Monitoring growth. The shape and separation of Pd nanoparticles evolve as Pd is added to MgO(100) at 650 K (1). Equivalent Pd thickness (assuming Pd is spread uniformly over the surface): **(left)** 1 nm, **(middle)** 2 nm, and **(right)** 3 nm. Size and separation of the particles have been scaled to aid visualization.

been used to produce a monochromatic x-ray beam with a lateral coherence length of 5 μm and a longitudinal coherence length of 0.3 μm (12). With this type of source, "oversampling methods" can be used to image single crystals that are smaller than the coherence length. A spatial resolution of 8 nm has been achieved for a 2D object with x-rays (13), and a resolution of 0.1 nm has been predicted in a simulation of coherent electron diffraction with oversampling phasing (14).

The results presented by Renaud et al. (1) beautifully demonstrate that a grazing incidence small-angle x-ray scattering (GISAXS) experiment can be configured to reveal details of nanoparticle growth in situ and in real time. Such real-time monitoring of a nanoparticle ensemble during growth has not been realized by the meth-

ods described above, nor previously by GISAXS. The technical breakthrough that enabled the measurements was the windowless connection of the x-ray source at the European Synchrotron Radiation Facility to the growth/detector chamber, which produced nearly background-free measurements.

Because the method does not involve charged particles, it is ideally suited to measurements at elevated pressures. To do so will, however, require isolating the high pressure of the growth chamber without unduly degrading the spatial resolution. If this technical challenge is successfully overcome, it would give GISAXS the capability of in situ control of nanoparticle growth using methods such as metal organic chemical vapor deposition.

References
1. G. Renaud et al., Science **300**, 1416 (2003).
2. A. T. Bell, Science **299**, 1688 (2003).
3. M. Valden, X. Lai, D. W. Goodman, Science **281**, 1647 (1998).
4. W. U. Huynh, J. J. Dittmer, A. P. Alivisatos, Science **295**, 2425 (2002).
5. H. C. Manoharan, C. P. Lutz, D. M. Eigler, Nature **403**, 512 (2000).
6. C. Binns, Surf. Sci. Rep. **44**, 1 (2001).
7. S. Baldelli, A. S. Eppler, E. Anderson, Y.-R. Shen, G. A. Somorjai, J. Chem. Phys. **113**, 5432 (2000).
8. P. W. Murray, J. Shen, N. G. Condon, S. J. Pang, G. Thornton, Surf. Sci. Lett. **380**, L455 (1997).
9. T. M. Wallis, N. Nilius, W. Ho, Phys. Rev. Lett. **89**, 236802 (2002).
10. M. Weyland, Top. Catal. **21**, 175 (2002).
11. P. L. Hansen et al., Science **295**, 2053 (2002).
12. I. K. Robinson, I. A. Vartanyants, G. J. Williams, M. A. Pfeifer, J. A. Pitney, Phys. Rev. Lett. **87**, 195505 (2001).
13. J. Miao et al., Phys. Rev. Lett. **89**, 088303 (2002).
14. J. Miao, T. Ohsuna, O. Terasaki, K. O. Hodgson, M. A. O'Keefe, Phys. Rev. Lett. **89**, 155502 (2002).

GEOLOGY

The Rodinia Jigsaw Puzzle

Trond H. Torsvik

Earth's surface is divided into a dozen tectonic plates that either drift apart, creating new oceanic crust, or collide, generating mountain belts such as the Himalayas. In the past, continents have coalesced into single supercontinents, which had dramatic effects on both surface and deep Earth processes. But while much is known about Pangaea (the most recent supercontinent on Earth), the earlier Rodinia supercontinent remains shrouded in mystery.

Pangaea started to form ~330 million years ago and reached its maximum extent in the Late Permian (250 million years ago) (see the first figure). Not all continents coalesced simultaneously; some were added along Pangaea's margins just as others rift-

ed off. The supercontinent changed the distribution of land and sea areas and brought about unusual climatic and biological conditions. Increased mantle temperatures and continental bulging in the interior of Pangaea may also have occurred as a result of long-term shielding of large parts of the underlying mantle (1). The ultimate breakup of Pangaea ~175 million years ago was preceded by and associated with widespread magmatic activity.

There is some evidence that supercontinents have formed periodically during Earth's history. The existence of a supercontinent in the Precambrian (before 544 million years ago) was proposed in the 1970s, when many geologists noted a large number of mountain belts with similar ages (1300 to 1000 million years old) that are today located on different continents (2). In the early 1990s, the name Rodinia was adopted for this supercontinent (3–5). Most Rodinia models have sought to match the 1300- to 1000-million-year-old

mountain belts. In these models, Laurentia forms the core of the supercontinent, with Australia–East Antarctica situated along its present-day western margin and Baltica–Amazonia along the eastern margin (see the left panel, second figure).

The models assumed that the geometry of the supercontinent, after its formation, remained static until it broke up around 700 million years ago, when Australia–East Antarctica rifted off the western margin of Laurentia. Many other continents such as Baltica and Amazonia rifted off Laurentia later (600 to 550 million years ago), opening the Iapetus Ocean between them.

Paleomagnetism—the study of the permanent magnetism in rocks, which provides the latitude and rotation for a continent—has been used to reconstruct the timing of the growth and dispersal of Rodinia. Early paleomagnetic studies were broadly supportive of the existence of a Rodinia supercontinent (6–8). But the quality of the data was insufficient for rigorous tests, in part because many of these early paleomagnetic studies were not tied to a precise radiometric age. Newer studies combining paleomagnetic and isotopic age data from 750-million-year-old rocks from the Seychelles islands and India (9) also gener-

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The Pangaea supercontinent in the Late Permian. At the time of its maximum extent, Pangaea did not contain North and South China, and new oceanic crust was formed along the eastern margin. Precambrian terranes or continents often discussed in Rodinia reconstructions (but at different locations; see the second figure) are shown in yellow. Gondwana, in the Southern Hemisphere, was formed ~550 million years ago. In the Northern Hemisphere, the earlier terranes of Laurentia, Avalonia, and Baltica combined in the Early Devonian (418 to 400 million years ago) to form Laurussia. Gondwana and Laurussia later collided to form Pangaea.

ally support classic Rodinia configurations.

However, these data have been contradicted by recent paleomagnetic data from Australia (*10*), which radically change our notion of Rodinia at 750 million years ago (see the right panel, second figure). The revised latitude for Australia displaces Australia–East Antarctica (considered as a coherent landmass) 1400 kilometers southward. In such a configuration, India could not have been connected to East Antarctica as portrayed in the left panel. Therefore, East Antarctica–India fits used in traditional Rodinia models only appear valid after India collided with East Antarctica around 550 to 500 million years ago during the growth of Gondwana (which ultimately became part of Pangaea; see the first figure).

Current paleomagnetic data usually only allow testing of Rodinia paleogeographic relationships between two or three continents at discrete time intervals (*11*). However, for 750 million years ago, data exist from at least seven continents or microcontinents. Recent Rodinia models show a more dynamic planet at 750 million years ago than previously realized. If Rodinia formed 1100 to 1000 million years ago, the demise of the supercontinent probably occurred before 750 million years ago. Disruption likely began with the opening of an ocean between western Laurentia and Australia–East Antarctica (right panel). The East Gondwana landmass could not have been a coherent block 750 million years ago (*9, 12*), and India–Madagascar–Seychelles must have been located west of Australia. Recent maps (*13*) also show Baltica geo-graphically inverted relative to Laurentia (right panel).
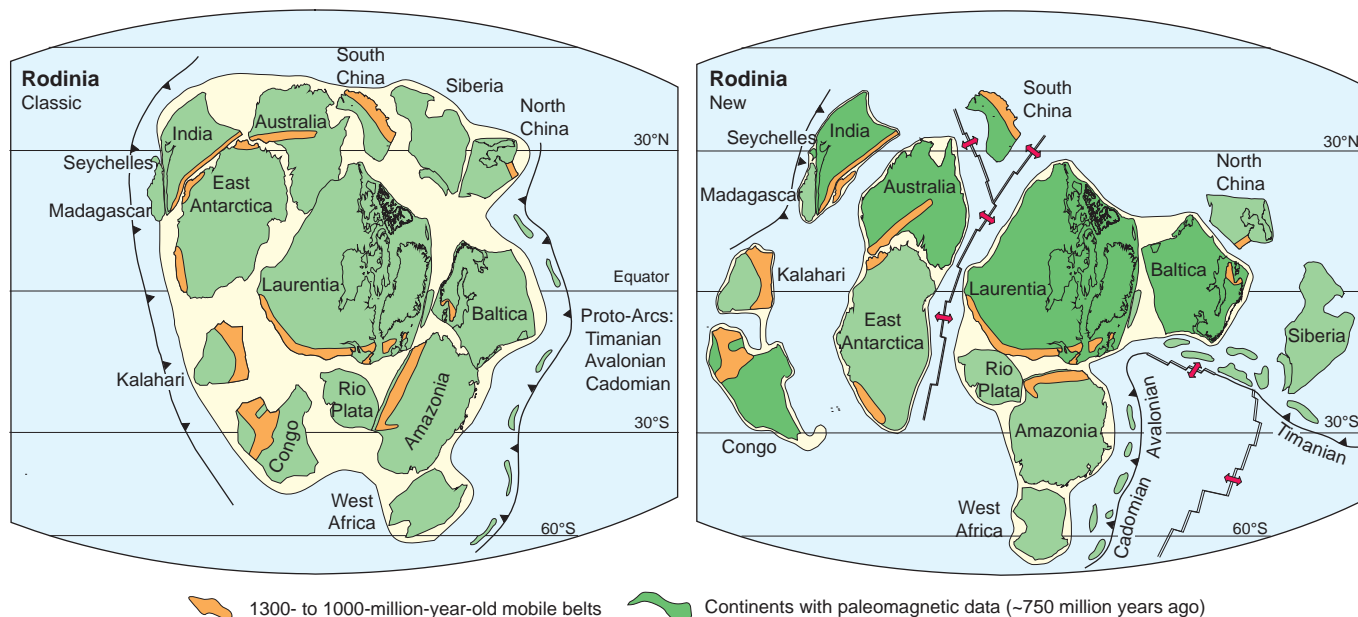
Large uncertainties concern the position of Siberia. Early Rodinia reconstructions show Siberia north of Laurentia (*5, 9, 14*), whereas others place Siberia along the western margin of Laurentia. Yet another extreme shows Siberia west of Baltica (right panel). The positions of Amazonia–Rio Plata and Congo–Kalahari also differ substantially between the old and new models (see the second figure), demonstrating the fluid and controversial nature of Rodinia reconstructions. Before 750 million years ago, the Congo and Kalahari cratons were probably in very different locations in Rodinia (*12*). For Amazonia, paleomagnetic data now suggest early collision (~1200 million years ago) with Laurentia near Texas (*15*), followed by a later move along the Laurentian margin to its position at 750 million years ago (see the right panel).

The current data indicate that the internal geometry of Rodinia changed considerably during its few hundred million years of existence. Geologic and paleomagnetic data suggest that the supercontinent consolidated at 1100 to 1000 million years ago and most likely disintegrated between 850 and 800 million years ago. However, eluci-

Rodinia old and new. (Left) Classic Rodinia reconstruction at 750 million years ago. **(Right)** Alternative reconstruction of Rodinia at 750 million years ago. The positions of Australia–East Antarctica (*10*) and Congo have been revised (*12*). The Amazonia–West Africa reconstruction follows Hoffman (*5*), and North China is tentatively placed north of Baltica. Continental fragments and magmatic arcs (Avalonian, Cadomian, and Timanian) along the southeastern margin of Rodinia were welded onto West Africa, Amazonia, Baltica, and Siberia in the Late Precambrian.

CREDIT: SECOND FIGURE, LEFT PANEL ADAPTED FROM (7, 14)

dation of its amalgamation, continental makeup, and fragmentation is hampered by the fact that at any given time, the latitudes for only a few continents are known.

To overcome these problems, we must tie paleomagnetic information to geologic matching of rock units with the same age between various continents. Doing so requires more precise dating of mobile belts and rift sequences associated with Rodinia's breakup. New paleomagnetic studies conducted in close conjunction with radiometric age studies are urgently needed to shed new light on the supercontinent's evolution. Until then, our efforts resemble a jigsaw puzzle where we must contend with missing and faulty pieces and have misplaced the picture on the box.

References
1. M. Gurnis, *Nature* **333**, 695 (1988).
2. J. F. Dewey, K. C. A. Burke, *J. Geol.* **81**, 683 (1973).
3. I. W. D. Dalziel, *Geology* **19**, 598 (1991).
4. E. M. Moores, *Geology* **19**, 425 (1991).
5. P. F. Hoffman, *Science* **252**, 1409 (1991).
6. C. McA. Powell *et al.*, *Geology* **21**, 889 (1993).
7. T. H. Torsvik *et al.*, *Earth Sci. Rev.* **40**, 229 (1996).
8. A. B. Weil, R. Van der Voo, C. MacNiocall, J. G. Meert, *Earth Planet. Sci. Lett.* **154**, 13 (1998).
9. T. H. Torsvik *et al.*, *Precambrian Res.* **108**, 319 (2001).
10. M. T. D. Wingate, J. W. Giddings, *Precambrian Res.* **100**, 335 (2000).
11. J. G. Meert, C. McA. Powell, *Precambrian Res.* **110**, 1 (2001).
12. J. G Meert, *Tectonophysics* **362**, 1 (2003).
13. E. H. Hartz, T. H. Torsvik, *Geology* **30**, 255 (2002).
14. I. W. D. Dalziel, *Geol. Soc. Am. Bull.* **109**, 16 (1997).
15. E. Tohver *et al.*, *Earth Planet. Sci. Lett.* **199**, 185 (2002).

PHYSICS

Broken Cooper Pairs Caught Bouncing Around
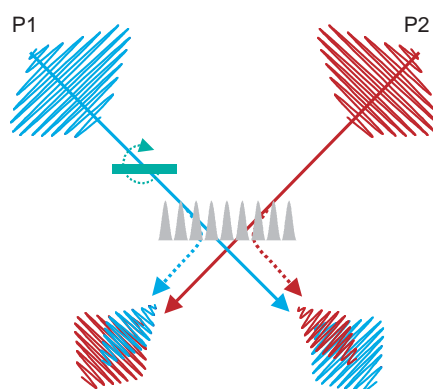
Bernhard Keimer

The explosion of research activity after the discovery of high-temperature superconductivity in 1986 is the stuff of legends. But while the "Woodstock of Physics" has long subsided, research on the superconducting copper oxides ("cuprates") has remained steady. The field may even be experiencing a second, more measured boom.

It took years to perfect the synthesis of cuprate compounds with optimal purity and minimal defect concentration. Today, excellent single-crystal samples are widely available. Meanwhile, advances in measurement techniques have made it possible to obtain scanning tunneling spectroscopy images of electronic states on cuprate surfaces (*1*), resolve minute (~0.1%) changes in the optical absorption spectrum at the superconducting transition temperature (*2*), and detect magnetic excitations by neutron scattering in millimeter-sized crystals (*3*).

On page 1410 of this issue, Gedik *et al.* add a new experimental method to our arsenal (*4*). They use laser pulses to temporarily degrade the superconductivity in a cuprate by breaking up the "Cooper pairs" of electrons and holes that carry electrical currents without resistive losses. They then track the erstwhile partners while they are bouncing off the remains of other broken Cooper pairs and other obstacles in their way. The experiment provides new insights into the forces responsible for the formation of Cooper pairs.

To appreciate the contribution of Gedik *et al.*, it helps to recall that most experiments on cuprates have been carried out in thermal equilibrium. In a measurement of the electrical conductivity, for instance, an external el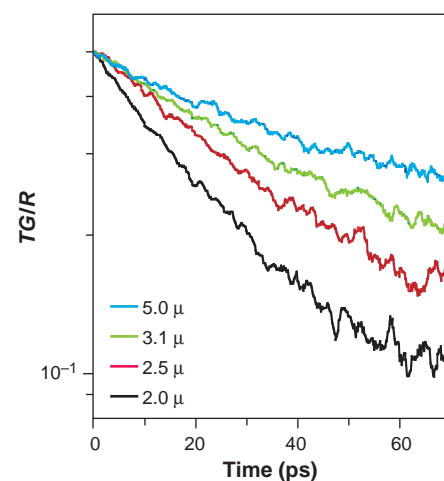ectric field promotes electrons into current-carrying excited states, and the response of the material (the electric current) is measured after the electrons have come into equilibrium with the surrounding lattice. The conductivity is the response function linking current and field. Other common equilibrium measurements yield functions describing the response of the material to time-dependent and spatially nonuniform electric (*1*, *2*) and magnetic (*3*) fields. Theorists have recently found that calculations based on coupling of electrons to spin excitations agree well with several independently measured response functions (*5*). However, it remains controversial whether the electron-electron interactions mediated by spin fluctuations are strong enough to explain the formation of Cooper pairs at high temperatures (*6*).

The report by Gedik *et al.* is based on an entirely different experimental approach that is widely used in chemistry and physics: A nonequilibrium population of "hot" electrons is generated by an intense "pump" beam from a pulsed laser, and the response of the material is monitored by a weaker "probe" beam at regular time intervals following the pump pulse. The subpicosecond time resolution required to monitor electronic relaxation processes can be routinely achieved in this way.

When the pump-probe approach is applied to high-temperature superconductors, hot "quasi-particles" (both electrons and holes) are generated by the laser pulse. These quasi-particles affect the complex index of refraction of the superconductor and hence the intensity of the reflected probe beam. The reflected beam thus yields information about the interaction of the hot quasi-particles with their environment (*7*–*9*). Some of these data have been interpreted as evidence of strong coupling between charge and spin excitations (*8*), providing qualitative support for the models developed on the basis of equilibrium experiments (*5*). However, the data themselves have barely made it onto the radar screens of theorists looking for experi-

A new tool. (Left) Quasi-particle grating detection by coherent laser pulses. Each of the two probe beams (P1 and P2) is split at the grating into transmitted and diffracted beams. The transmitted P1 and diffracted P2 are collinear. Each pair of pulses is directed to a photodetector (not shown). Measuring the detector current as a function of the time delay between the two probes yields the average quasi-particle density *R* and the peak-to-trough variation *TG*. **(Right)** Dynamics of the quasi-particle density grating as a function of the grating period λ. *TG/R* decays with time as quasi-particle diffusion depletes the grating crests and fills the troughs. Analyzing the decay rate of *TG/R* as a function of λ yields the quasi-particle diffusion coefficient with high precision.

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