When did plate tectonics begin?

A. V. Sankaran

Plate tectonic theory, advanced in 1968, conceives earth's outer shell as a mosaic of several lithospheric plates (~ 100 km thick) exhibiting converging or diverging movement of a few tens of millimetres per year relative to one another. This theory has revolutionized the understanding of the thermal evolution of the earth and has served as a good framework to explain all of our planet's tectonic and magmatic activities. But, certain aspects of plate tectonics are still much discussed, particularly, its beginnings in the earth's evolution. According to established view, this began during Meso- to Neo-Proterozoic times (2.0–0.8 Ga)[1,2] but others believe that this process had its roots in Hadean-Archaean transition (4.2–4.0 Ga), and with the gradual development of thick crust the subduction style of plate tectonic recycling commenced during late Archaean[3]. Over the last two decades, multidisciplinary studies which have provided voluminous field and laboratory data on the dynamics of early mantle have prompted revision of existing ideas on this phenomenon, especially in judging early earth plate tectonics from its present-day style of operation.

The operation of plate tectonic process is inferred from the crustal plate motions and rotations, by the presence of subduction zones, oceanic ridges marking lateral spread of the plates, magmatic arcs, accretionary wedges, forearc basins and occurrence of ophiolites and other igneous rocks including high-pressure assemblages. Till a few years back, most of these 'hallmark' features were reported only from the Phanerozoic strata (< 542 Ma), and this had led to the belief that plate tectonics operated only in this time period. However, increasing finds of equivalent hallmark rocks and settings from older Archaean strata are pushing the beginnings of plate tectonics to still earlier times, and in the process has unfolded a temporal evolution in the pattern of its operation. Examples of such finds have come from several well-known Archaean granite-greenstone belts like the Superior Province (Canada), Kaapvaal (South Africa), Pilbara (Australia) and in India from the Dharwar, Singhbhum and Bastar cratons, and recently from North China craton and these are considered progressive accretions at plate convergent margins[3–5].

According to the orthodox view[1] which discounts plate tectonism prior to 2.0 Ga, the reported Archaean assemblages are considered different in many aspects. For example, they (a) lack the typical ophiolite-type succession, (b) depart from mafic and ultramafic petrology, (c) their tonalites and felsites are more felsic and display steeper REE pattern, (d) lack the low temperature metamorphic rocks seen in the younger period subduction zones and (e) have different stratigraphic and structural signatures (rifting, rotation, subduction, oceanic separation or collision tectonics). They are, however, reckoned as oceanic plateaus delivered by copious plume activities of the Archaean. Their greenstone belts are either volcano-sedimentary sequences laid on a basement of sialic crust (granite-gneiss) or networks of synclines or diapiric upwelling from sunken early crust. More importantly, the higher temperature, lower viscosity and weaker strength of the early earth upper mantle, as well as the destructive spells of bolide impacts earth experienced in this period are considered unfavourable for the development of cold dense lithospheric plates that could remain stable, grow as protocontinents and develop plates which could sink in subduction zones[1,2,6].

A thermochemical mantle convective model[7], which also rules out Archaean plate tectonics, believes that the generation of anomalously thick Archaean basaltic crust (greenstone terranes) was formed by partial melting of underlying mantle and its upwelling (diapirism). This is initiated by the sinking of large crustal segments (600 × 600 or 1200 × 1200 km) into the mantle due to phase transition to denser eclogite in the lowermost crust. Magma from partial melting of the latter crust was the source for the felsic intrusives and extrusives within these Archaean terranes. A similar process of gravity sinking ('sagduction') followed by diapiric upwelling is conceived for the Neoarchaean Bababudan greenstone belt[8] (Dharwar craton) while some of the other granite-greenstone terranes in India and elsewhere are viewed as typical network of melts of mobilized composite batholiths[1,9].

Contrary to the formal view, data from geological, geochemical, petrological and seismic studies have shown that for every volcanic rock claimed unique to the Phanerozoic or contemporary intra-oceanic or convergent margin setting, the Archaean greenstone-granite terranes have an equivalent and also their geodynamic setting indicates that these terranes could not have formed without plate translation[4]. Further, neither the geochemical or isotopic data of the TTG suite of rocks, predominant in Archaean greenstone belts, support the contention that they could be volcano-sedimentary sequences laid on a sialic crust[10].

Ophiolites, so characteristic of Phanerozoic plate tectonic settings (e.g. New Guinea, Oman, Tasmania, Newfoundland and Southern Urals) have their equivalents in the flows of bonninites ($SiO_2 > 53\%$, Mg > 69). These rocks typical of intra-oceanic subduction environments are now reported from several Archaean cratons including Indian occurrences in the Gadwal greenstone belt[11] (eastern Dharwar craton) and Bastar craton[12] as accretionary products of Archaean subduction processes. These finds imply that intra-oceanic subduction environment existed even as early as Palaeoarchaean (3.6–3.2 Ga). Other subduction-generated volcanic rocks like the picrites, adakites, high-Mg andesites, low-Ti tholeiites, and Nb-enriched basalts, hitherto regarded exclusive to the Phanerozoic, occur also in the Archaean belts of Greenland, North America, Central America, Eastern Europe, Russia and North China. These ultramafic and mafic volcanic assemblages are considered as ocean island and forearc ophiolites, which were later dismembered and incorporated into the accretionary complex[4].

Geodynamically, there does not appear to be any distinguishing feature to delimit plate tectonism to Phanerozoic times. Some of the geodynamic processes evolving the Archaean granite–greenstone terranes such as plume–subduction interaction, plume–lithosphere interaction, subduction accretion[5], continental rifting[13], orogenic collapse, strike-slip faulting[5] appear to have operated in Phanerozoic belts too, e.g. Tonga forearc, Siberian traps, Iceland-North America, Himalayas and the Canadian Cordillera[4]. Plate tectonics related magmatism arising from converging micro-plate collisions, subducting slab-induced diapirism, accretionary boundaries have been part of the Archaean–Proterozoic evolution of the Singhbhum belt in Eastern India[9]. The 'accretionary type' orogenic belts characteristic of the Archaean cratons like Yilgarn, Superior Province, Cordillera as well as those in the southern and eastern India and the 'continent–continent' collision type orogeny that formed the Cenozoic Himalayas and Alps are both explained through plate tectonic processes[4].

The assembly and breakup of oldest palaeo-continent belonging to the 3.2–3.0 Ga period, known as Kenorland or Ur, which included the cratons of western Dharwar and Singhbhum in India, Kaapvaal in South Africa, and Pilbara in western Australia, have all in common the accretionary style greenstone orogens explained through plate tectonism[14]. These lands subsequently broke up and dispersed and reassembled (around 1.8 Ga), their suturing marked by orogenic belts with clear evidences for subduction of oceanic lithosphere. The formation of earliest supercontinent around 2.7 Ga (Neoarchaean) is believed to be the outcome of subduction process. It is postulated that several subducting early Archaean crustal slabs that had stopped in their progress at the 660 km discontinuity barrier, catastrophically sank into the mantle (slab avalanching) and in this process caused upwelling of huge volume of magma to form the supercontinent[15]. Further proofs for the Archaean subduction geodynamics are the palaeo-subduction zones, and detached slabs detected by seismic reflection studies in the Baltic region (by the BABEL working group) and in Canada's Archaean terranes in Superior Province (LITHOPROBE studies). But the conservative opinion[1] doubt these conclusions on grounds that they are based on negligible travel time variations and that there could be non-subduction alternatives also to explain their presence.

Current thinking, based on the new models, takes a broader perspective of the Archaean plate tectonic phenomenon and interprets it in harmony with mantle's changing physics, convective heat flux and geodynamics and their impact on the continental growth. A recent study[16] has brought out the influence of these parameters on the style of plate tectonic operation since the Archaean. In this study, the Archaean heat flux is derived from present day earth's thermal budget condition (~ 44 TW comprising ~ 8 TW of radiogenic and ~ 36 TW of convection heat) 40% of which is contributed by the continental crust. During the Archaean times, continental growth was considerably less and therefore the impact of mantle heat must have been quite different and changing over time with progressive cooling. In tracing the thermal evolution, the study has brought out the effect of core cooling on rheology-based plume dynamics and how the compositional buoyancy of a thick depleted lithosphere effectively influences the energetics of mantle convection during the Archaean and in turn, the style of plate tectonics. In short, the style of plate dynamics is much dictated by the internal heating of the period and during the Archaean, the state of the mantle convection could have supported only slow moving plates[16]. Further inferences based on the above parameters are that steep subduction prevailed during 2.0–1.6 Ga and flat subduction between 4.0–2.5 Ga[17].

In spite of enormous database on the Archaean geology, geodynamics and isotopic information obtained through several interdisciplinary studies, the inertia to overcome notions confining the operation of plate tectonics to < 2.0 Ga still exists. Perhaps, the experts who met at the Penrose Conference of the Geological Society of America recently, could sort out various issues related to the thermal history, plate driving forces and impact of progressive cooling on them and also revise the hallmark lithological and tectonic signatures and redefine plate tectonism itself, taking a broad outlook of this process.

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A. V. Sankaran lives at No. 10, P&T Colony, First Cross, Second Block, RT Nagar, Bangalore 560 032, India.
e-mail: av.sankaran@gmail.com