PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Plate Tectonics through Geological Time [and Discussion]

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Plate tectonics through geological time

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Geological processes controlled by plate tectonics govern the time–space distribution of key rock assemblages. Stratal components of geosynclinal prisms, igneous provinces of orogenic belts, and regional facies of metamorphic terranes all display patterns controlled by inferred plate motions. Similarities between most Precambrian rock assemblages and Phanerozoic counterparts, coupled with analogies between Precambrian and Phanerozoic apparent polar wander paths, suggest that most surviving crustal rocks of all ages owe their origins to plate-tectonic processes. Archaean crustal blocks resemble collages of oceanic island arcs and volcanic archipelagoes whose tectonic juxtaposition to form cratonic nuclei was probably accomplished by subduction and crustal collision. Thereafter, similar Proterozoic oceanic elements were gradually accreted to growing continental margins and eventually crushed between colliding continental blocks of progressively larger size. Meanwhile, Archaean terranes within the interiors of cratons were generally shielded from further deformation, with their oceanic aspects largely preserved. In time, Phanerozoic oceanic terranes will systematically be destroyed by subduction or modified by incorporation into consolidated continental blocks. Differences between Precambrian and Phanerozoic plate tectonics and related assemblages reflect secular decline in global heat flux of radiogenic origin and progressive growth in the dimensions of cratonic blocks of continental crust.

Introduction

Magnetic anomalies at sea indicate that seafloor spreading proceeded according to the tenets of plate tectonics throughout the break-up of Pangaea by continental drift. However, this pattern of plate behaviour is thus conclusively documented only for the last 5% of Earth history. The reign of plate tectonics is extended to include the last 15% of Earth history by interpretations that analogous tectonic regimes prevailed during the formation of Palaeozoic rocks and those latest Precambrian rocks involved in the so-called Pan-African orogenies (Hurley 1972). For the bulk of Proterozoic and Archaean time, representing together about 70% of Earth history, opinions about the importance of plate tectonics have been sharply divided. Various alternate or severely modified tectonic schemes have been proposed for the Precambrian, but no single theory has gained wide acceptance. With adaptations of modest scope, plate tectonics seemingly remains the best model. The question is largely moot for the first 15% of Earth history because there is essentially no surviving rock record of that time.

Geothermal history

Plate tectonics is the surface expression of mantle convection driven by radiogenic heat. Two considerations imply that the intensity of mantle convection was greater in the past than at present. First, the overall production of radiogenic heat within the earth has declined exponentially through time as the global content of radioisotopes has been reduced by radioactive decay (Dickinson & Luth 1971). Secondly, the proportion of the radiogenic heat generated within the mantle has been reduced by the transfer of surviving radioactive heat sources from the mantle to the crust.

Only during the initial accretion of the Earth and its subsequent bombardment by cataclysmic meteors could the intensity of mantle convection have been increasing instead of decreasing. From evidence on the moon (Taylor 1979), these events were confined to the period before 3750 Ma B.P., for which there is almost no surviving rock record on Earth. Consequently, nearly all crustal rocks available for study now belong to times marked by mantle convection of lessening intensity. Any crustal rocks that pre-date plate tectonics thus must have formed while mantle convection was still too rapid to allow the development of surficial slabs cool enough to attain the rigidity of modern plates.

Crustal growth

All the existing oceanic crust has been produced by mantle upwelling along divergent or spreading plate boundaries since the break-up of Pangaea. However, at least some of the rocks that form the continental blocks are more than an order of magnitude older. Still uncertain are the times at which the earliest segments of the present continental crust formed and the rates at which the remainder grew. With respect to plate tectonics, two contrasting points of view are possible: (1) nearly all the materials of the continental crust emerged early from the mantle by unspecified pre-plate processes and have since been recycled by plate tectonics (Armstrong 1968); (2) the continental crust has evolved progressively through time as subduction and magmatism along convergent or consuming plate junctures have added successive increments of material derived from the mantle to the edges of growing continental blocks (Dewey & Horsfield 1970). Intermediate hypotheses postulate that continuing crustal growth through plate tectonics is continually retarded by partial recycling of previously formed crustal materials (Veizer & Jansen 1979).

Perhaps these seemingly opposed viewpoints can be reconciled if crustal growth is ascribed to plate tectonics whose tempo has varied systematically with the declining rate of radiogenic heat production within the earth. With this provision, and assuming that the oldest known continental rocks signal the initiation of plate tectonics at about 3750 Ma B.P., then about half of the mass of the present continental crust would have emerged from the mantle before 2500 Ma B.P. if all radiogenic heat produced were available to drive plate tectonics at strictly proportionate rates. Moreover, if the progressive transfer of radioactive heat sources from mantle to crust through time is assumed to reduce the proportion of total radiogenic heat available to drive mantle convection, then perhaps two-thirds of the crust could have formed during the same time span without appeal to systems other than plate tectonics. An appropriate recycling function could further increase the proportion of continental crust inferred to have formed before 2500 Ma B.P., during the Archaean.

Petrogenetic processes

One way to evaluate Precambrian plate tectonics is to compare Phanerozoic and Precambrian rock assemblages to detect similarity or dissimilarity. The most voluminous rock masses in process of formation at present are igneous and associated metamorphic rocks related to spreading or subduction along plate boundaries. The most voluminous intraplate assemblages are igneous rocks generated by hotspot volcanism, and sediment prisms deposited along rifted continental margins or within foreland basins. Ophiolitic rocks of the sea floor tend to be destroyed systematically by plate consumption. Sedimentary sequences along or just within continental margins are eventually deformed and incorporated into orogenic belts after being metamorphosed in part. The main rock associations with good chance of being preserved for long periods while retaining their characteristic features are thus the igneous and metamorphic rocks developed within orogenic belts along convergent plate junctures. These include arc orogens where oceanic lithosphere is consumed continuously, and collision orogens where attempted subduction of continental lithosphere is arrested by the buoyancy of continental crust.

Arc orogens include two different types, although oceanic materials are accreted by subduction to the flanks of each. The crustal profile of intraoceanic island arcs is constructed by the addition of magmatic increments to an oceanic substratum. In continental-margin Cordilleran arcs, however, magmatic additions are emplaced within or erupted through pre-existing continental crust. The two kinds of arc orogen are doubtless but two end members of a gradational spectrum. The magmas that build island-arc crust are derived directly from the mantle or from subducted oceanic crust of mantle derivation, but Cordilleran magmatism may involve remelting of the underlying lower crust to achieve an internal fractionation of the crustal profile (Jakes 1973). Even in Cordilleran arcs, however, a significant if not dominant fraction of the granitic magmas are derived from subjacent mantle (Brown 1977).

Collision orogens include suture belts between continental blocks or island arcs that are brought together by consumption of intervening oceanic lithosphere. All collision orogens thus evolve from ancestral arc orogens. Tectonic suturing involves structural juxtaposition of arc terranes with other crustal elements. After crustal collision, detachment of previously subducted oceanic lithosphere by rupture or delamination may allow mantle upwelling beneath the suture belt to expose the basal crust of the collision orogen to a large heat flux (Bird 1978). If so, extensive post-collision plutons of anatectic origin within the crust may augment the volume of pre-collision arc plutons along the trend of the resulting orogenic belt.

Precambrian assemblages

If plate tectonics governed the evolution of Precambrian as well as Phanerozoic terranes, then age belts of Precambrian igneous and metamorphic rocks defined by radiometric geochronology must represent some combination of arc and collision orogens. Each age belt need not represent a single orogenic pulse in Phanerozoic terms, but rather a whole chain of orogenic events during the development of a mature arc or collision orogen whose evolution spanned 200 Ma or more.

Calculated bulk compositions of key Precambrian terranes are strikingly close to estimated average compositions of presumed Phanerozoic counterparts (see table 1). If comparable rocks imply comparable origins, then plate tectonics controlled much Precambrian petrogenesis.

Mimicry of plate tectonics by non-plate behaviour is unlikely, for the geologic relations of many Precambrian terranes can be interpreted in terms of plate interactions (Burke & Dewey 1972). Greenstone suites variously resemble rift-trough, marginal-basin, or island-arc volcanics; moreover, some greenstone belts are composite volcanic piles with rift-related lower horizons and arc-related upper horizons (Condie & Harrison 1976). These belts may preserve a dual record of both the extensional or constructive and the contractional or destructive phases of the Wilson oceanic cycle as it affected the margins of Precambrian crustal blocks. Ancient granitic gneiss belts can be viewed as the exposed roots of Cordilleran magmatic arcs (Windley & Smith 1976). Other metamorphic terranes may constitute zones of reactivated basement rocks developed deep in the crust along collision belts where cratonic blocks were welded together (Dewey & Burke 1973).

Table 1. Mean compositions of some key orogenic rock suites

(Values recalculated volatile-free to 100 % of major element oxides.)

	(*a*)	(*b*)	(*c*)	(*d*)	(*e*)	(*f*)	(*g*)	(*h*)
SiO_2	56.4	57.3	56.5	59.1	64.6	66.0	66.6	69.3
TiO_2	1.0	0.7	0.8	0.9	0.6	0.5	0.6	0.4
Al_2O_3	15.7	17.5	18.0	16.9	16.7	16.2	15.7	15.5
Fe_2O_3	2.4	3.0	4.2	2.7	1.3	1.5	1.3	1.4
FeO	7.7	5.1	4.6	4.3	3.8	3.1	3.6	1.9
MgO	5.3	3.9	3.4	3.9	2.4	2.3	2.0	1.2
CaO	7.8	8.5	8.1	6.7	5.3	3.5	3.2	3.2
Na_2O	3.0	3.1	3.1	3.6	3.3	4.2	3.5	3.4
K_2O	0.7	0.9	1.3	1.9	2.0	2.7	3.5	3.7

Andesitic suites ((*a*)–(*d*)): (*a*) weighted average volcanic rock of four Precambrian greenstone belts of the Canadian Shield; (*b*) average of 27 Cainozoic andesitic provinces of island arcs; (*c*) weighted average Cainozoic volcanic rock of Kamchatka; (*d*) average of 19 Cainozoic andesitic provinces of continental margins.

Granitic suites ((*e*)–(*h*)): (*e*) weighted average Mesozoic plutonic rock of southern California batholith; (*f*) average Archaean basement of Canadian Shield; (*g*) average Proterozoic basement of Canadian Shield; (*h*) weighted average Mesozoic plutonic rock of Sierra Nevada batholith.

References: Dickinson (1970) (*a*), (*c*), (*e*), (*h*); Fahrig & Eade (1968) ((*f*), (*g*)); Gunn *et al.* (1974) ((*b*), (*d*)).

Some pecularities of Precambrian terranes are more difficult to reconcile with plate tectonics. Chief among these is the general lack of ophiolites representing oceanic crust and blueschists representing subduction zones. Also troublesome is the presence of anorthosite and komatiite, which are both unfamiliar in Phanerozoic terranes.

Preservation of Phanerozoic ophiolite sequences results from tectonic emplacement of rare scraps of oceanic crust above the underthrust edges of continental blocks. Within Precambrian orogenic belts, subsequent erosion may have systematically removed any analogous surficial sheets once present above dissected cryptic sutures. Blueschists may similarly have been eroded from overthrust subduction complexes or may have been metamorphosed beyond recognition during collision events. Alternatively, higher Precambrian heat flow may mean that greenschists once were the typical products of subduction. Anorthosite massifs are probably residues of partial melting in the lower crust within arc or collision orogens (Frith & Currie 1976).

The occurrence of magnesian lavas called komatiites in Archaean greenstone belts has been used as evidence for special thermal or tectonic régimes early in the Precambrian (Weaver & Tarney 1979). Their discovery in Phanerozoic terranes weakens such arguments (Upadhyay 1978). Similar magnesian lavas, called boninites, indeed may be characteristic of modern forearc volcanism during initial stages of subduction when the mantle wedge above the descending slab of lithosphere is abnormally hot (Cameron *et al.* 1979). Moreover, Elthon

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(1979) argues persuasively that the parental magma for modern seafloor basalts is essentially as magnesian as some komatiites. This concept finds support in the differentiation of certain Proterozoic sills from komatiite to tholeiite (Francis & Hynes 1979).

Palaeowander paths

In principle, palaeomagnetic positioning of continental blocks offers the best means to test for Precambrian crustal movements at rates compatible with plate tectonics (Talbot 1973). In practice, the inability to measure palaeolongitude, the ambiguity between north and south palaeolatitude owing to magnetic reversals, and the difficulty of dating the remanent magnetization preserved in metamorphic and plutonic rocks combine to make most interpretations uncertain. It is clear, however, the apparent polar wander paths for continental blocks during the Proterozoic form curvilinear tracks linked by 'hairpins' in patterns analogous to Phanerozoic results (Irving 1979). Both the lengths of palaeowander tracks and rates of change in palaeolatitude are even greater for the Proterozoic than for the Phanerozoic. Phanerozoic hairpins marking changes in drift direction tend to coincide with times of orogenesis at continental margins, and there are hints that Precambrian hairpins also coincide with orogenic activity along nearby mobile belts (Piper 1974).

Palaeomagnetic data thus imply that either plate tectonics or another scheme of roughly comparable crustal mobility was operative in the Precambrian. Matters are clouded, however, by the fact that many pairs of older Precambrian cratons now separated by younger Precambrian mobile belts display palaeowander paths that are compatible with coordinate motions occurring even before orogenesis occurred along the mobile belts between them (McElhinny & McWilliams 1977). Such relations suggest that many Precambrian mobile belts were not arc or collision orogens marking former ocean basins destroyed by plate consumption during orogenesis.

There are two possible ways to resolve this paradox without rejecting Precambrian plate tectonics. First, palaeomagnetic compilations are not generally precise enough to detect separations of less than 1000 km, or 10°, between crustal blocks, and thus can never document oceans narrower than that. Secondly, palaeomagnetic methods cannot detect relative motion in a strictly east–west sense. If two crustal blocks separate without changing relative latitude, and later rejoin in the same fashion, no subsequent record of the opening and closing of an intervening ocean basin would be preserved in their apparent polar wander paths.

Archaean plates

Plate tectonics probably did not pre-date formation of the oldest surviving continental crust at about 3750 Ma B.P. (Moorbath 1975*a*), because continental blocks are not destroyed by plate interactions. Initial strontium isotope ratios of Precambrian rocks indicate that increments of continental crust continued to emerge from the mantle through the remainder of the Archaean and during the Proterozoic (Moorbath 1975*b*). Probably most of this crustal growth was an integral facet of plate tectonics. Figure 1, a plot of radiometric dates for orogenic rocks around the globe, shows no prominent discontinuities that might reflect a fundamental change in tectonic régime after about 3500 Ma B.P.

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Early stages of subduction may have been associated with a permobile phase of Archaean tectonism during which rigid plates were not present owing to the higher global heat flux (Burke & Dewey 1973). Recent analyses suggest, however, that Archaean plates closely resembled modern ones. Mineral assemblages in Archaean gneisses and granulites imply that continental geotherms averaged perhaps 25–30 °/km, comparable to values for modern sedimentary basins, except where perturbed by advective heat from diapiric magmas (Tarney & Windley 1977; Watson 1978). These estimates are in harmony with the observation that crustal thicknesses are similar for continental basement of all ages dating back to Archaean (Condie 1973). If ancient geothermal gradients had been much steeper than at present, crustal melting would have prevented development of Archaean terranes with crust as thick as that in younger continental segments (Burke & Kidd 1978).

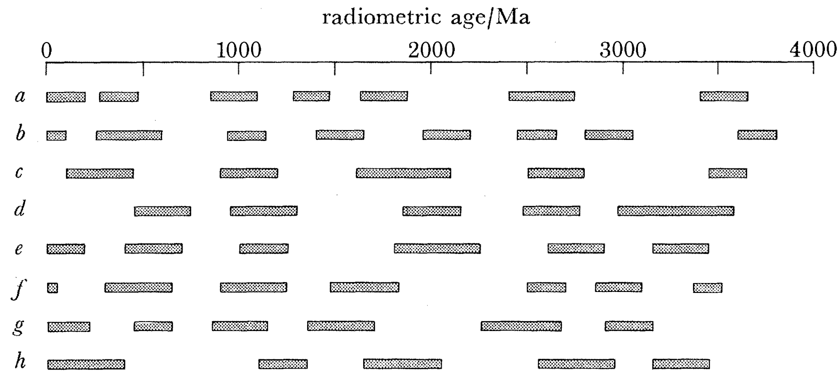

FIGURE 1. Approximate spans of radiometric ages for orogenic rock masses within and fringing Precambrian shields and cratons around the world (data from various sources): *a*, Canada and U.S.A.; *b*, Greenland and Europe; *c*, Baltic and west U.S.S.R.; *d*, Africa and Arabia; *e*, Brazil and Andes; *f*, Australia and Antarctica; *g*, India and China; *h*, Aldan and east U.S.S.R.

Gentle geothermal gradients cannot account for the enhanced global heat loss required during the Archaean by conduction through lithosphere alone. Consequently, the greater Archaean heat flux must have been accommodated by more rapid convective production and consumption of oceanic lithosphere (Davies 1979). Either faster spreading rates or more spreading centres could have achieved the needed heat loss. In either case, oceanic plates would have been somewhat thinner on the average than at present (Bickle 1978). The prevalence of thinner plates implies less elevation contrast between the surfaces of continental blocks and the mean depth of the sea floor. Gradual deepening of ocean basins through time may help to explain the maintenance of nearly constant continental freebroad since 2500 Ma B.P. (Wise 1974). Ocean basins of constant mean depth could not contain an unchanged volume of ocean water as crustal growth augmented the net area of continental blocks.

EVOLUTIONARY MODEL

Perhaps the whole Archaean world resembled a complex modern ocean basin containing scattered microcontinents and island arcs. Although the isolated pieces of continental lithosphere were nearly as rigid as today, oceanic plates may have been more pliable. Seafloor volcanism and magmatic arc activity dominated global magmatism because the widely spaced continental blocks were rarely involved in crustal collisions. Igneous suites resembled those of intraoceanic and circumoceanic provinces during the Phanerozoic (Engel *et al.* 1974). By the end of the Archaean, formerly separated island arcs were aggregated by sequential arc collisions to form the first extensive cratonic nuclei (Langford & Morin 1976). Before such gathering events, which everywhere marked the effective local close of the Archaean, few segments of continental crust were large enough to escape episodic reworking by orogenesis associated with evolving plate boundaries (Talbot 1973). The main assembly of dispersed Archaean crustal fragments into the oldest extensive continental terranes took place from about 2750 to 2500 Ma, and is recorded by the earliest global peak of orogenic activity for which there is surviving evidence (see figure 1).

Thereafter, during the Proterozoic, seafloor and island arcs presumably continued to form within oceanic regions. However, these oceanic rock assemblages were steadily accreted to evolving Cordilleran orogens bordering the growing continental blocks. In time, nearly all the arcs were crushed within collision orogens that developed systematically between the now abundant continental blocks that crowded the globe. Plutons of potassic granite appeared along collision belts as anatexis affected older crust (Mitchell 1975). Repetitive basement reactivation within the orogenic belts eventually metamorphosed many Proterozoic arc assemblages beyond easy recognition. Meanwhile, Archaean arc terranes already assembled into cratonic blocks were preserved intact within continental interiors, where they were shielded from the effects of Proterozoic collision events along continental margins.

Phanerozoic arc terranes resemble the protected Archaean terranes simply because we now see the existing ocean basins and their margins at a single point in time. In the future, modern arc terranes will doubtless be involved in collision events that will convert them into close counterparts of terranes within the Proterozoic mobile belts. Thus, Archaean terranes and Phanerozoic terranes related to subduction are similar, because the former date from a time before major continents existed and the latter are associated with surviving ocean basins. The disparate Proterozoic terranes are related to the final closing of intercontinental ocean basins that lay among an ever more dense population of continental blocks.

Global peaks in recorded Proterozoic orogenic activity may thus reflect the progressive assembly of available continental blocks into relatively few supercontinents. Such is the case for the assembly of Pangaea in the late Precambrian and early Phanerozoic (Hurley 1974). Conversely, global nulls in Proterozoic orogenic activity may mark the temporary existence of a dominant supercontinent like Pangaea. If so, pre-Pangaea supercontinents of comparable significance probably existed at about 800 and 2300 Ma B.P., in both the early and late Proterozoic, and possibly at about 1300 Ma B.P., in the middle Proterozoic, as well (see figure 1).

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Discussion

A. Kröner (*Department of Geosciences, University of Mainz, F.R.G.*). Professor Dickinson sees very similar rock assemblages in Phanerozoic and Precambrian settings and infers from this that the processes that formed these rocks were identical. I question this approach since it has been shown that many Archaean volcano-sedimentary greenstone belt successions are unlike those in modern arc systems, particularly if the trace element geochemistry is considered. Also, there is no modern case where ridge-type volcanic rocks such as primitive tholeiites or komatiites are overlain, in the same sequence, by andesites and bimodal assemblages typical of a subduction environment. Furthermore, there is as yet no Archaean volcanic sequence that has an internal structure and succession as found in modern ocean floor. Particularly, the sheeted dyke complex has not been found in Archaean suites despite their excellent state of preservation. Neither have blueschist assemblages been found in rocks older than about 1000 Ma despite the fact that many greenstone belts of the Archaean and mobile belts of the Proterozoic represent upper crustal levels. Could it not be, as Dr Moorbath suggested in his opening address to this meeting, that uniformitarian causes had non-uniformitarian effects and that the above differences in volcanic rock assemblages through time reflect varying intensities of subcrustal processes, which were controlled by the decreasing heat flow since the Archaean?

W. R. Dickinson. Dr Kröner raises longstanding questions that do merit further discussion. The degree of similarity between key Phanerozoic and Precambrian rock assemblages noted in my paper does not force the conclusion that the respective rock-forming processes were identical in every particular. Their similarities do suggest to me that the processes responsible for their formation were closely analogous. Due allowance can and should be made for faster convection driven by a higher global heat flux and for fewer continental blocks early in the Precambrian. However, the idea that rock assemblages and structural relationships common to both Phanerozoic and Precambrian terranes were produced by plate tectonics during the Phanerozoic, but by a wholly different set of petrogenetic processes during the Precambrian, seems to me to be a tenuous proposition.

Dr Kroner implies that no andesitic suites produced by Phanerozoic subduction ever directly overlie primitive basaltic suites produced by seafloor spreading. However, precisely such a relationship is likely to exist in the buried roots of intraoceanic island arcs like the Marianas. Moreover, hints that stratigraphic relationships of this kind may be common within Phanerozoic orogenic belts have come from studies of Palaeozoic and Mesozoic ophiolitic successions. Indeed, future studies of Phanerozoic ophiolite terranes within which seafloor and arc volcanics seemingly coexist may well sharpen interpretations of some Archaean greenstone belts.

The interpretation that Dr Kröner places on the lack of Archaean sheeted-dike complexes is permitted but not required by available data. On the one hand, plate tectonics preferentially destroys oceanic crust, whose retention as dismembered scraps within subduction zones need not have occurred at all during the Archaean even though it has occurred rarely and locally during the Phanerozoic. In addition, full development of the sheeted-dyke structure seen in some ophiolites may well require spreading rates slower than those that probably prevailed during the Archaean.

The scarcity of blueschists in Precambrian mobile belts remains a problem of uncertain significance. Blueschists are rare in many Phanerozoic orogenic belts, and Precambrian subduction assemblages may have been mostly greenschists. In addition, blueschists cannot survive later thermal pulses of any origin, and only local relicts remain even in some Mesozoic terranes where they were initially widespread.

Finally, it seems to me that varying intensity of subcrustal processes controlled by a decreasing heat flux does not preclude the concept of Precambrian plate tectonics. Logically, varying intensities of processes do not require differing kinds of processes until some threshold of behaviour is passed. I have argued simply that such a threshold was reached about 3750 Ma ago when rocks of familiar aspect began to form as a signal that plate tectonics was operative thereafter.