Stability of ancient cratons and lithospheric mantle composition

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Most of the earth’s continents have regions of very old crust with high geological stability, undisturbed by tectonic events since Precambrian times. These lithospheric segments, better known as cratons, have crystalline basement rocks or shields surrounded by sediment-covered platforms, unaffected by deformation or metamorphism. In India, such areas occupy parts of southern, eastern and northern regions. These are the well-studied 3.5–2.0-Ga-old (Archaean–early Proterozoic) cratonic greenstone–granitic domains with cratonized central core region of supracrustals, the 3.0–0.5-Ga-old (late Archaean-Proterozoic) high-grade granulitic rocks, and the middle-to-late Proterozoic intracrustal belts of platformal sediments called the Paranáns, formed at the margins of these cratonized central core region (Figure 1). This Indian Shield, like other similar areas in Fennoscandia, Siberia, Central Africa, Brazil and Australia carries major metallocenic provinces of iron, gold, copper and nickel, which are all products of intense granitoid magmatism and episodes of ultrabasic and basic volcanism during late Archaean period, particularly between 2.74 and 2.66 Ga (ref. 2).

The earth’s lithosphere forms the outer rigid shell (0–70 km) above a low seismic velocity zone of partially molten soft uppermost parts of the mantle, called asthenosphere (70–250 km). According to classical concepts, the lithosphere is the region of the crust and uppermost mantle capable of ‘statically supporting disruptive stresses’ over geologically long periods, whereas the asthenosphere is the region below the lithosphere where ‘mass flows associated with isostatic adjustments’ occur5. Geophysical and geochemical studies, over the years, have brought out the importance of the lithosphere–asthenosphere interface in the evolution of geochemical reservoirs arising from thermal processes in earth’s interior (Figure 2 a). Of these reservoirs, the asthenosphere, which is a convecting region, is considered as the source for the mid-ocean ridge basalts (MORB). The lithosphere is non-convecting, heterogeneous and preserves records of the physical and chemical changes associated with the tectonic events through time. The lithospheric mantle is supposed to have undergone significant melting to be ‘depleted’ in Al, Ca, Fe, Ti and the asthenosphere, by contrast, is usually richer in these basaltic constituents and geochemically more homogeneous, because it convects. The development of plate tectonic theories enabled division of the earth’s surface into a mosaic of plates exhibiting large-scale horizontal motions without much deformation. Their motions are thought to arise in response to a number of forces, mainly gravitational instability triggered by heat production in the earth’s interior as well as by the earth’s attempts to overcome the uneven distribution of mass. A special term ‘tectosphere’ is used for the region occupied by these plates3,5.

Heat flow and seismic data have revealed that the thickness of the continental tectosphere is highly variable – thin (<100 km) in regions of great instability and thick (up to 300–400 km) beneath stable cratonic areas and platforms. A thick tectosphere would imply that the bottom of such stable regions extends much deeper into the mantle, i.e. the regions have deep roots or ‘keels’ (Figure 2 b). Seismic tomographic studies have shown that the roots of the Indian cratonic areas, formed in the Archaean–Proterozoic times, extend to depths between 60 and 300 km6,7 and some of these cratons have a record of tectonic stability over long geological periods. But how the development of such deep roots confers stability to the crustal segments above, has been engaging the attention of scientists. The fact that Archaean cratonic regions in many countries, including India, are tectonically stable, has led to the belief that age is a major factor in their strength and stability. Now this relationship is doubted and instead, changes in physical and chemical constitution of the lithospheric mantle zone like depletion due to basaltic magmatism are attributed. This composition-related crustal stability was put forward during 1960s and 1970s (refs 3–5) and results from recent isotopic studies in the Cordilleran Mountain Belt in western United States have added support to this view5.

Generally, tectonic stability of continental crusts differs considerably from
that of oceanic crusts. Continental lithosphere is more susceptible to deformation unlike the oceanic lithosphere, an aspect related to differences in their compositional structure. Parameters that disturb the stability of continental crusts are the mutually related thermal, chemical and density gradients. These do not remain constant and are known to have changed over geological time and have also varied spatially along the same depth. The internal processes that may help to resist their disruptive tendencies have been subject of several studies over the past few decades and a most plausible mechanism, referred to as the 'isopycnic' or 'equal density' hypothesis, was advanced some years ago. According to this hypothesis the 'negative buoyancy' imposed by the hotter thermal state of mantle beneath the continents is exactly compensated by a lower intrinsic density of the mantle beneath the continents. Any thermally produced mass excesses within such sublithospheric continental tectosphere are compensated by chemically produced mass deficiencies. Subtraction of basalt from mantle, which has a garnet lherzolite mineralogical composition, will leave a less dense residual mantle. If the degree of depletion has a negative correlation with temperature, the tectosphere can achieve hydrostatic equilibrium with the adjacent mantle. Actual findings have shown that the average continental garnet lherzolite is less dense than the oceanic garnet lherzolite by about 1.3 ± 0.2%, a density difference sufficient to offset volume contraction resulting from cooling of about 400°C, which is within the range of ocean-shield temperature contrast. Thus, these dynamic processes adjust the compositional gradients and the tectosphere extending below the lithosphere achieves hydrostatic equilibrium with the surrounding mantle and remains stable. It is, therefore, clear from the isopycnic hypothesis that the strength and bulk composition are related, since a mantle depleted in basaltic constituents and heat-producing radiogenic elements generates a thinner and hence weaker thermal boundary layer. 

The mass deficiencies occur as a result of removal of basaltic composition magma, from the lithospheric mantle. Such depletions usually occur during magmatism associated with continental rifting, episodes of flood basalt and volcanism along the wedges of convergent plate boundaries. Active continental evolution, particularly during the Proterozoic and Phanerozoic eras, had witnessed magmatism of these kinds. Depletion followed by consolidation and thickening, i.e. extension of root or keel takes place during tectonic development (Figure 2 b). The depleted nature of this zone has been verified from the composition of mantle xenolith samples or their minerals like garnet, chromite, and diamond, brought up from the root or the keel region. These have been found to be notably depleted in basaltic constituents Al₂O₃, FeO, CaO, H₂O and CO₂ compared to the samples from regular or 'fertile' mantle. The removal of iron and volatiles makes these cratonic roots more buoyant, rigid with higher melting temperature, thereby enabling them to hold out against tectonic forces.

Inasmuch as depletion and tectonic stability are observed to be associated in many areas, a direct correlation between stability and the age of the craton was assumed since the degree of depletion is expected to be greater where the cratons were formed very early in the Archean. But such a correlation failed in the studies in Cordilleran Belt in western United States. Here the lithospheric mantle that is depleted is the younger (1.6–2.0 Ga) undeformed Colorado Plateau. The older (2–2.6 Ga) Archean lithosphere of Basin and Range Province of this Belt has been deformed during Palaeozoic and Cenozoic orogenic events. The degree of depletion of basaltic constituents, as measured from Mg/Mg + Fe ratio (an index on the state of depletion), revealed that the younger undeformed Colorado Plateau is underlain by thick lithospheric mantle that is 'depleted' and deficient in minerals extracted by partial melting, whereas the older Archean region (Basin and Range Province) is underlain by a 'fertile' thinner mantle, not depleted by melt extraction.

Dating of the underlying root zone is essential to determine the age of stabilization of the crust. Some of the conventional techniques for this purpose have limitations, particularly because of the open-system geochemical behaviour in these zones. In this respect, the Re-Os isotope system is considered ideal for dating and tracing the geochemical pedigree because of its high concentrations in mantle peridotites, especially as inclusions of sulphides in olivine grains. Also, the compatible nature of Os and its

Figure 2. a. Subcontinental structure and basalt source regions; b. Stable Archean craton having deep root or keel composed of lithospheric mantle depleted of basaltic constituents. The degree of depletion controls the thickness of the craton root (adapted from refs 16 and 18).
relative immunity to post-crystallization disturbances (sulphide inclusions in olivines are shielded by the host mineral) make this method suitable\textsuperscript{14}. Studies, using this isotope system, on xenoliths from a number of cratons (Kaapvaal, Siberia, Wyoming, Slave and Tanzania) have shown how the crust and mantle parts of stable continental lithospheric roots have remained coupled since formation in the Archaean, despite continental drift\textsuperscript{15,16}. In the Cordilleran Mountain Belt also, Re–Os studies have confirmed that the age of the xenoliths was the same as the crust above. In this context, it may be mentioned that during the break-up of Gondwanaland and separation of India from Australia–Antarctica, cratonic roots of India may have been disrupted during drift. This is inferred from osmium isotopic studies of xenoliths of Proterozoic age, from Kerguelen Island (southern India Ocean)\textsuperscript{17}. These xenoliths distinctly belong to the continental lithosphere, caught up in the newly forming oceanic lithosphere.

The stability of some of the continental crusts, undoubtedly, appears to be controlled by density, the depleted mantle intrinsically less dense than the fertile mantle, due to loss of iron extracted during melting. If cooling by conduction leads to the lithospheric mantle thickening further, its deepest parts will be forced to sink into the mantle because of their low buoyancy\textsuperscript{15}. The degree of depletion, which regulates the thickness, thus creates a thermal boundary layer between the deep convecting mantle and the crust, thereby reducing or eliminating convection-related tectonic instability at the surface. Only those Archaean crusts that developed a strong, thick, high viscosity, thermal and less-dense boundary layer achieved ability to resist tectonic forces\textsuperscript{10}. Stabilization of nuclear Archaean cratons in the interval 2.8–2.0 Ga period possibly marked the earliest phase of formation of thick lithospheric root zones conferring long-term stability. The observed geological stability of some of the Archaean cratonic areas in India may, therefore, be attributed to their 200–300 km deep\textsuperscript{16} lithospheric roots. It is possible that these areas may be lying over depleted lithospheric mantle, though there is presently no Re–Os isotopic data on mantle xenoliths of Archaean–Proterozoic age for these areas to substantiate this inference.


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**COMMENTARY**

**On the state of physics in India – Personal viewpoint**

**S. Dattagupta**

Today we are in the 55th year of independence, and if we look back, in 1947, we hardly had any semblance of what may be called organized physics. The geniuses of our country, such as J. C. Bose, M. N. Saha, C. V. Raman, S. N. Bose, K. S. Krishnan and others, achieved great heights, essentially through individual efforts. But, today’s world is different. In order to make progress, one needs collective, cooperative approaches backed by effective infrastructural support.

If we analyse all that has happened in organized physics in India in the last 54 years, we realize that we have come a long way. We have different ministries such as the Ministry of Atomic Energy and Space, the Ministry of Science and Technology, the Ministry of Human Resource Development, the Ministry of Planning, etc. looking over physics. Under these ministries, we have different organizations such as the Bhalla Atomic Research Centre, the Indian Space Research Organization, the Tata Institute of Fundamental Research and a plethora of other institutions, busy in carrying out research and development activities. In the city of Kolkata itself, we have several research institutes, supported by one ministry or another, such as the Saha Institute of Nuclear Physics and the Variable Energy Cyclotron Centre of the Department of Atomic Energy, the S.N. Bose National Centre, the Jagadish Bose Institute and the Indian Association for the Cultivation