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The secular evolution of plate tectonics and the continental crust: An outline

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ABSTRACT

The main conclusion of this paper is that some form of plate tectonics started at ca. 3.0 Ga or possibly as early as 3.1 Ga., and that, since then, plate tectonics has steadily become dominant over plumes as a mechanism of heat loss. Modern plate tectonics started at ca. 0.6 Ga. The volume history of the continental crust is one of fast Early Archean growth to generate a, probably, globally continuous crust, then a growth, probably exceeded or balanced, long-term, by crustal return to the mantle reservoir.

Keywords: secular tectonic evolution of Earth, inversion, plate tectonics.

INTRODUCTION

This short essay is not intended as a thorough, scholarly, fully referenced work. Rather it is a distillation, a précis, and a personal statement of my views about Earth's evolution based upon seeing, recording, and thinking about rocks and their relationships around the globe for the past fifty years. Like Warren Hamilton (2003), with whose views about the tectonic evolution of Earth, in principle, I largely agree, the paper is not fully referenced with all those papers that are important and deserve reference in a thorough work; I apologize to all those who believe that their relevant work is not referenced. My views about Earth's tectonic evolution have changed and oscillated as I have been influenced by the views and experiences of many geologists. I have now returned, in principle, to my view of the early 1970s, which espouses secular evolution from an Archean, pre-plate-tectonic, permobile Earth to a Phanerozoic plate-tectonic Earth (Burke et al., 1976b).

Of the planets in the solar system, only Earth has extant plate tectonics. Past and present crustal mobility and deformation, indicative of convective processes, is evident in other planets and moons, but only on Earth do plates form a lithospheric thermal boundary conduction layer that is broken into a number of torsionally rigid spherical caps or shells, whose relative motion can be described by an angular rate around a pole of rotation. One-plate (continuous lithosphere) planets (Solomon, 1978) are characterized by early expansion, rifting, and volcanism, followed by contraction and thrusting. In today's Earth, plate tectonics is driven by slab-pull and ridge-push; the generation and conductive cooling of the lithosphere is the principal engine of global heat loss. The other mechanism of heat loss is by the formation of large igneous provinces, the surface expression of mantle plumes, commonly, though not exclusively, associated with mega-dike swarms and continental breakup. These two expressions of convection differ critically in that horizontal motions and slab subduction form narrow linear/arcuate zones to characterize plate tectonics, whereas vertical mass transfer typifies plumes and large igneous provinces. Secular tectonic change and evolution are certain consequences of Earth's thermal evolution; as radiogenic heat production declined, plates have cooled, thickened and strengthened, and flat-slab subduction is likely to have diminished in favor of steeper-slab subduction. Geologic

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data indicate, clearly, that there have been associated secular changes in rock associations, facies, and structures. Also, there have been episodic/periodic changes related to the assembly, fragmentation, and dispersal of continents with Wilson cycles of oceanic opening and closing. A key question in evaluating the rock assemblages that record, partially, the history of Earth, is the relative importance of plates and plumes with time. Was there a time before which plate tectonics did not operate and when tectonic processes were plume-dominated with globally pervasive convective overturn up to the shallowest levels of the crust?

Although many, if not most, of the processes that make and modify the continental crust (volume 5.25×10^9 km^3, mass 1.44×10^{25} g) are known in a general way (Dewey and Windley, 1981), their mechanisms (e.g., origin of arc volcanism, mechanisms of ultrahigh-pressure [UHP] exhumation, secular evolution) and, especially, rates, such as volume of continental crust, through time) are poorly or imperfectly understood. Although it is difficult to interpret the terrane collage of surface geology, our knowledge of the deep crust is limited to xenoliths, seismic data, and rare direct observation (e.g., Kapuskasing, Ronda, Finero, Beni Bouchera, Ivrea; Dewey, 1986). Whereas the principal engine of global heat loss is the accretion, cooling, subsidence, and subduction of the younger-than-160 m.y., dense and torsionally strong, relatively simple, oceanic lithosphere, the buoyancy and weakness of the exceedingly complicated continental crust allows its growth but prevents, at least in the extant plate-tectonic regime, its wholesale recycling back into the mantle, hence the preservation of rocks from almost 4 Ga.

Addition (transfer of mass from the mantle to the continents) occurs by subduction zone magmatism (major), mafic under- and overplating, and the incorporation of fragments of oceanic crust and seamount/plateaux (minor). Subtraction (transfer of mass from the continents to the mantle) may occur by delamination of a mafic lower crust, and subduction erosion (Dewey, 1980), and does not include shallow recycling, which is merely the transfer of tectonically decreted material from shallow to deeper, crustal subduction levels. Delamination of a mafic lower crust allows the trend toward a more silicic bulk composition. Growth/diminution are, respectively, the net gain/loss of continental crust, and equal addition minus subtraction. Accretion/decretion are, respectively, area increase/decrease by the addition or redistribution of mass at the edges of continents. Enlargement/reduction are, respectively, increase/decrease in continental area by stretching/shortening and accretion/decretion. Differentiation is the development of an upper potassic/silicic minimum-melt crust rich in radioactive and large-ion lithophile elements, and a refractory lower crust. The putative secular trend toward an increasing potash/soda ratio from general Archean values <1.0 to Proterozoic-Phanerozoic values >1.0 would indicate progressive growth, differentiation, and cratonization. My estimate, based upon a long-term and extensive global study of continental geology, is that crust was generated, during the Archean and Archeo-Proterozoic, at a growth rate of $\sim 11.17 \times 10^{15}$ g/yr, some six times faster than the Proterozoic-Phanerozoic rate of 1.64×10^{15} g/yr (Dewey and Windley, 1981).

The Archean nucleic cratons are a tiny remnant of the globally continuous Archean crust. The Armstrong (1968, 1981, 1991) and Fyfe (1978) growth curves probably are close to reality but modified as follows: During the Hadean, a global basaltic/komatiitic crust was recycled into the mantle from ca. 4.0 to 3.85 Ga. During the Archean, from ca. 3.85 to 3.0 Ga, a new global crust was formed, which has been recycled, largely, back into the mantle reservoir. Since the Late Archean, there has been a rough balance between growth of the continental crust, in arcs and by mafic underplating, and its return to the mantle reservoir. The mechanisms of return include the deep subduction and delamination of eclogitized crust in collision zones (Ryan and Dewey, 1997) and tectonic erosion in subduction zones (Dewey, 1980; Scholl and von Huene, this volume). Subtraction of continental crust is well documented in the India-Asia collision zone where there is a substantial volume deficit (Dewey et al., 1989). However, not all subducted, eclogitized, crust is returned to the mantle reservoir; there are several exhumed high-pressure/low-temperature coesite-eclogite terrains (Krabbendam and Dewey, 1998). What determines whether such crust is returned to the mantle or exhumed may be related to its density/hydration history. There are other views of the volume, area, growth, and destruction of continental crust with time (e.g., Hurley and Rand, 1969; Veizer and Jansen, 1979), which will not be discussed and evaluated because this short paper is concerned, principally, with tectonic styles and mechanisms with time; I recognize, however, that the issues are related intimately.

EARTH EVOLUTION

There is little doubt that a secular evolution of tectonic style has occurred through Earth's history (Dewey and Spall, 1975; Hamilton, 2003). Also, there has been diminishing bolide frequency and size. These secular trends were punctuated by episodic and, possibly, periodic events. The assembly, fragmentation, and dispersal of at least three supercontinents, during the Proterozoic-Phanerozoic, has led to a plate-tectonically driven episodic/periodic "cyclic" repetition of structural, sedimentary, igneous, metamorphic, and climatic events (Dewey, 1988a), of which the Wilson cycle of oceanic opening and closing is a consequence. During the assembly of a supercontinent, continental collisions cause mountain building, far-field inversion of rifts, continental shortening, lowering of sea level, a high clastic/carbonate ratio, rise in ^{87}Sr/^{86}Sr, drop in pCO$_2$, and low benthic diversity. Continental fragmentation is accompanied or caused by subduction rollback in circum-Pangea extensional arcs, alkaline magmatism, the extensional collapse of intra-Pangea orogens, and the rapid exhumation of mid and lower crustal rocks. Maximum continental dispersal is recorded by Andean-type orogeny, the obduction of supra-subduction-zone ophiolites, blueschists, carbonate shelves, deep-marine and platform euxinites, few clastics, low ^{87}Sr/^{86}Sr, rise in pCO$_2$, and high benthic diversity.

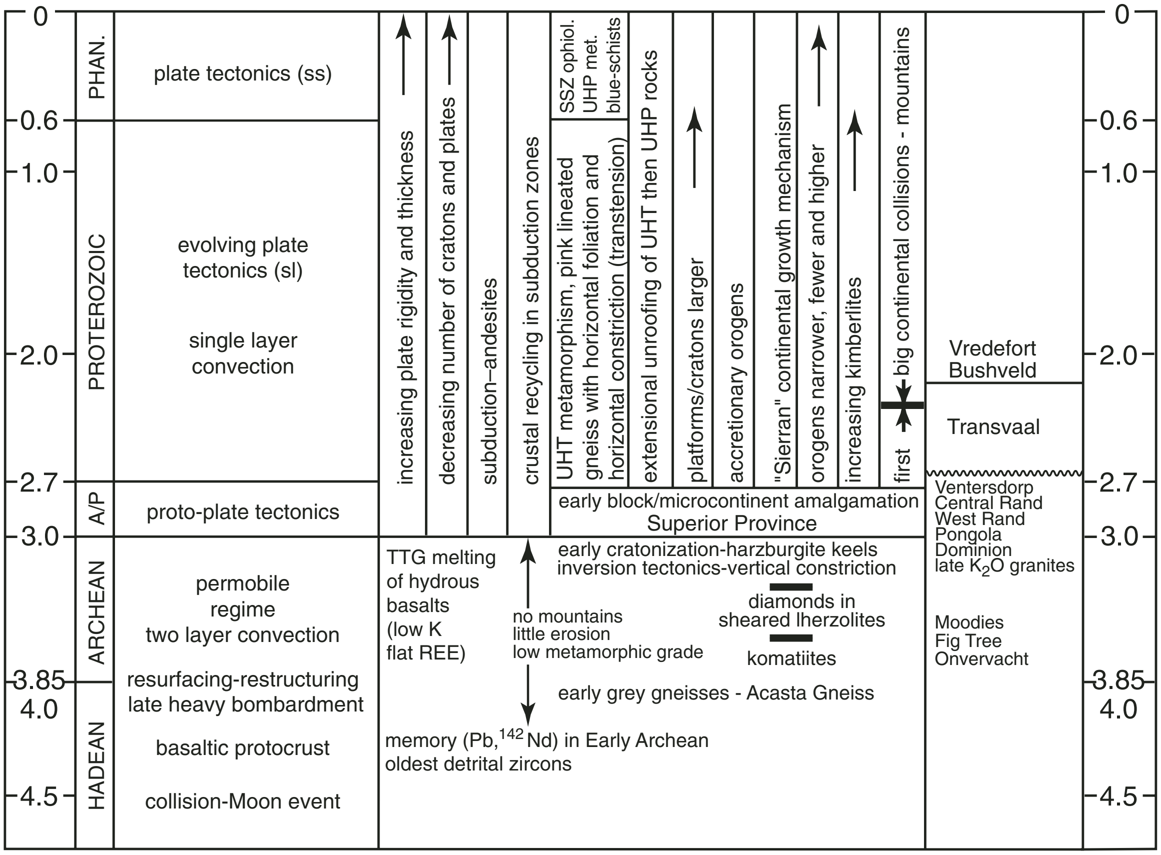

Figure 1. Suggested tectonic evolution of Earth. A/P—Archeo-Proterozoic (new term); REEs—rare earth elements; SSZ—supra-subduction-zone; TTG—tonalite-trondhjemite-granodiorite; UHP—ultrahigh-pressure; UHT—ultrahigh-temperature.

We should place eon and other boundaries at important events and changes in Earth history rather than at arbitrary numbers and unconformities: 3.85 Ga for the Hadean/Archean boundary, 3.0 Ga, perhaps a little earlier at 3.1 Ga, for the Archean/Archeo-Proterozoic (new term) boundary, 2.7 Ga for the Archeo-Proterozoic/Proterozoic boundary, and 0.6 Ga (base of Ediacaran) for the Proterozoic/Phanerozoic boundary. My view of Earth's evolution, summarized in simple tabular form in Figure 1, is similar to that of Burke and Dewey (1972, 1973; especially see Fig. 1 of 1973) and Hamilton (2003) but with temporal differences outlined below.

The Hadean, from 4.7 to 3.85 Ga, was an eon of a global basaltic proto-crust, which was wholly recycled before and during the intense late bombardment, from which only a few 4.4–4.3 Ga zircons, from presumed felsics, remain. Some fragmentary gray gneisses, in which a 4.36–4.1 Ga Pb and ^{147}Nd and Sr "memory" is preserved, could be late Hadean remnants. The Acasta Gneiss (Bowring et al., 1989) and Isua supracrustals (Moorbath et al., 1973) may be the oldest preserved rocks on Earth but not generated by a plate-tectonic process. The Hadean-Archean transition may have been a time, during the late heavy bombardment, of complete crustal/lithospheric turnover such as the process that may characterize the periodic (500 m.y.) evolution of Venus (Phillips and Hansen, 1998).

Arguments about post-Hadean secular tectonic evolution persist (Eriksson et al., 2004), especially processes responsible for Archean evolution. Kroner (1981) argued that rock assemblages and paleomagnetic data indicate that some form of plate tectonics must have operated back to, at least, the Late Archean. One view is that vertical diapiric inversion generated the "greenstone keel/gregarious batholith" pattern so typical of the Archean crust (MacGregor, 1951; Talbot, 1968; Burke and Dewey, 1973; Burke et al., 1976b; Hamilton, 2003). The opposing view (Burke and Dewey, 1972) is that Archean crust was generated by subduction processes some six times faster than modern processes. The geology of the Barberton Mountain Land (Anhaeusser, 1983) appears in some ways similar to that of western Newfoundland and western Ireland during the Ordovician (Van Staal et al., 1998) and that of the Sierra Nevada foothills during the early Mesozoic, where the growth and collisional amalgamation of primitive oceanic arcs was followed by the intrusion of tonalite batholiths from migrated and/or flipped subduction zones. In the Barberton Mountain Land, the Onvervacht could be interpreted as an Archean oceanic crust, the Fig Tree as an accretionary complex, the Moodies as an episutural sequence, the tonalite plutons as crust-forming arc intrusions, and the late adamellite sheets as a cratonizing event. Alternatively, the Onvervacht could be seen as primitive, highly magnesian lava sequences, on an older tonalite-trondhjemite-granodiorite (TTG) continental crust, representing a period of massive mantle partial melting, followed by diapiric inversion. In this gravity-driven model, the two-layer high-density komatiite, low-density TTG package inverts with broad, rounded-profile TTGs rising diapirically and sharp "greenstone keels" sinking. The latter is my preferred model because, especially, it explains the structure of Early Archean rocks with vertical constrictional fabrics in the cores of greenstone keels to the oblate marginal fabrics of ballooning plutons. If the TTGs were oceanic island arcs, it is strange that they lasted 300 m.y., that komatiite sequences rest, unconformably, upon older continental crust (Bickle et al., 1975), and that they have a blobby aspect with no obvious sutures. Andesites are rare in the Archean, suggesting the absence of slab subduction.

During the Archean, from 3.85 to ca. 3.0 Ga (the permobile regime; Burke et al., 1976b), the first continental crust (gray gneisses) formed as the earliest stage of mantle partial melting. The TTGs probably formed by the partial melting of Hadean hydrous basalts (amphibolites) that were "inverted" into the mantle during the late Hadean–Early Archean resurfacing and restructuring. This was followed by the supracontinental eruption of massive thick komatiite sequences, to leave a refractory, depleted harzburgite mantle keel. Data from the Belingwe Greenstone Belt (Bickle et al., 1975) suggest that the komatiite sequences accumulated in deepening basins upon a weak hot TTG crust with thick sequences in basin centers and thin on basin margins. This led to gravitational instability between the heavy komatiitic upper crust and the TTG lower crust, and their inevitable turnover. During the turnover, diapirically rising and ballooning TTGs developed oblate marginal fabrics that transitioned through plane strain into vertical constrictional fabrics in the cores of the greenstone triangles. This was a pre-plate-tectonic period of Earth history when no obvious sign or result of plate-tectonic processes can be discerned in the rock record. We do not know whether this phase generated a continuous global crust that has been mainly recycled into the mantle reservoir or whether the extant Archean nuclei represent microcontinental survivors, between which plate tectonics turned over an Archean oceanic lithosphere; my preference is for the former. I now incline to the Fyfe (1978) view that the Archean nuclear pre–3.0 Ga cratons are remnants of a once continuous global crust and depleted harzburgite upper mantle lithosphere, most of which was returned to the mantle reservoir by inversion in the Archeo-Proterozoic and/or the well-documented process of subduction erosion (Dewey, 1980) during the Proterozoic-Phanerozoic.

Plate tectonics has been the engine of convective/conductive global, radiogenic heat loss during the Proterozoic and Phanerozoic, but the pre–3.0 Ga Earth was tectonically quite different, when heat loss was effected by pervasive convective inversion, as on Venus (Hansen, 2005), by episodic/periodic convective turnover, wholesale in the late Hadean and shallow diapiric during the Archean. Most Early Archean terrains are low-grade, suggesting little erosion of a never very thick crust. Erosion rates were low and there were no mountains. Tectonics was blobby and nonlinear. The only suggestion of some form of subduction, perhaps an ultradeep inversion process, is the existence of Archean diamonds in sheared lherzolites that were erupted in Kaapvaal Craton Cretaceous kimberlites, suggesting the subduction or inversion of surficial carbon into the mantle. By 3.0 Ga, the oldest, extant, cratonic lithosphere was developed with a greenstone/TTG crust, and with a mantle consisting of depleted granular harzburgite above and sheared lherzolite below with diamonds at ~220 km. Clearly, little has happened to the remaining Archean lithosphere since it formed because Archean diamonds stayed in their stability field until their Cretaceous rapid eruption in kimberlites. The late high-K_2O granite sheets (3.2–3.1 Ga) seal this early cratonization, upon which cratons the earliest rift and mobile cratonic shelf sequences (Dominion <3.074 Ga, Pongola 2.985–2.837 Ga, West and Central Rand 2.985–2.764 Ga) were deposited during the latest Archean and Archeo-Proterozoic.

The Archeo-Proterozoic, from ca. 3.0 to 2.7 Ga, during which the Superior province was developed and assembled, was a period of the first widespread andesites, indicating subduction, and geological assemblages and relationships that suggest the first clear evidence of some form of a plate-tectonic-like convective overturn of a lithosphere, including greater linearity and terrane assembly (Burke et al., 1981). Island arc complexes are suggested by petrology and geochemistry (Anhaeusser et al., 1983; Burke and Dewey, 1972; Mueller et al., 2002; Wyman et al., 2002). These terrains have a lenticular rather than the Archean, blobby, "gregarious batholith", triangular greenstone keel form. Possibly extensive flat-slab subduction of thin hot lithosphere was responsible for the early recycling of much of the Archean lithosphere. Missing from the Archeo-Proterozoic are many of the clear plate-tectonic arrangements of facies and assemblages that characterize the Phanerozoic, such as clear arc–forearc–accretionary complex triplets, linear/arcuate orogens, blueschists, ophiolites, low-angle thrusts, and extensional detachments. Perhaps this was a result of early proto-plate-tectonic terrane assembly of arcs and microcontinents operating in a higher-heat-flow, more mobile regime with more smaller and weaker plates. Metamorphic grades remained generally low; high-pressure and -temperature metamorphic rocks are rare, with the exception of eclogites in the Baltic Shield (Volodichev et al., 2004), suggesting a not-very-thick crust, little erosion, and no mountains. Burke and Dewey (1973) suggested that the Archeo-Proterozoic style was the result of weak collisions between small microcontinents and arcs. I see the Archeo-Proterozoic as the transitional period from Archean inversion tectonics to plate tectonics. As radiogenic heat production declined, the thermal/instantaneous lithosphere thickened, during the evolving plate-tectonic regime, to narrow plate boundary zones and enlarge cratons. As remnant Archean and Archeo-Proterozoic microcontinents collided and amalgamated, plate tectonics began and evolved.

The Proterozoic, from 2.7 to ca. 0.6 Ga, has most of the basic hallmarks of the Wilson cycle throughout, and records clear evidence of plate-tectonic processes operating in linear/

sublinear/arcuate belts of widely varying widths, and with most plate-tectonic indicator rock assemblages and structures, including sutures, rift and passive continental margin sequences, and linear/arcuate orogens, such as the Coronation-Wopmay (Hoffman et al., 1974), Labrador, Cape Smith, Grenville, Dahomey, Gariep, Damara, and Mozambique (Dewey and Burke, 1973; Burke and Dewey, 1972, 1973). The Early Proterozoic Trans-Hudson (Lewry and Stauffer, 1990) contains island arc volcanics that are geochemically identical to those of modern oceanic arcs (Wyman et al., 2002) including boninites (Wyman, 1999), and assemblages and relationships that indicate plate tectonics (Lucas et al., 1996). The reported sheeted complex of alleged ophiolite origin (Scott et al., 1992) is more problematic; there is no clear sequential relationship with a full ophiolite sequence; local sheeted dike complexes can be generated in the floors of rifts. Moller et al. (1995) recorded mafic eclogites in the 2.0 Ga Usugarian Belt of Tanzania, which were rapidly exhumed at Phanerozoic rates. The Svecofennian orogen (1.96–1.75 Ga) consists of a collage of terranes accreted to the Karelian Craton, which must have involved horizontal tectonics (Korja and Heikkinen, 2005; Korsman et al., 1999). The first major, transpressive, continental collisions occurred at ca. 2.0 Ga (Limpopo, Ubendides). The 2.1 Ga Birrimian (Abouchami et al., 1990) and 2.45–1.9 Ga Pechenga-Varzuga Belt (Sharkov and Smolkin, 1997) record oceanic and arc terrains. During the Early Proterozoic, the first large cratons were stabilized, as witnessed by the Transvaal sequence. However, these early cratons were more mobile vertically than later cratons in their very thick "platform" sequences; the Transvaal sequence is over 10 km thick. The Proterozoic, uniquely, saw ultrahigh-temperature (UHT) metamorphism, with opx/sapphirine/osumilite/sillimanite assemblages. These were generated in orogenic regions of widespread crustal melting above thick mafic underplates. The crustal partial melts formed granite sheets commonly emplaced in late orogenic transtensional regimes with lineated and subhorizontally foliated, constrictional, pink, potassic gneisses, rapidly extensionally exhumed beneath gently dipping detachments, very similar to Phanerozoic detachments (Dewey, 1988b; Dewey et al., 1993), as in the 1 Ga Namaqua Belt (Dewey et al., 2006). Paleomagnetic data from Proterozoic rocks are not only compatible with but demand the relative motion of continental blocks now welded by Proterozoic sutures (Burke et al., 1976a; Meert and Torsvik, 2003; Pesonen et al., 2003).

Throughout the Phanerozoic, plate-tectonic regimes, facies, assemblages, and structures show little variation. Blueschists and the generation and obduction of supra-subduction-zone ophiolites occurred mainly during the Ordovician and Cretaceous periods of continental dispersal and high sea level. Ultrahigh-pressure (UHP) metamorphic assemblages are, uniquely, Phanerozoic, contrasted to ultrahigh-temperature (UHT) metamorphic assemblages, which are, uniquely, Proterozoic. This must reflect the thermal evolution of Earth with declining heat production and flow with a thickening lithosphere and narrower, steeper, and colder subduction zones. The origin and evolution of higher plants and metazoan life was likely related to the development of well-defined continental margins and their upwelling zones.

COROLLARIES

Eclogites may play an important role in secular crustal evolution. They allow the subduction of continental crust into the mantle, overthickening of continental crust (Dewey et al., 1993), and cause long-term weakening of the continental lithosphere that is one, or a partial, explanation of the Wilson cycle of constant oceanic opening and closing along roughly the same lines (Ryan and Dewey, 1997). Their role as "sinkers" and in crustal delamination is likely to have been increasingly important, especially during the Phanerozoic, as the lithosphere enjoyed secular thickening.

There are many different types of continental crust with different strength (sailboard) profiles that generate many different tectonic responses to shortening and extension; each has a distinctive profile of strength distribution and décollement/detachment/thrust horizons, which generate quite different patterns of thrust stacking and extensional detachments. The secular evolution and thickening of the lithosphere is likely to have profoundly influenced detachment levels, nappe thickness, and structural style. As the lithosphere thickened and heat flow declined, the lithosphere became more difficult to deform in, progressively, narrower zones; décollements, detachments, and thrusts that are rooted in basement went ever deeper.

CONCLUSIONS

Plate tectonics, as operating in modern Earth, is a Phanerozoic process; plumes play a minor role in heat and mass transfer. Conversely, early Earth was dominated by plume mass and heat transfer from a hotter asthenosphere until ca. 3.0 Ga. The Archean (3.85–3.0) Ga saw the growth of a, possibly, globe-covering sialic crust, which, largely, has been recycled back into the mantle reservoir. During the Archeo-Proterozoic (new term), proto–plate tectonics was an early form of heat loss by the creation and destruction of small plates with weak arc and microcontinent collisions. During the Proterozoic, plate tectonics evolved to its Phanerozoic form as the lithosphere thickened. A difficult problem in continental tectonics is that, although plate tectonics generates the cross-sectional templates for plate boundary zones, most plate boundary zones become complex terrane collages that are not easy to decipher and reconstruct; orogenic belts commonly achieve a final linearity by collisional smearing, which rearranges elements of a long and complicated oceanic plate-tectonic history (Van Staal et al., 1998). We are victims of the inversion problem; we can forward model the most complex systems but cannot satisfactorily and uniquely backward model even the simplest systems. Kinematic and numerical forward models are useful in giving us ideas and showing us how complicated, or sometimes simple, is plate boundary evolution, but they can never uniquely describe the real world. They are useful chimeras that, like concepts of stress, paraphrase reality. Research in the earth sciences is moving away, too fast and too far from the reality of the rocks. Ultimately, the current, blinkered, obsession with process must be tempered by the historical perspective of the record preserved in the rocks. Rocks and their relationships are complicated and, commonly, difficult to interpret, but that is scarcely an excuse for not looking at rocks and substituting modeling.

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