 2 (TM1 and TM2) and in the pore α helices (see the figure). They then labeled the helices with nitroxide spin labels, and analyzed the change in spin-label mobility and intersubunit spin-spin coupling as the channel gated in response to changes in pH. They found that TM1 and TM2 underwent conformational changes (rigid-body translations and counterclockwise rotations around the channel's central cavity) as the pore opened. Opening of the pore seemed to be directly coupled to the movement of the four TM2 helices: Their displacement increased the diameter of the permeation pathway at the point where the helices converge. The involvement of the four pore α helices in gating is still speculative. Although the amino terminus of each pore helix re-

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