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Earth science

Hard-cored continents

Andrew A. Nyblade

Each continent contains pockets of ancient crust that appear to have been unaffected by tectonic forces since they formed billions of years ago. Why? There's now a fresh twist on the usual explanation.

The existence of the small, ancient cores of continents, known as cratons, has long been a puzzle. Cratons were created during the Archaean eon, more than 2.5 billion years ago, and form the oldest parts of Earth's tectonic plates. Yet they have somehow remained largely unmodified by tectonic forces. By contrast, younger parts of the continents bear the geological scars \of repeated tectonic buffeting, and appear to be weaker and less stable. So, why are cratons tectonically stable? Lee and co-workers (page 69 of this issue[1]) provide new insight into this question.

Not much is known about the processes that formed cratons in the Archaean. But it has been suspected for some time that their tectonic longevity derives from 'keels' — as on sailing vessels — that extend deep into the Earth (Fig. 1). These keels are made of lithospheric mantle more than 2.5 billion years old and more than 200 km deep. The lithosphere is Earth's outermost rigid layer, and consists of the crust and uppermost mantle. The chemical composition of craton keels is thought to stem from their depletion of the basaltic constituents (Al_2O_3, FeO, CaO) and volatile molecules (H_2O, CO_2) compared with the 'fertile' mantle that is the source of basaltic volcanism along mid-ocean ridges[2,3].

According to theory, a combination of the loss of basalt and volatiles makes the keels strong enough to resist wholesale destruction by tectonic forces. This is because extraction of basaltic constituents during volcanism removes iron from the remaining mantle, making it more buoyant than its surroundings. In addition, removal of volatiles from the mantle during mantle melting increases the melting temperature and stiffness of the remaining material, making it even more resistant to tectonic forces.

Lee *et al.*[1] show that depletion of basaltic constituents does indeed influence the strength of lithospheric mantle, mainly by controlling the thickness to which the keel can grow. But they find that the degree of depletion is not always a function of age. Their evidence is geochemical, and comes from two regions of southwestern United States where small pieces of lithospheric mantle, called xenoliths, have been brought rapidly to the surface by volcanoes. One location is in the southern Basin and Range province, where crust 2.0–2.6 billion years in age is being deformed by tectonic forces. The other is in the Colorado plateau, a tectonically stable region of crust 1.6–2.0 billion years old that borders the Basin and Range province to the east (see map on page 70.)

By measuring the abundance of rhenium and osmium isotopes in the xenoliths, Lee and co-workers show that the lithospheric mantle beneath the sampling localities is similar in age to the overlying crust. The bulk composition of the xenoliths, together with the pressure and temperature conditions under which some of their component minerals formed, also reveal that the lithospheric mantle beneath the Basin and Range province is thinner and less depleted of basaltic constituents — that is, more fertile — than it is beneath the Colorado plateau. So it seems that it is not the age of the lithospheric mantle that correlates with its tectonic stability. Rather, given the greater basaltic depletion and thicker lithospheric mantle found under the younger yet more stable crust of the Colorado plateau, it is depletion and in turn thickness that are the determining factors.

The authors next turn to the question of how this loss of basalt controls the thickness of the lithosphere. Here they draw upon the observation that cratonic keels must in fact be neutrally buoyant, even though they contain less basalt, because they are not associated with significant perturbations in Earth's gravity field. According to the isopycnic (equal-density) condition proposed by Jordan[2], the negative buoyancy resulting

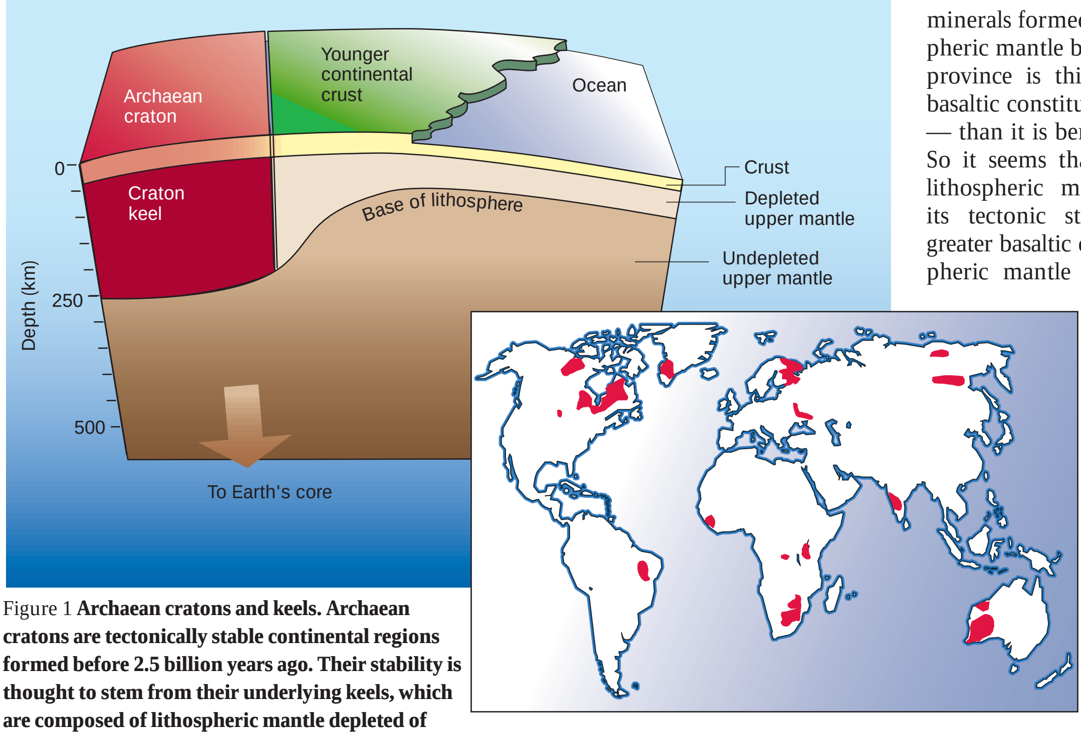

Figure 1 **Archaean cratons and keels. Archaean cratons are tectonically stable continental regions formed before 2.5 billion years ago. Their stability is thought to stem from their underlying keels, which are composed of lithospheric mantle depleted of basaltic components and are at least twice as thick as the lithospheric mantle beneath younger parts of the continents and oceans. As reported by Lee *et al.*[1], the thickness of the keel is controlled by the degree of basalt depletion in the lithospheric mantle. The inset map shows the global distribution of Archaean cratons. (Main graphic modified from ref. 2.)**

from basalt depletion is offset by the positive buoyancy that results from the lower temperatures in the keel relative to those in the surrounding, convecting mantle.

Lee *et al.*[1] compare estimated variations in the thickness, temperature and density of the lithospheric mantle with values calculated by assuming the isopycnic condition, and find that the condition holds for the southwestern United States. So, if the lithospheric mantle were to thicken further by conductive cooling in their study area, the deepest parts of the mantle lithosphere would become less buoyant and sink into the convecting mantle — as long as chemical depletion did not offset the increase in negative thermal buoyancy. In this way, the degree of basalt depletion modulates the thickness of the lithospheric mantle.

A further implication of the results[1] is that more continental crust may have formed before 2.5 billion years ago than is indicated by the present distribution of cratons. The presence of thin Archaean lithospheric mantle beneath the Basin and Range province raises the possibility that there could be similar lithospheric mantle under other regions of the continents. We simply may not have recognized it because Archaean lithospheric mantle is commonly, but mistakenly, assumed to be thick and strong. Alternatively, the weakness of this thin lithosphere may have led to its preferential destruction through tectonic recycling. In either case, much more continental crust could have formed in the Archaean than today's distribution of cratons would indicate. ■

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Fundamental physics

Resistance of a perfect wire

Albert M. Chang

Intuition tells us that a wire without defects should have zero resistance. But in the real world all conductors, however perfect, have some resistance. A new study confirms that electrical contacts are the problem.

It is the dream of physicists and electrical engineers alike to build electronic devices that can conduct electrical currents with the minimal amount of resistance. The miniaturization of electronics will soon lead to devices of the smallest possible physical dimensions, in which quantum effects become important. In this context, the ultimate conductor would be a very thin one-dimensional wire that has no defects to inhibit resistance-free currents. Electrons in such a wire are ballistic — that is, the wire is so clean that the distance travelled by the electrons between collisions is longer than the wire itself. On page 51 of this issue de Picciotto *et al.*[1] describe electrical conduction in a nearly perfect, ballistic one-dimensional wire. This groundbreaking work helps to establish fundamental limits on the current-carrying capacity of ideal wires and their connections.

Imagine a perfect, extremely thin, straight wire in which electrons are allowed to move only along the wire. A perfect wire has no defects, kinks or obstacles other than a connection at each end to allow current to pass through an external circuit, and perhaps two probes along the wire to measure the voltage (Fig. 1a, overleaf). Will the motion of the electrons and hence conduction of electricity in this wire proceed without resistance? De Picciotto *et al.*[1] have created this imaginary wire in the laboratory. They find that the resistance of a wire can be separated into two parts: an 'intrinsic resistance' due to the scattering of electrons by imperfections in the wire, and a 'contact resistance' associated with the connections to the external circuit. The intrinsic resistance is measured by the two voltage probes, which draw negligible current. The authors find that in their defect-free wire the intrinsic resistance does actually reach zero, although there is a finite contact resistance of around 13 kΩ.

The vanishing of the intrinsic resistance agrees with the simple notion that the current-carrying electrons should move freely if there are no obstacles. Our picture of electrical resistance as the result of momentum-changing deflections on charge-carriers dates back to the work of Drude around 1900. The most effective deflections are those that scatter charge-carriers in the opposite direction to that of their flow. In the late 1950s, Landauer[2] became fascinated with the idea of electronic miniaturization and proposed a conceptual framework for understanding electrical conduction in one-dimensional wires. Landauer realized that the wire can be thought of as being connected to electrochemical potential reservoirs, in which many electrons of different energies are available for conduction (Fig. 1b). Once an electron enters the wire it cannot change energy, and only momentum changes can affect the electrical current. So where the wire is connected to the reservoirs there is a mismatch of energies and a contact resistance develops. Conversely, in a regular three-dimensional wire, the contact resistance is very small and so tends to go unnoticed. But in a one-dimensional conductor, with no impurities, the intrinsic resistance must vanish although the contract resistance is high.

Until the 1980s most current measurements on mesoscopic devices (typically a micrometre or less in size) used a two-terminal geometry, in which voltage difference is measured solely between the current source and drain. But after Webb *et al.*[3] developed the technology to place multiple terminals on small metallic wires and rings, it was discovered that the four-terminal — two voltage probes in addition to two current leads — resistance of a non-ballistic wire changes if the direction of an external magnetic field is reversed. This unexpected result was explained by Buttiker[4], who generalized Landauer's ideas to devices with multiple terminals. He pointed out that, in the absence of magnetic impurities, a four-terminal resistance should be unchanged by swapping over the current and voltage probes and reversing the magnetic field.

After considering the multiple-terminal case, Buttiker proposed that a two-terminal resistance must always contain a contact resistance, even if the wire is ballistic. This contact resistance can be measured directly between point contacts that are shorter than the mean free path of electrons in a non-ballistic conductor[5,6]. Two-terminal measurements of ballistic wires also found their resistance to be quite large, around 13 kΩ. Is this resistance just the sum of the contact resistances?

De Picciotto *et al.*[1] have built a multi-terminal one-dimensional conductor to address this issue. Classically a wire is considered to be one-dimensional if its width exactly accommodates the size of the charge carriers with no room for wiggling. Electrons are essentially point objects, so this is technically unfeasible. But this is where quantum mechanics comes to the rescue. If an electron is made to occupy the lowest quantum-mechanical energy state in the lateral directions, without access to higher excited states, it would be free to move only in one dimension. The key is to confine electrons so tightly that the energy levels of the excited states are too high for them to reach. One way of doing this is to cool the wire to sufficiently low temperatures — but not superconducting temperatures — so that the excited states are thermally inaccessible and conduction is strictly one dimensional.

To create the perfect one-dimensional