The quest for earth's oldest crust

A. V. Sankaran

Geologists have been probing various continental terrains in search of possible remnants of earliest crust that may have survived more than four billion years (b.y.) of earth's history, the first 10 to 100 million years (m.y.) of which were catastrophic, marked by intense volcanism and impacts from meteorites. Earlier views of a globe circling veneer of 'sialic' crust arising from a residuum of crystallizing molten earth, are not favoured and it is now believed that the pre-4 b.y. crusts were essentially oceanic basalts or possibly high magnesian komatiites produced under the prevailing high temperature conditions[1–3]. In fact, crust formation studies, based on Nd isotopes, have revealed that roughly 8% of crust had formed by the time the earth was 0.5 b.y. old and about 60%, by 2.6 b.y. (refs 1, 4). Now, the discovery of 4.14–4.28 b.y. old detrital zircons[5–7] within younger sedimentary strata in Mt. Narryer complex in western Australia and a few near 4 b.y. old zircons from other places have spurred interest among the geological community to look for their provenance or parent rocks. Since zircons occur as accessories, mostly in granites, it is likely that their source rocks were granitic, which must have remained stable for periods long enough to be weathered down to provide materials, including these zircons for the younger sedimentary sequences.

For the past two decades, attempts by geologists to find crusts that had formed between 4.0 and 4.5 b.y. could lead them only close to the 4 b.y. mark. The Acasta gneissic area in the Slave Province (NW Territories, Canada) forming part of a meso- to palaeo-Archaean continental crust in the Canadian Shield was found retaining rocks older than 3.6 b.y., the oldest among them being 3.96 b.y. (ref. 8). Exposures quite close in age to these gneisses occur in western Greenland (3.8–3.6 b.y. Itsaq gneisses)[9,10], Montana-Wyoming in USA (3.4 b.y. gneisses)[11], W. Australia (3.63 b.y. orthogneiss)[12], Antarctica (3.9 b.y. granulites, Enderby Land)[13] and China (3.8 b.y. Sino-Korean Craton)[14] (Figure 1). In India, 3.0 to 3.3 b.y. rocks have been reported in Singbhum, N. Orissa (tonalite gneisses within Singhbhum granite)[15,17], Karnataka (Gorur-Hassan gneiss)[18], Goa (trondjemite gneiss)[19] and Rajasthan (amphibolite, Udaipur)[20]. The discovery of such crusts in India and elsewhere, formed close to 4 b.y. mark (although the slightly higher ages reported are contested) indicating development of stable geological conditions by then, had raised hopes for locating still older relicts. In this quest over the last few years, field and laboratory investigations by geologists from Canada, USA and Australia in the Acasta gneissic region pushed the record of rock age closer than ever before to the 4.5 b.y. mark.

Recognition of rocks formed within 0.5 b.y. of earth formation requires a precise isotope dating technique and availability of suitable materials preserving *in toto* the radiogenic products to testify their antiquity. The mineral zircon, highly resistant to weathering processes and low-grade metamorphism, is ideal in this respect. However, alpha particles from decaying uranium, present in small amounts, damage the mineral's lattice (metamictization) making it susceptible to alteration and consequent leak

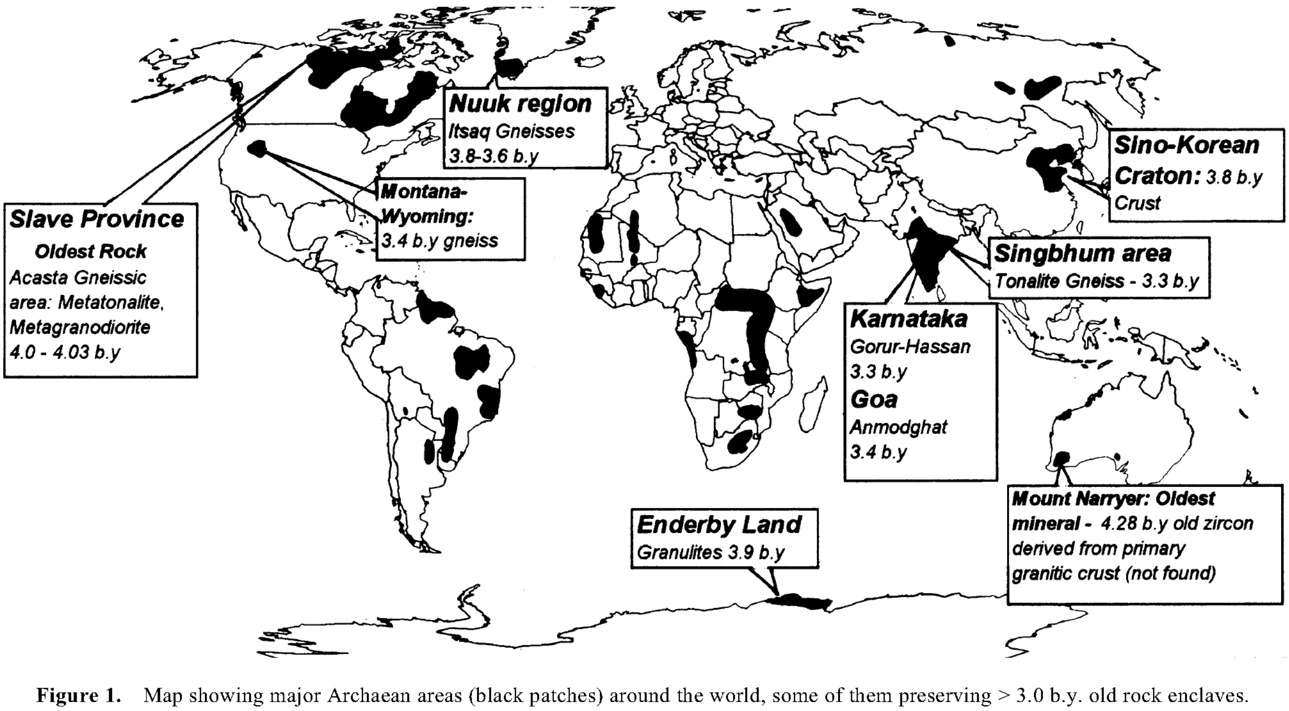

Figure 1. Map showing major Archaean areas (black patches) around the world, some of them preserving > 3.0 b.y. old rock enclaves.

of radiogenic Pb. This phenomenon, therefore, restricts the utility of this mineral to its undamaged portions only, which alone could provide reliable dates. Hence, a special microprobe to selectively extract materials from such unaltered areas was developed at the Australian National University in Canberra during the 1980s called SHRIMP, an acronym for sensitive high-resolution ion microprobe. This probe employs a beam of oxygen ions to ablate micron-sized unaltered (non-metamict) portions from the zircon grains to produce a stream of atoms, which could be dated by U–Th–Pb mass spectrometry. Employing SHRIMP techniques in the Acasta area, Slave Province, geologists dated zircons from two metatonalites and one metagranodiorite which yielded igneous ages 4.0–4.055 b.y. (refs 21–23). These dates have shown that this oldest known crust in the Canadian Shield is even older than hitherto considered and for the first time, rocks within 500 million years of formation of earth could be located.

The survey of Acasta gneisses and the surrounding area in the Slave Province has revealed a succession of quartzites (often chromite bearing, hinting possible komatiitic derivation), banded iron formations (BIFs), laid on weathered surface of gneisses and intruded by 2.9 b.y. old volcanic rocks. Interestingly, a similar sequence of rocks is also met with in other cratonic areas of the world, including Singbhum and Karnataka in India. These obviously point to their coexistence, at one time, as a composite landmass or a supercontinent during pre-3 b.y. period. Though this postulate is now widely accepted, it has triggered lengthy debates, firstly about the mechanism by which such continental crusts were initially extracted from early earth, and secondly about the geological process that had led to the breakup of such a supercontinent.

Exposures of early crustal rocks around the world generally consist of granite-greenstone belts and gneisses, the latter more common and composed of felsic (Na-rich) plutonics – tonalite-trondjemite-granodiorite (TTG) suite of rocks. One view considers these TTGs were products of partial melting of young oceanic lithosphere subducted due to the higher heat flow during the Archaean[1,34,35]. Thus, the intermediate composition gneisses, such as the Acasta gneisses, are products of partial melting of subducted slabs or intracrustal reprocessing of mantle derived magmas and juvenile crust[8]. It is also suggested that these rocks could also be derived directly from mantle melts[8,24,25]. Large areas of such TTG rocks occurring as enclaves in the Karnataka and Singhbhum cratons in India are also, likewise, considered products of the thermal and chemical evolution of early mantle[25].

The mechanism for the assembly and breakup of the Archaean supercontinent has remained a contentious issue among the geologists. Several geochemical, geophysical and palaeogeographic studies have supported views about rifting of early continents periodically (at 2.7 b.y., 1.8 b.y., 900 m.y. and 300 m.y.)[26] and massive crust formations associated with these events[1,4]. In younger Proterozoic and Phanerozoic periods, plate tectonism is the accepted cause for rifting and breakup, but such mechanisms are considered non-existent during the Archaean when surface tectonics were confined to mere recycling of the thin oceanic crust without distinguishable lithosphere and asthenosphere. According to Warren Hamilton, one of the proponents of the plate tectonic theory, the distinctive assembly that characterizes the Phanerozoic convergent plate system such as ophiolites, magmatic arcs, accretionery wedges, fore-arc basins and other associated features, is not seen in the Archaean terrains and even the few basic and ultrabasic rocks of the period do not resemble ophiolites, either in their stratigraphic disposition or in petrology[27]. Besides, these Archaean rocks lack features typifying rifting, rotation and reassembly seen in the Proterozoic and Phanerozoic equivalents. Further, the juxtaposition of rocks of different ages, sometimes a billion years apart, he feels, is an unlikely feature if formed by plate tectonic process of gradual accretion at plate boundaries. They could, instead, be only episodic products of plume tectonism gradually adding up to the edges of the continental nucleii. Rifting of the ancient continent was possibly initiated by deep mantle plume events which triggered submarine volcanism around 2.7 b.y. leading to continental breakup[1,27]. Apart from these considerations, some geologists feel that the thermal state of the earth then was also not conducive for the stability of newly formed rigid plates, as the earth at that time was too hot for plate formation. They say that even if these plates did form and survive, their buoyancy must have prevented their subduction, a process so vital for plate tectonism to operate. Plate tectonic mode of rifting, therefore, is not considered to have operated during Archaean but supposed to have commenced much later, by about 2.0 b.y., and in an essentially modern mode, from about 0.8 b.y. ago[27]. Studies on the evolution of high grade and granite-greenstone terrains in the Indian Shield also point to the role of mantle heat release through plume tectonics in bringing about the rifting and breakup of the ancient supercontinent of which India was a part[25].

Yet, a group of geologists strongly believe that plate tectonic processes operated during early Archaean itself and that several short-lived plates existed, colliding and rifting 4.0 b.y. ago[1,28]. They cite evidences such as sea-floor spreading, accretionery segments adjoining continental edges noticed in some of these ancient cratonic areas like the Slave Province of Canada. Further, contrary to the belief that the Archaean earth was too hot for plate stability, recent experimental and other observations[28] have shown that this period was not excessively hotter than today, as the earth had lost heat effectively through dominant dehydration process which commenced 4.5 b.y. onwards.

Though several geochemical and isotopic studies have contributed considerably in deriving models about growth and development of an early continent[1,8,29–31], Archaean crustal evolution and continental breakup have remained subjects of great debate and speculation. The few very early crusts seen today owe their survival to their thick lithospheric roots and growth of favourable conditions concerning asthenosphere cooling and underplating by subducted oceanic crust[8,26,32]. However, in only one such early fragment (Acasta area) could the search yield an enclave of pre-4 b.y. rock. This area happens to be uplifted and exposed and could, therefore, be surveyed systematically. But, large cratonic areas elsewhere on earth are known to lie hidden, as basement rocks, for younger strata and they could be potential sites preserving similar enclaves. This assumption becomes all the more significant in the light of recent high-resolution seismic tomographic studies which have shown that all Archaean cratons happen to be high seismic velocity regions and some of the fastest areas of this age are today covered by thick ice caps and sediments[33]. This should induce search for locating more enclaves of the earth's oldest crust below such hidden cratonic areas.

Perseverance of earth scientists to detect the oldest crust has progressively taken them from Archaean (Isuan 3.5–3.8 b.y.) to late Hadean (3.8–4.0 b.y.) and now into early Hadean (4.0–4.5 b.y.). Needless to mention, future claims pushing the record further back in time will have to be backed by highly accurate dating on materials not affected by geological processes which alter their isotopic composition and homogeneity, especially when the size of the sample dated, as happens often, is small. Fortunately, advances in instrumentation would enable extraction of adequate sample size from sparsely available natural materials. Judicious choice of techniques such as Laser ablation-inductively coupled mass spectrometery (LA-ICPMS), secondary ion mass spectrometry (SIMS), apart from the high mass resolution–high transmission capabilities of SHRIMP technique already extensively employed in Slave Province of Canada should greatly help to achieve the temporal resolution, precision and accuracy required for dating in the narrow Hadean time. Hopefully, with discoveries of more pre-4 b.y. crusts, a reconstruction of Archaean palaeogeography could be possible and some aspects of early crustal evolution could then be rewritten.

---

1. Taylor, S. R. and McLennan, S. M., *Rev. Geophys.*, 1995, **33**, 241–265.
2. Campbell, I. H. and Jarvis, J. T., *Precambr. Res.*, 1984, **26**, 15–56.
3. Chase, C. G. and Patchett, P. J., *Earth Planet. Sci. Lett.*, 1988, **91**, 66–72.
4. McCulloch, M. T. and Bennett, V. C., *Lithos*, 1993, **30**, 237–255.
5. Maas, R. and McCulloch, M. T., *Geochim. Cosmochim. Acta*, 1991, **55**, 1915–1932.
6. Maas, R., Kinney, P. D., Williams T. R., Froude, D. O. and Compston, W., *Geochim. Cosmochim. Acta*, 1992, **56,** 1281–1300.
7. Amelin, Y., Lee, D. C., Halliday, A. N. and Pidgeon, R. T., *Nature*, 1999, **399**, 252–255.
8. Bowring, S. A. and Housh, T., *Science*, 1995, **269**, 1535–1540.
9. Nutman, A. P., Friend, C. R. L., Kinney, P. O. and McGregor, V. R., *Geology*, 1993, **21,** 415–418.
10. Kambler, B. S. and Moorbath, S., *Chem. Geol.*, 1998, **150**, 19–41; McGregor, V. R., *ibid*, 2000, **166**, 301–308; Kambler, B. S. and Moorbath, S., *ibid*, 2000, **166**, 309–312.
11. Bowring, S. A., Williams, I. S. and Compston, W., *Geology*, 1989, **17**, 971–975.
12. Froude, D. O., Ireland, T. R., Kinny, P. D., Williams, I. S. and Compston, W., *Nature*, 1983, **304**, 616–618.
13. Black, L. P., Williams, I. S. and Compston, W., *Contrib. Mineral. Petrol.*, 1986, **94**, 427–437.
14. Liu, D. Y., Nutman, A. P., Compston, W., Wu, J. S. and Shen, Q. H., *Geology*, 1992, **20**, 339–342.
15. Sharma, M., Basu, A. R. and Ray, S. L., *Contrib. Mineral. Petrol.*, 1994, **117**, 45–55.
16. Moorbath, S. and Taylor, S. R., *J. Geol. Soc. India*, 1988, **31**, 82–84.
17. Saha, A. K., *Mem. Geol. Soc. India*, 1994, **27**, 151–176.
18. Beckinsale, R. D., Drury, S. A. and Holt, R. W., *Nature*, 1980, **283**, 469–470.
19. Dhoundial, D. P. and Paul, D. K., *Precambr. Res.*, 1989, **36**, 289–302.
20. McDougal, J. D., Gopalan, K., Lugmeir, G. W. and Roy, A. B., Workshop on correlation of Archaean crusts, INSD Tech. Repts., **80–03**, 55–56.
21. Bleeker, W. and Stern, R., *Can. J. Earth Sci.*, 1999, **36**, 1083–1109.
22. Bowring, S. A. and Williams, I. S., *Contrib. Mineral. Petrol.*, 1999, **134**, 3–16.
23. Stern, R. A. and Bleeker, W., *Geosci. Canada*, 1998, **25(1)**, 27–32.
24. Shirley, S. B. and Hanson, G. N., *Nature*, 1984, **310**, 222–224.
25. Mahadevan, T. M., in *Charnockites and Granulite Facies Rocks* (eds Murthy, N. G. K. and Ram Mohan, V.), University of Madras, Chennai, 1999, pp. 153–174.
26. Anderson, D. L., *Geology*, 1994, **22**, 39–42.
27. Hamilton, W. B., *Precambr. Res.*, 1998, **91(1–2)**, 143–179.
28. De Wit, M. J., *Precambr. Res.*, 1998, **91**, 181–227.
29. Sylvester, P. J., Campbell, I. H. and Bowyer, D. A., *Science*, 1997, **275**, 521–523.
30. Moorbath, S., *Philos. Trans. R. Soc., London A*, 1978, **288**, 401–413.
31. Armstrong, R. L., *Rev. Geophys.*, 1968, **6**, 175–199.
32. Abbott, D., *Geophys. Res. Lett.*, 1991, **18**, 585–587.
33. Anderson, D. L., Tanimoto, T. and Zhang, Y., *Science*, 1992, **256**, 1645–1651.
34. Martin, H., *Geology*, 1986, **14**, 753–756.
35. Green, M. G., Sylvester, P. J. and Buick, R., *Tectonophysics*, 2000, **322**, 69–88.

A. V. Sankaran lives at No. 10, P & T Colony, I Cross, II Block, RT Nagar, Bangalore 560 032, India.