GEOCHEMISTRY

When Continents Formed

Island arc rocks provide a better constraint on when the continental crust was generated.

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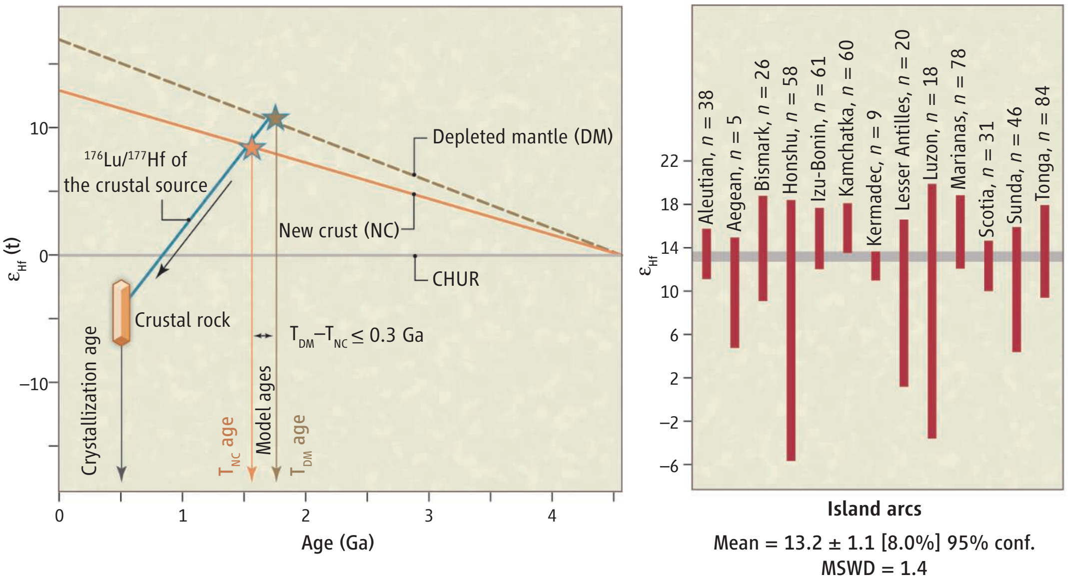
When and how the continental crust was generated remains a fundamental question in Earth sciences. It has been widely believed that the trace element–enriched continental crust and the depleted upper mantle are complementary reservoirs, and that the continental crust has grown from the depleted upper mantle (*1*, *2*). Model ages for neodymium (Nd) and hafnium (Hf) isotopes reflect when new continental crust was generated (*2*), and traditionally they have been calculated for crust derived from the depleted mantle (see the figure, left panel). The implication is that the isotope composition of the depleted mantle is similar to that of new continental crustal material as it is extracted from the mantle. However, the isotope composition of island arc rocks, and hence of new continental crust, is different from that of the depleted mantle (*3*, *4*). We argue that model ages should be calculated using the composition of new continental crust, which is generally more enriched isotopically than the depleted mantle.



Setting a date. (**Left**) Graphical representation of the Hf isotope evolution of the depleted mantle (DM) and of new continental crust (NC). The DM and NC evolution curves are those for linear evolution from a chondritic uniform reservoir (CHUR) value at Earth's formation [i.e., 0 at 4.56 billion years ago (Ga)] to ε_{Hf} = 17 at the present for the depleted mantle (*6*, *7*), and ε_{Hf} = 13.2 for the new crust (see right panel). Hafnium "model ages" represent when new continental crust was generated, and they are typically calculated using an average ^{176}Lu/^{177}Hf ratio for the crustal source of the magma analyzed. Hafnium model ages are younger when calculated from the evolution curve for new continental crust (T_{NC} ages) than for the depleted mantle (T_{DM} ages). (**Right**) A worldwide compilation of Hf isotopes in volcanic rocks from 13 modern island arcs (whole-rock analyses, *n* = 534; GEOROC online database compilation, http://georoc.mpch-mainz.gwdg.de/georoc/Entry.html). Red vertical bars represent the average value (at 2-SD precision) for each island arc. The weighted average of the means of 13 arcs (ε_{Hf} = 13.2) is taken as a proxy for the composition of the present-day new continental crust.

Mass balance calculations indicate that at least 80% the continental crust was generated along destructive plate margins (*5*). This implies that magmas generated along destructive plate margins should be used to constrain the isotope composition of new crust at the time of its formation. The Hf isotope records from modern island arcs worldwide are thought to be more representative of the isotope ratios of new crust being generated from the mantle than are magmas generated along active continental margins, which are more prone to shallow-level processes of crustal contamination. The Hf (and Nd) isotope ratios in island arcs are on average lower than the present-day value for the depleted mantle (see the figure, right panel) (*3*, *4*, *6*, *7*), primarily because of contributions from subducted sediment (*3*, *4*, *8*).

Zircons are the only widely used record available for the first 500 million years of Earth history, and the development of in situ analyses of integrated U-Pb and Hf isotopes in zircon has had a major impact in studies of the evolution of the continental crust (*1*). Hf isotope ratios are expressed as ε_{Hf}, which denotes the deviation of the ^{176}Hf = ^{177}Hf ratio of the sample from the contemporaneous ratio of the chondritic uniform reservoir (CHUR), multiplied by 10^4. Thousands of analyses are now available, and zircons present in sediments and sedimentary rocks provide more representative records than the zircons in igneous rocks (*1*). Analyzing the Hf isotope composition and crystallization age of thousands of zircons worldwide shows that very few zircons plot close to the depleted mantle (*1*) and hence have model ages similar to their crystallization ages. For instance, there is widespread agreement that appreciable volumes of new crust were generated in the late Archean around 2.7 billion years ago (*9*), but late Archean samples all plot appreciably below the depleted mantle curve (*1*). These observations reaffirm that the model ages of continental crust formation should not be calculated from the depleted mantle composition, but rather should be calculated relative to the isotope composition of material that represents new continental crust at the time of its extraction from the mantle (see the figure, left panel).

The best estimate for the present-day composition of the average new crust is ε_{Hf} = 13.2 ± 1.1, the weighted average of the means of 13 modern island arcs worldwide (see the figure, right panel). The secular evolution of the new continental crust is represented by the red curve in the left panel. Its

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linear evolution is consistent with models for continental growth in which new continental crust is continuously generated along destructive plate margins (*1*, *10*). Relatively few zircons (<2%) plot between the depleted mantle and the new crust curves (*1*), which suggests that incorporation of preexisting crustal material into the mantle source of the pristine continental crust has been a long-standing feature, at least since the onset of plate tectonics and the development of supercontinents around 3.0 billion years ago (*11*).

Model ages calculated from the composition of the new crust are up to 300 million years younger than model ages traditionally calculated from the depleted mantle. As a result, new crust ages are generally more consistent with the geological record, which opens new perspectives in crustal evolution studies based on radiogenic isotopes.

References

1. C. J. Hawkesworth *et al.*, *J. Geol. Soc. London* **167**, 229 (2010).
2. D. J. DePaolo, *Nature* **291**, 193 (1981).
3. W. M. White, P. J. Patchett, *Earth Planet. Sci. Lett.* **67**, 167 (1984).
4. C. Chauvel, E. Lewin, M. Carpentier, N. T. Arndt, J.-C. Marini, *Nat. Geosci.* **1**, 64 (2008).
5. R. L. Rudnick, *Nature* **378**, 573 (1995).
6. V. J. M. Salters, A. Stracke, *Geochem. Geophys. Geosyst.* **5**, Q05B07 (2004).
7. R. K. Workman, S. R. Hart, *Earth Planet. Sci. Lett.* **231**, 53 (2005).
8. T. Plank, *J. Petrol.* **46**, 921 (2005).
9. K. C. Condie, *Geophys. Res. Lett.* **22**, 2215 (1995).
10. S. R. Taylor, S. M. McLennan, *The Continental Crust: Its Composition and Evolution* (Blackwell, Oxford, 1985).
11. P. A. Cawood, A. Kröner, S. Pisarevsky, *Geol. Soc. Am. Today* **16**, 4 (2006).

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PHYSICS

A New Twist for Electron Beams

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Passing an electron beam through carefully prepared holograms creates electron vortex beams that improve resolution and allow samples to be manipulated.

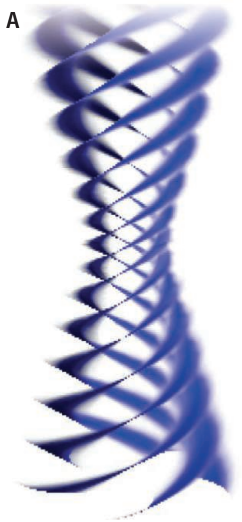
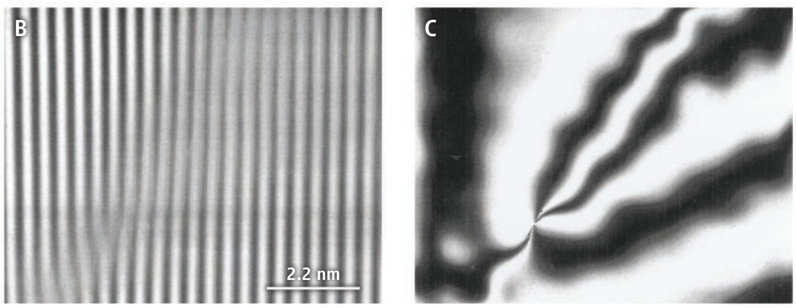
The transmission electron microscope (TEM) has primarily been used by physical and life scientists for imaging structures and compositions ranging in size from atoms to cells. New applications are likely to emerge from recent demonstrations that it is possible to change the nature of the primary electron source used to create images. Normally, an electron is emitted from its source in a TEM as a plane wave. However, as shown on page 192 of this issue by McMorran *et al*. (*1*) as well in recent studies by Verbeeck *et al*. (*2*), passing the electron plane wave through a hologram that contains a dislocation causes it to undergo diffraction and split into an electron vortex beam. This type of electron beam can be used to create higher-resolution images and to manipulate the structure and properties of the sample.

When an electron beam diffracts from these holograms, it has a singularity in the quantum mechanical phase along the center of the beam; the phase is not well defined. Interference effects cause the central beam intensity to vanish, creating instead a vortex of twisted beams spiraling around this node that passes through the microscope (see the figure, panel A). The absence of intensity at the beam center can be used to improve the resolution of the scanning mode of electron imaging, because resolution is determined by the beam's spot size, and the central beam is the most difficult to focus.

Another useful property of these vortex electron beams is that they have an associated orbital angular momentum (OAM). Like an ice dancer doing a spin, the spiraling wavefront of the electron vortex beam carries OAM. However, the electron beams are charged, so the OAM can couple with electrons, electrostatic charges, and magnetic potentials in the sample. Electron vortex beams could be used to induce currents in superconductors, apply magnetic fields at the nanoscale, and make or break electronic bonds. New types of electron beam lithography may enable the building of three-dimensional nanostructures in which atoms are picked up, moved, and set in place rapidly and accurately.

The singularity at the center of the electron vortex also has a topological charge of m that is a measure of the number of the twists per electron wavelength. Here, m increases with the higher-order diffracted beams and enables greater coupling with the atomic structures. The holograms are nanofabricated gratings with a dislocation where one or more lines are added to half of the grating. A dislocation core that adds one line (one grating line forks into two) produces $m = 1$ for the first diffracted beam, $m = 2$ for the second diffracted beam, and so forth. McMorran *et al*. created a hologram with 25 lines added at the dislocation that has $m = 25$ for the first diffracted beam, $m = 50$ for the second diffracted beam, and up to $m = 100$ for the fourth diffracted beam. However, this higher topological charge comes at a price—the intensity of the diffracted beam is lower, and may be too low for adequate coupling with some types of structures.

These limitations aside, an immediate application of electron vortex beams is to produce new types of communication and

Crystal defects underlie new microscopy tools. (**A**) Electron beams that pass through a hologram containing a dislocation form a vortex of diffracted beams. A simulation by McMorran *et al*. of a higher-order diffracted beam illustrates the helical structure of the wavefronts. (**B**) A hologram is created from a GaAs crystal bearing a dislocation by the interference of the 000 beam (a plane wave) with a diffracted beam (an electron vortex beam) (*6*). (**C**) The reconstructed phase image of the hologram (amplified by a factor of 8) shows a singularity at the position of the dislocation core.

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