ARTICLE IN PRESS
LITHOS-02372; No of Pages 20
Lithos xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated

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ARTICLE INFO

Article history:
Received 7 May 2010
Accepted 11 December 2010
Available online xxxx

Keywords:
Crustal evolution
Mantle evolution
Proterozoic
Archean
Plate tectonics
Delamination

ABSTRACT

Archean, Paleoproterozoic, and Mesoproterozoic rocks, assemblages, and structures differ greatly both from each other and from modern ones, and lack evidence for subduction and seafloor spreading such as is widespread in Phanerozoic terrains. Most specialists nevertheless apply non-actualistic plate-tectonic explanations to the ancient terrains and do not consider alternatives. This report evaluates popular concepts with multidisciplinary information, and proposes options. The key is fractionation by ca. 4.45 Ga of the hot young Earth into core, severely depleted mantle, and thick mafic protocrust, followed by still-continuing re-enrichment of upper mantle from the top. This is opposite to the popular assumption that silicate Earth is still slowly and unidirectionally fractionating. The protocrust contained most material from which all subsequent crust was derived, either directly, or indirectly after downward recycling. Tonalite, trondhjemite, and granodiorite (TTG), dominant components of Archean crust, were derived mostly by partial melting of protocrust. Dense restitic protocrust delaminated and sank into hot, weak dunite mantle, which, displaced upward, enabled further partial melting of protocrust. Sinkers enriched the upper mantle, in part maintaining coherence as distinct dense rocks, and in part yielding melts that metasomatized depleted-mantle dunite to more pyroxenic and garnetiferous rocks. Not until ca. 3.6 Ga was TTG crust cool enough to allow mafic and ultramafic lavas, from both protocrust and re-enriched mantle, to erupt to the surface, and then to sag as synclinal keels between rising diapiric batholiths; simultaneously upper crust deformed ductily, then brittly, above slowly flowing hot lower TTG crust. Paleoproterozoic and Mesoproterozoic orogens appear to be largely ensialic, developed from very thick basin-filling sedimentary and volcanic rocks on thinned Archean or Paleoproterozoic crust and remaining mafic protocrust, above moderately re-enriched mantle. Subduction, and perhaps the continent/ocean lithospheric dichotomy, began ca. 850 Ma – although fully modern plate-tectonic processes began only in Ordovician time – and continued to enrich the cooling mantle in excess of partial melts that contributed to new crust. "Plumes" from deep mantle do not operate in the modern Earth and did not operate in Precambrian time.

1. Introduction

The widely accepted concepts that plate tectonics has operated throughout all or most of geologic time and that plumes from deep mantle have delivered heat and material to the crust are contradicted by powerful multidisciplinary evidence, some of which is summarized here. Pre-Neoproterozoic rocks, individually and as associations, and their geologic and crustal structures, are very different from modern ones, and include none of the definitive indicators of plate interactions that are abundant in the Phanerozoic record. The assumption that plumes rise from deep mantle is derived from false 1950s assumptions that Earth has evolved slowly from a cold start, and survives as dogma despite disproof of its early basis and of its subsequent generalizations and predictions. The history of science contains many gaps between consensus and truth, but most mainline literature presumes that consensus favoring ancient plates and plumes obviates the need for evaluation of assumptions, evidence, and alternatives.

I have been a major critic of plate-tectonic interpretations for the Archean (Hamilton, 1998) and, later (Hamilton, 2007a), for all of pre-Neoproterozoic time. Stern (2005, 2008) is one of the few others who have argued against pre-Neoproterozoic plate tectonics. A very small minority rejects plate tectonics for the Archean, but not for most of the Proterozoic. Among them, Bédard and associates (Bédard, 2006; Bédard et al., 2003; Maurice et al., 2009) recognized stark contrasts with Phanerozoic convergent-plate geology, and advocated non-plate vertical tectonics for the northeastern Archean Superior craton. Bédard proposed derivation of Archean TTG (tonalite–trondhjemite–granodiorite, the dominant rock types of preserved Archean crust) from plume-generated oceanic basalt plateaus, whereas I see instead evidence for an ancient thick basaltic protocrust, and propose delamination of dense degranitized protocrust as a major trigger for subsequent magmatism. Anderson (2007) discussed geophysical

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doi:10.1016/j.lithos.2010.12.007

Please cite this article as: Hamilton, W.B., Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated, Lithos (2011), doi:10.1016/j.lithos.2010.12.007

aspects of delamination and its efficiency as a recycling mechanism. Some geologists (e.g., Groenewald et al., 2003; Van Kranendonk et al., 2004) argue against plate tectonics for specific Archean regions and times but accept it for others. Another minority (e.g., Bickford and Hill., 2007; Hollis et al., 2009; McLaren et al., 2005; White, 2005) rejects operation of plate tectonics for some Paleoproterozoic and Mesoproterozoic orogens. Robin and Bailey (2009; also earlier papers by Bailey) argued, from thermal and viscoelastic modeling (as I did from geologic and geophysical evidence: Hamilton, 2007a) that Archean crust was far too weak and mobile to behave as plates or to support mountains.

2. Mantle evolution

Mainline geochemistry, geodynamics, and Precambrian tectonics incorporate assumptions derived from 1950s misconceptions that Earth accreted slowly and cold, is still gradually heating by radioactivity, and is slowly fractionating core and crust. Although slow accretion and heating and continuing core formation had been disproved by the time plate-tectonic relative motions were proved in the late 1960s, the derivative speculation that slow unidirectional fractionation of the silicate Earth is still far from complete and began only after Earth accreted had become geochemical dogma, and was accepted by most geodynamicists. Derivative assumptions also now dogma are that lower mantle is still "primitive" (mostly unfractionated) except for early loss of metal to the core; that upper mantle has been progressively depleted by net continental growth and is kept well mixed by convection; and that the entire mantle circulates together as plates subduct into deep mantle and plumes rise from it. Some of the abundant evidence that discredits these and related popular assumptions was presented by Hamilton (2007a,b) and is summarized and updated here.

Isotopic and cosmological evidence requires hot, fast and early major accretion and separation of core and protocrust (e.g., Carlson and Boyet, 2009; Jacobsen et al., 2008). Earth rapidly reached protoplanetary size, and heating by increasingly violent impacts, by concurrent gravitational separation of the core, and by short-lived radioactive isotopes likely formed a molten shell, wherein refractories precipitated and sank while fusibles accumulated and rose. This magma ocean zone-refined its way upward through added material as the planet grew, and lower and upper mantle likely fractionated irreversibly as physical-property and density-phase boundaries migrated with continuing accretion and fractionation (Anderson, 2007). Incompatible elements, including long-term heat-producing U, Th, and K, were concentrated in protocrust atop the magma ocean that migrated with accretionary growth. If a Moon-forming giant impact occurred, it probably melted the entire planet and vaporized much of its silicate; but even without that, impact erosion would have severely depleted more volatile components (O'Neill and Palme, 2008). This scenario predicts that at the end of main accretion, ca. 4.45 Ga, the entire mantle was extremely depleted, consisting mostly of magnesian olivine in its shallow part and otherwise of various primary and secondary higher-pressure depleted-mineral phases, and that a thick mafic protocrust contained most components of all subsequent continental and oceanic crust.

Empirical evidence supports this scenario. The low-density lithospheric mantle now held by its buoyancy against Archean cratonic crust consists mostly of dunite and harzburgite (Begg et al., 2009; Griffin et al., 2009) with remarkably uniform high-Mg olivine, $Fo_{92.6–92.9}$ (Bernstein et al., 2007). Even the minor magnesian orthopyroxene was not in high-*T* equilibrium with this olivine and records later silicic metasomatism (Bernstein et al., 2007). The olivine uniformity accords with precipitation in a magma ocean from which mafic protocrust separated, but not with long-progressive melt loss by time-varying local processes, such as plumes or seafloor spreading, as usually visualized. (Bernstein et al. compromised with the standard model and regarded the olivine as residual after partial melting to exhaustion of orthopyroxene.) The fertile lherzolite, pyroxenite, eclogite, and other rocks that now accompany dunite and harzburgite as mantle xenoliths (Griffin et al., 2009) could not have formed in high-temperature equilibrium with the dunite, or even the harzburgite, and are metamorphic rocks variably equilibrated at lower temperatures. They represent in part high-density materials arrested as they sank from above into light, hot dunite, and in part enrichment of dunite by metasomatism from below (e.g., Artemieva, 2009; Malkovets et al., 2007). Both seismic analysis and xenolith thermobarometry show the upper mantle beneath buoyant dunite to be more fertile (Yuan and Romanowicz, 2010). Conventional analysis relates this fertility to material rising from deeper primitive mantle, but if the zone-refining magma-ocean concept is approximately valid, rising metasomatizing melts instead record partial melting of re-enriching materials that sank through capping dunite into deeper upper mantle. Upper mantle has become progressively more fertile (opposite to the standard model) as re-enrichment *from the top* has ever since exceeded withdrawals of partial melts of re-enriched material to the crust of the cooling Earth. Armstrong (1991 and earlier papers) demonstrated long ago that downward recycling accounted for isotopic evidence commonly claimed to require progressive depletion of upper mantle and was required by plate tectonics [and by delamination], but only recently has even a small minority of geochemists acknowledged that he was correct.

The time-progressive Lu–Hf and Sm–Nd systematics of Archean and early Paleoproterozoic high-Mg komatiites (ultramafic lavas) provide direct evidence for this option, for they require severe and early depletion of upper-mantle sources that became more, not less, enriched with time (Blichert-Toft and Puchtel, 2010). Many recent studies of mantle xenoliths indicate re-enrichment of ultradepleted mantle. Isotopic age determinations from subcratonic mantle xenoliths are extremely erratic because of long histories above closure temperatures and the variability of post-primary-fractionation changes in both metasomatized peridotite and sunken crustal restites, but, for example, $^{187}Re/^{187}Os$ dates of secondary and often multigenerational sulfides commonly are markedly older for harzburgite, for which they scatter back to 3.5 Ga, than for more fertile rocks (Griffin et al., 2004; Heaman and Pearson, 2010). Similarly, "the incoherent behaviour of incompatible element abundances, the unrelated enrichment in the fluid-mobile elements W, As, and Zn, and the unsupported radiogenic Os and recent Re-enrichment in some sulfides suggest repeated metasomatic processes" of enrichment (Aulbach et al., 2004, p. 61). Lithospheric mantle beneath Proterozoic orogens shows highly variable, and generally greater, enrichment of initially-depleted Archean mantle (Griffin et al., 2009), which is consistent with the direct geologic evidence (Section 5) that those orogens may have been built mostly on pre-existing Archean crust. Highly variable lithospheric mantle beneath Phanerozoic orogenic crust is still more enriched.

Oceanic mantle also is highly variable, not homogenized by mixing as assumed in most modeling. Top-down enrichment of extremely depleted protomantle is compatible with many studies of dredge and xenolith samples from ridges, islands, and arcs, and also from outcrop samples of late Phanerozoic collision complexes. See Neumann and Simon (2009) for summary of compositions. Shallow moderately re-enriched ancient mantle extends hundreds of km out under oceanic crust on both sides of the South Atlantic, and occurs as stranded scraps in central parts of the ocean (O'Reilly et al., 2009). This mantle is sampled by xenoliths in the Cape Verde Islands, and contamination of lavas by it accounts for isotopic features conventionally ascribed to a plume (Coltorti et al., 2010). Warren et al. (2009) showed that the extreme isotopic variability of Sm/Nd, Rb/Sr, and U/Pb systems in Southwest Indian Ridge peridotites cannot be reconciled with time-increasing depletion. Many of their samples retain compositions permissive of extreme depletion ca. 4.5 Ga.

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Subduction now conveys young slabs and accompanying material into the upper half of the upper mantle whereas older slabs are plated down in the transition zone, and both must release partial melts from fertile components as they are heated (Hamilton, 2007b). Lamination by shear of partial melts and solids, between subduction-propelled plates and subjacent mantle, accounts for geophysical and thermal characteristics of oceanic mantle and obviates all need for deep-sourced plumes; conversely, plume theory does not explain those characteristics (Anderson, in press). Shearing also smears out deep subcontinental lithospheric mantle. Subduction did not operate during most of Precambrian time, but delaminated protocrustal materials presumably then also sank no deeper than the transition zone (Section 3.1), which, however, would have had different boundaries in the hotter, younger Earth.

"Model ages" based on isotopic ratios of Sm and Nd are widely used to classify Precambrian felsic igneous rocks either as juvenile (generated directly from the mantle, often invoked although petrologically impossible, or after brief residence in mantle-derived mafic melt or rock; defined by model ages similar to zircon U–Pb crystallization ages) or as reworked (containing material from pre-existing continental crust; defined by model ages older than zircon ages). Model ages are calculated from hypothetical Sm/Nd ratios of upper mantle thought to be evolving by progressive loss of fusible components to crust throughout geologic time. A little of the direct evidence against this conjecture was noted above. Early calculations (Nd T_{CHUR}, time of separation from "CHondritic Uniform Reservoir" mantle) assumed Archean upper mantle to have had carbonaceous-chondritic Sm/Nd ratios, which could be rationalized as compatible with data then available from Archean crustal rocks assumed to be juvenile. However, calculated-initial Sm and Nd isotopes in progressively younger crustal rocks also assumed to be juvenile diverge markedly from a CHUR-evolution curve, so an empirical mantle-evolution curve (Nd T_{DM}, time of separation from Depleted Mantle: DePaolo, 1988) was fitted to data from the younger crustal rocks within the assumed framework of progressive upper-mantle depletion.

The model-age concept is based on 1950s conjecture that upper mantle was unfractionated in earliest Archean time and has become progressively more depleted by extraction, still far from complete, of continental crust. This assumption is opposite to the scenario, summarized above, of extreme early depletion of the mantle by separation of a thick mafic protocrust, followed by progressive re-enrichment of the upper mantle by sunken crustal materials that have continued throughout geologic time. Insofar as Nd model ages have validity in my terms, they may approximately date separation from protocrust, or from its residues or other ultimate derivatives that were recycled downward into the upper mantle.

Hafnium "mantle-separation ages" (Hf T_{DM}) also are used to designate Precambrian rocks as juvenile or reworked, and similarly are based on the dubious concept of slowly depleting upper mantle. The constraining radioactive and radiogenic isotopes are ^{176}Lu and ^{176}Hf, respectively, as measured primarily in zircons of crustal rocks. Contents of Lu and Hf in upper-mantle xenoliths are neglible in olivine, low to very low in orthopyroxene, and significant primarily in garnet and clinopyroxene (e.g., Ionov et al., 2005), so, in my terms, Lu and Hf were largely removed from the mantle by early-Earth fractionation of protocrust, and were re-introduced by top-down processes. The Lu/Hf "ages" thus also relate vaguely to partial melting of recycled materials, not to depleting mantle.

Earth's enormous heat content is largely retained from its early history, although net heat loss is slowed by heat released by core crystallization and by decreasing heat from decay of U, Th, and K, which may be almost entirely in the crust and upper mantle. Current radiogenic heat production is only approximately known, Earth's content of volatile potassium being particularly uncertain, but likely is close to current heat loss, which is substantially lower than commonly assumed because barriers to convection and conduction much exceed those usually modeled. Hypothetical global heat loss of ~44 TW, assumed in much modeling, may be almost 50% too high, for it is calculated with the false assumption of constant surface-rate thermal conductivity through oceanic lithosphere, whereas actual conductivity decreases by a factor of about two in both felsic rocks and olivine from 0° to 500 °C (Hofmeister and Criss, 2005). Thermal diffusivity, which incorporates heat capacity and is the rate at which heat transfer by conduction responds to changing heat input, of felsic rocks decreases to a third of its surface value (and half of the constant value used in most modeling) at a temperature of ~500 °C, and varies little at higher temperatures (Whittington et al., 2009).

These properties indicate lithosphere to be a much better insulator, and Earth to cool more slowly, than commonly modeled. They also show that much partial melting of uppermost mantle or lower crust is to be expected from heat generated within the continental crust or introduced beneath it. Large amounts of melt can accumulate beneath the crust or the lithosphere, which accounts for rapid, voluminous eruptions of large igneous provinces with no need for plumes. Conventional assumptions of mantle temperatures, thermal gradients, and adiabaticity likely are far in error (Anderson, in press).

3. Modern and Phanerozoic plate tectonics

My career emphasis on products and processes of active and Phanerozoic convergent plate tectonics is relevant to my credentials as a skeptic of Precambrian plate tectonics. I saw early (Hamilton, 1969, 1970) that plate tectonics held the key to Phanerozoic evolution of continents. Geophysics and tectonics of active systems are well known to many marine investigators but commonly are misrepresented in textbooks and journal articles, and my monograph on Indonesia and surrounding regions (Hamilton, 1979, + wall maps) remains the most comprehensive integration of marine geophysics and onshore geology of a huge active region of complex convergent tectonics. I integrated that work with other regions (e.g., Hamilton, 1978, 1988), and my 1978 paper laid out what others soon termed the "exotic terrane" concept. Hamilton (1995) analyzed vertical crustal variations in exposed arc-magmatic systems. Hamilton (2007b) reviewed characteristics and kinematics of actual plate interactions and constraints on mantle circulation, including documentation for many statements made in the present report. I argued that subduction is self-organized and driven by the density inversion consequent on top-down cooling of oceanic lithosphere, that plate circulation is limited to the upper mantle above the discontinuity near 660 km, and that the kinematics of plate behavior accord with these constraints. A number of other geodynamicists also have presented powerful evidence that plate tectonics is self organized and driven from the top (e.g., Anderson, 2007, in press).

Many geodynamic modelers provide visual aids for conventional speculations by assuming a nearly isochemical fertile and adiabatic mantle with unrealistic properties. Smooth whole-mantle circulation cannot operate if more realistic properties, including pressure-controlled very high viscosity and very low thermal expansivity of lower mantle, are incorporated. Popular models do not account for Earth's first-order plate behavior, including the very slow spreading of the nonsubducting Atlantic in contrast to rapid spreading of the shrinking subduction-rimmed Pacific. That contrast provides some of the abundant evidence for hinge rollback and for subduction control of plate circulation. On the real Earth, but not the one usually modeled, fixed plate boundaries cannot exist, and spreading cannot be driven from below because, for example, it stops where ridges intersect trenches.

Popular cartoons show subducting lithosphere turning abruptly downward at fixed hinges, which define steep-sided trenches against which overriding plates are crumpled. This nowhere occurs. Actual

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oceanic and continental-margin trenches are gentle dihedral angles between oceanic crust and thin wedges of scraped-off materials in front of advancing plates, and hinges are broad curves well back under overriding plates whose thin fronts commonly are not crumpled. Hinges commonly roll back into subducting plates as overriding plates follow passively. Magmatic arcs form on overriding plates in response to subduction beneath them, and can be abandoned, split, or plated out rapidly as irregular sheets in response to hinge rollback and evolving curvatures in plan and section. Most magmatic arcs form under extension, not shortening.

The Phanerozoic has been the era of plate tectonics, for its orogens contain abundant indicators both for separation of continents by seafloor spreading and for amalgamation of arcs and continents by subduction, including voluminous accretionary-wedge mélanges, blueschists, ophiolites, and oceanic and continental magmatic arcs. These indicators are sparse and incomplete in the Neoproterozoic, and wholly lacking in older Precambrian terrains. When I began looking at Archean geology about 20 years ago, I expected to find evidence for modified plate tectonics, but instead found unfamiliar rock types, associations, and structures, and none of the indicators of Phanerozoic-type convergent and divergent plate interactions. I next assumed that plate tectonics began in early Proterozoic time, but abandoned that notion also when I looked more closely. My broadest prior statement from these inquiries is a long multidisciplinary paper (Hamilton, 2007a).

3.1. Nonexistence of plumes and deep subduction

The conjecture, unrelated to evidence for plate tectonics, that plumes bring deep-mantle heat and material to upper mantle and crust is another derivative of 1950s cold-accretion misconceptions, and is widely invoked to explain much modern and Archean geology. The plume concept was devised almost 40 years ago to explain the southeastward younging of Hawaiian volcanic seamounts and islands by eruption of a long-continuing fixed vertical jet from deep in the mantle through a Pacific plate moving northwestward. Many other fixed-plume "hotspot tracks" were then postulated in accord with the assumption that a "hotspot reference frame" for plate motions was defined by Hawaii plus the fixity of whatever other "hotspots" appeared to be compatible with it. Geochemists and isotopists claimed plumes to generate unique volcanic rocks incorporating material from "primitive" lower mantle, and proposed many other plumes from compositional criteria. Modelers postulated behavior of plume heads and tails in terms of assumed mantle evolution, without incorporating realistic viscosity and thermal expansivity, and predicted geophysical properties. These and other early conjectures of fixity, progression, behavior, and chemistry were soon dogmatized, and are accepted as facts by most currently active geoscientists — but all have been disproved in many instances. Many pro- and anti-plume reports, which can be evaluated side by side, are concentrated in Foulger et al. (2005) and Foulger and Jurdy (2007), and at www.mantleplumes.org. Foulger (2010) gives a comprehensive overview with an anti-plume bias. Important new arguments against the plume concept include those by Anderson (in press), who integrated the known vertical and horizontal seismic anisotropy of the dynamic boundary layer beneath top-driven plates to demonstrate that "hotspots" are sourced in the upper mantle and that prevalent assumptions of the thermal structure of the layer are mistaken.

Harsh criticism of plume speculations comes mostly from skeptics, but much strong anti-plume geometric and geochemical evidence is presented by plume advocates themselves, who document failed predictions and generalizations but then give the many misfits pro-plume rationalizations incompatible with the reasons for their initial designations as plumes. For example, plume advocates Tarduno et al. (2009) summarized some of the evidence that shows most of the "hotspots" initially proposed as plumes because they appeared to be fixed relative to Hawaii in fact are moving relative to it at moderate to high rates. They invoked "mantle winds" to blow moderately errant plumes off course, and migrating ridges to grossly displace other hypothetical plumes including the Emperor Seamounts half of the purported Hawaiian track. Early assumptions of many Hawaii-like volcanic progressions have been disproved by subsequent extensive dating, so intermittent magmatism of any composition and chronologic and geographic distribution, in vague systems thousands of km long of disconnected components selected because they can be assigned to zones with desired orientations, is commonly now assigned to single hypothetical plumes, for example by advocates Morgan and Morgan (2007, electronic supplement). Similar vague alignments can be drawn in other random directions. General invalidation of early characterizations of chemical and isotopic features of purported plumes have been met with unique rationalizations for the many misfits. Thus, White's (2010) broad review acknowledged many failures of geochemical and isotopic predictions and generalizations originally claimed as evidence for plumes, including features still widely cited as requiring lower-mantle origins, and presented complex pro-plume explanations for them.

Inferences by some seismic tomographers that plumes rise, and subducting slabs sink, through the 660-km discontinuity are severely flawed. Most non-seismologists accept their tomographic models as confirming these concepts, whereas most seismologists (e.g., Dziewonski, 2005, and brief statements by many top seismologists regarding the Wolfe et al., 2009, Hawaiian tomography, as posted on www.mantleplumes.org) regard purported examples as artifacts of sampling, processing, and selective display. Plume advocates commonly place published profiles only where visually suggestive features can be seen, and truncate profiles laterally and downward to omit features inconsistent with deep circulation. Saturation of colors at very low velocity differentials renders faint calculated lower-mantle anomalies similar visually to robust upper-mantle anomalies with 15 times the amplitude. Upper-mantle vertical and horizontal anisotropy are disregarded, which results in downward smearing of actual anomalies (Anderson, in press).

Reliable body-wave tomography requires that all earth volumes be traversed in diverse directions by abundant recorded rays, for only then can simultaneous inversion of myriad linear equations solve for the contribution of each volume to retardation or acceleration, and the extremely uneven distributions of earthquakes and seismometers precludes meeting this requirement for purported deep plumes and slabs. The imperative crossfire requirement cannot even be approached for body-wave studies alone, with local seismometer records, of deep mantle beneath isolated islands and island groups, for the only recorded body waves that sample this mantle rise steeply through it. Further, large parts of most body-wave models are filled with assumed values that mislead nonspecialists.

All published tomographic models of purported deep plumes are severely flawed, but I discuss here only Hawaii, which provides the type example for rationalization of a "plume track" while disregarding both observed tectonic controls of magmatism and failure of geophysical predictions in plume speculations (Anderson, in press). Pro-plume tomographers Wolfe et al. (2009) depicted a low-velocity plume rising through much of the upper mantle beneath the Hawaiian region, and a disconnected narrow plume rising obliquely northwestward toward it from a depth of 1500 km in the lower mantle. Wolfe et al. modeled only steeply rising teleseismic *S* waves to calculate upper-mantle structure, and only steeply rising *SKS* waves to calculate mid-mantle structure with rays that came through the liquid core via phase conversions. The narrow seismometer spread precluded sampling deep mantle beneath the islands with moderately and gently inclined crossfire, and Wolfe et al. did not utilize any other steeply rising *S* and *P* rays that would have increased coverage, nor did they incorporate any surface waves, receiver functions, or Vp/Vs derivatives to constrain depths, amplitudes, and characters of possible

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anomalies. Wolfe et al. truncated their published model downward at 2000 km, but the narrow bundle of *SKS* rays that alone defined their purported lower-mantle plume rose northwestward through a poorly known lowermost-mantle region of low velocity (likely recording high iron content and high density, not high temperature), which they acknowledged could be modeled as their plume — but they claimed a plume to provide the "simplest" explanation. Wolfe et al. forced their *S*-wave time delay deep into the upper mantle by assuming that only moderate retardation occurred within either the crust or a shallow magma-generating system. Leahy et al. (2010; Wolfe was second author) showed, with receiver-function analysis of the same seismometer records, that the upper-mantle "plume" of Wolfe et al. (2009) was the product of downward smearing of the time delay within thickened Hawaiian Swell crust. Leahy et al. acknowledged previous observational proof that the Hawaiian region lacked plume-predicted high heat flow.

The plume concept requires that compensating dense material sink elsewhere, so deep subduction is postulated on the basis of similarly flawed tomographic models that permit a carefully placed, truncated, and color-exaggerated profile to depict a low-amplitude positive velocity anomaly postulated to record such subduction. The visually best, and most widely cited, example, a short profile in both d*Vs* and d*Vp* versions by Grand et al. (1997), is purported to show eastward subduction of the "Farallon slab" through most of the lower mantle beneath the Gulf of Mexico and southeastern United States. Dziewonski (2005) presented six longer d*Vs* profiles along the same great-circle path as those short profiles. One was through a revised 1999 model by Grand, and five were through recent models by other tomographers who used almost the same data but different processing. Only on the initial short, truncated profile by Grand et al. (1997) is the purported slab conspicuous and isolated — and that inclined anomaly can be designated only within a narrow map band, for no such anomaly is calculated to north or south. Grand's revised and longer profile depicts two other deep-mantle dangles of slightly high velocity comparable to his 1997 slab. One is immediately east of his short 1997 profile, inclined westward within the mid-mantle and vertical deeper; the other is inclined westward within the west part of the profile wherein Grand et al. earlier had default values; neither has a plausible subduction explanation. Most of the coincident profiles by the other five groups of seismologists show an irregular regional positive velocity anomaly that extends through the entire lower mantle for 2000 km westward from Grand's slab, and that also defies subduction explanations.

The purported local "Farallon slab" appears to be a sampling artifact defined by rays that originate high in the Andean slab, gain time advances as they exit obliquely downward through the anisotropic slab, and are recorded in and near North America. This sampling is illustrated by Fig. 1. The Andean time advances are not properly subtracted in processing because of scarcity of recorded local crossfire, and are misassigned to deeper-mantle volumes wherein subparallel paths are concentrated. Comparison of Fig. 1 with other published tomograms purported to show local lesser lower-mantle penetrations by slabs in western Pacific and Tethyan regions indicates that these also can generally be explained by bundled rays that gain time advances exiting upper-mantle slabs in which they are generated.

A series of close-spaced profiles, much better constrained, across the Japanese and Mariana arc systems shows their subducted slabs, as relatively high-amplitude positive d*Vp* anomalies, to be plated down on the 660-km discontinuity as far as 2000 km westward beneath China (Zhao, 2009). The downplating is, in my view, a product of hinge rollback, not of horizontal injection. A similar transition-zone positive velocity anomaly of 1 or 2% of d*Vs*, much larger in amplitude than the dubious "Farallon slab", that extends 1000 km or so inland beneath the western United States and northern Mexico was modeled from *S* and Rayleigh waves by Bedle and van der Lee (2009), and appears to be the actual Farallon slab, incompatible with purported deep-mantle subduction beneath it. The d*Vp* profile of Grand et al. (1997) also shows this transition-zone anomaly within the profile claimed to display the deep slab.

Kinematics of actual plate motions, including the shrinking of the subducting Pacific Ocean despite its rapid spreading, are explicable in terms of subduction limited to the upper mantle (Hamilton, 2007b), but not by whole-mantle circulation. The 660-km phase-petrologic discontinuity presents a thermodynamic obstacle to penetration in either direction because of its unusual negative Clapeyron slope (references in Hamilton, 2007b). Tomographic patterns, anisotropy, and heterogeneity change markedly at the discontinuity, incompatible

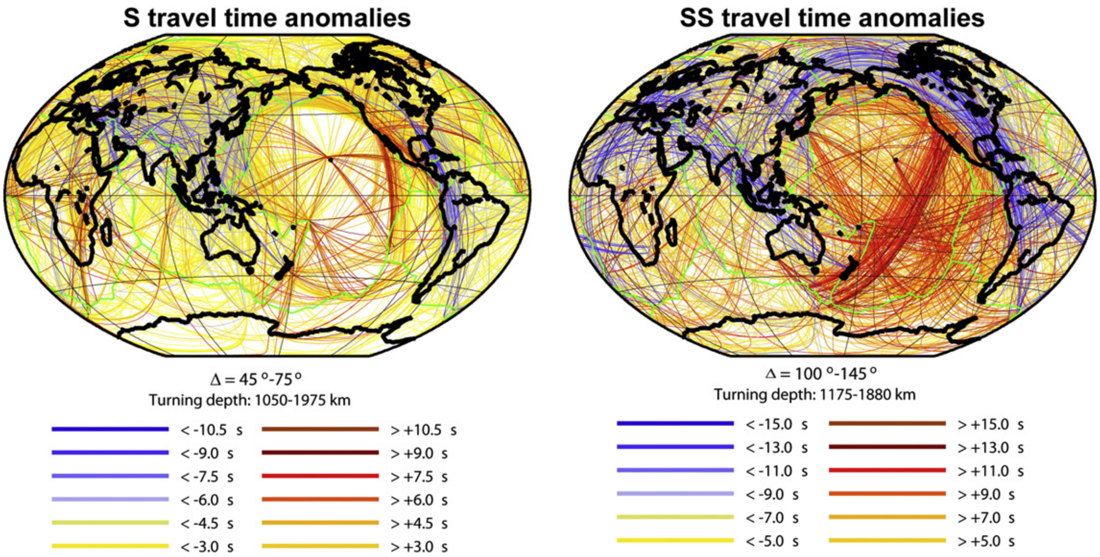

Fig. 1. Raypaths from earthquakes to recorders of *S* and *SS* waves that sample the middle mantle. Much of the Earth's interior is effectively unsampled, and much else is sampled primarily by subparallel rays, as shown here, rather than by the diversely crossing rays required for tomographic inversion. The purported deeply subducted "Farallon slab" (Grand et al., 1997) beneath the Caribbean and eastern United States appears to be an artifact of misassignment to mid-mantle depths of the time advances gained by rays exiting obliquely downward through the upper-mantle Andean subducting slab from earthquakes high in the slab. Rays of *S* waves are direct; *SS* rays have a surface bounce; Δ = great-circle length limits of paths plotted. Unpublished figure provided by Jeroen Ritsema.

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with free circulation across it (e.g., Dziewonski, 2005). The 660 may be a complete barrier to circulation between lower and upper mantle.

Advocates of Precambrian plumes claim recognition of ancient plumes with chemical discriminants based on early conjectures regarding modern plumes, and also invoke plumes to add heat to upper mantle and crust wherever desired. Other extrapolations from early assumptions of terrestrial plumology still dominate mainline interpretations of the unearthlike large rimmed circular structures that saturate much of the surface of Venus, and of the sparse huge unearthlike young "volcanoes" of Mars, features far better explained with bolide impacts in my view (e.g., Hamilton, 2007d).

3.2. Igneous rocks of island arcs

Popular speculation that Precambrian crust formed primarily by accretion of vast numbers of oceanic island arcs is incompatible with the utterly different character of modern and Phanerozoic arcs and their aggregates. Phanerozoic island-arc volcanic rocks are unimodal, with a mafic peak, whereas most Precambrian volcanic assemblages are sharply bimodal, with high mafic and felsic peaks. (For compositions of modern-arc upper-crustal rocks, see Murphy, 2007, and B.M. Gunn's many variation diagrams at www.geokem.com.) Modern oceanic arcs have only uncommon high-silica rocks in either volcanic edifices or plutonic complexes, and these are seldom potassic, whereas richly potassic high-silica rocks are voluminous in most Proterozoic terrains and many upper-crustal Archean ones. Compositions of upper-crustal and volcanic rock types in oceanic island arcs vary with degree of magmatic fractionation and recycling, which are functions of crustal size of magmatic constructs. Young, immature arcs, which have thin crust, small and narrow submarine ridges, and small subaerial volcanoes, have narrow mafic frequency peaks. As edifices thicken and widen by prolonged volcanism, intrusion, and underplating, the frequency distribution broadens, with a peak near 54% SiO_2 and a long decline through intermediate to silicic rocks. Erupted lavas change to more varied calc-alkaline types, including abundant high-alumina and two-pyroxene basalt and pyroxene andesite, and lesser felsic andesite and dacite. I used these compositional features to make what may have been the first identification of an oceanic island arc accreted to a continent (Hamilton, 1963), though I did not then understand the accretion mechanism. Upper-crustal plutonic complexes in evolved arcs are dominated by gabbro, diorite, and hornblende tonalite. Lower-crustal rocks are more mafic (Section 3.3), and the compositional features that typify upper-crustal island-arc rocks are products of complex crustal magmatic and partial-melting processes, not of deep sources as commonly assumed. Volcanic and upper-crustal plutonic rocks of continental magmatic arcs are much more felsic in bulk composition, with a frequency peak near 70% SiO_2, a long inclined intermediate and mafic tail, and a short high-silica tail.

The history of many active arcs changes dramatically along them because of lengthening with time, migration, collisions, and reversals, and the entire suite of progressive changes can be seen in single continuous arcs. Thus, the modern Sumatra–Java–Banda arc changes eastward in size, crust, and petrology from a continental arc through progressively smaller-volume oceanic-arc sectors of younger inception age to a nascent arc (Hamilton, 1979).

Most geochemical work on modern oceanic arcs has been done on little-altered subaerial rocks, but submarine complexes dominate crustal edifices and also preserved Phanerozoic arcs. U.S. Geological Survey geologists studied both subaerial and submarine complexes of most islands of the mature Aleutian arc. Major-element chemistry of their analyzed specimens of fresh-subaerial and often-altered submarine rocks is shown in Fig. 2, whereon it can be seen, as in petrographic study, that changes accompanying low-grade synmagmatic submarine metamorphism are primarily the highly variable substitution of seawater sodium for magmatic calcium. Analogous exchange in seafloor basalt is generally much smaller. This is relevant for evaluating the common assertion by Precambrian geochemists that major element contents are secondary and can be disregarded in tectonic analysis.

3.3. Depth variations, fractionation, and crustal recycling in Phanerozoic magmatic arcs

Modern island-arc rocks have been studied intensively as subaerial volcanic rocks, secondarily as upper-crustal volcanic and plutonic rocks, and very little as lower-crustal rocks. That only similar mafic melts reach the base of the crust of both continental and oceanic magmatic arcs of varying maturities, and that fractionation and crustal contamination and recycling explain the contrasts in erupted lavas, is made likely by the trends in continuous continental-to-oceanic modern arcs (Section 3.2), and also by study of rare exposures through arc crust. I have seen two of these crustal sections, the Cretaceous Kohistan island arc accreted in north Pakistan, and the late Paleozoic Ivrea continental arc in the Italian Alps. Both sections extend from geophysical mantle to volcanic upper crust. Aggregated island arcs are popularly invoked as the major builders of Precambrian crust, so the Kohistan section is particularly relevant here. The reconnaissance Kohistan literature is mostly based, like my view, on excellent exposures along the Karakoram Highway in the Indus and other gorges, and I summarize my perceptions without addressing agreements and disagreements with and among other reports. The section records generation of felsic melts by the breakdown of early mafic crust heated by, and fractionated from, underplated gabbronorite and subjacent more-mafic and ultramafic rocks. The exposed uppermost mantle consists of olivine and clinopyroxene cumulates — geophysical mantle but petrologic crust. Next is higher thick garnet-rich mafic granulite, and then several km of mafic garnet granulite, amphibolite, gabbro, and primary-garnet gabbro, presumably depleted by upward loss of fusible components. Above these is perhaps 10 km of broadly folded layered olivine-free gabbronorite, near the top of which olivine and plagioclase crystallized together as troctolite but reacted to clinopyroxene on cooling, defining depth there as about 30 km. Above this is the main granite factory, consisting of migmatitic amphibolite with superabundant intercalations and small sheets of tonalite and leucotonalite recording partial melting of mafic rock aided by hornblende breakdown. Common but minor garnet with hornblende indicates depths generally >18 km. Above this complex are many plutons of tonalite and other rocks intrusive into subordinate mafic metavolcanic rocks. Still higher crust is dominated by low-grade metavolcanic rocks, including flattened pillow lava. The top 5 km or so of initial crust is not preserved.

The similar Jurassic Talkeetna oceanic arc, accreted to southern Alaska, is the subject of many reports (e.g., Greene et al., 2006). It displays, in order upwards, tectonized harzburgite and dunite pre-arc mantle; petrologic-crustal olivine and clinopyroxene cumulates; garnet granulite and gabbro; ~10 km of layered gabbronorite; migmatites; a plutonic zone dominated by hornblende tonalite and diorite; and volcanic rocks, dominantly basalt and andesite but varying to rhyodacite. Bulk crustal composition is approximately high-Mg, low-Al basalt, markedly more mafic and less aluminous than the upper-crustal volcanic rocks whose compositions are commonly assumed to dominate arc crust.

Ivrea continental-arc deep crust also overlies olivine and clinopyroxene cumulates (petrologic crust but geophysical mantle), and has basal mafic garnet granulites beneath thick layered gabbro and norite. The lower part of the overlying granite factory is, however, dominated by migmatites and refractory residues of continental plutonic and metasedimentary rocks, and the granitic and volcanic melts that rose from there to upper crust and volcanic complexes were silicic and moderately potassic.

These crustal sections show that only similar mafic melts rise to and into both oceanic and continental arc crusts, that more evolved

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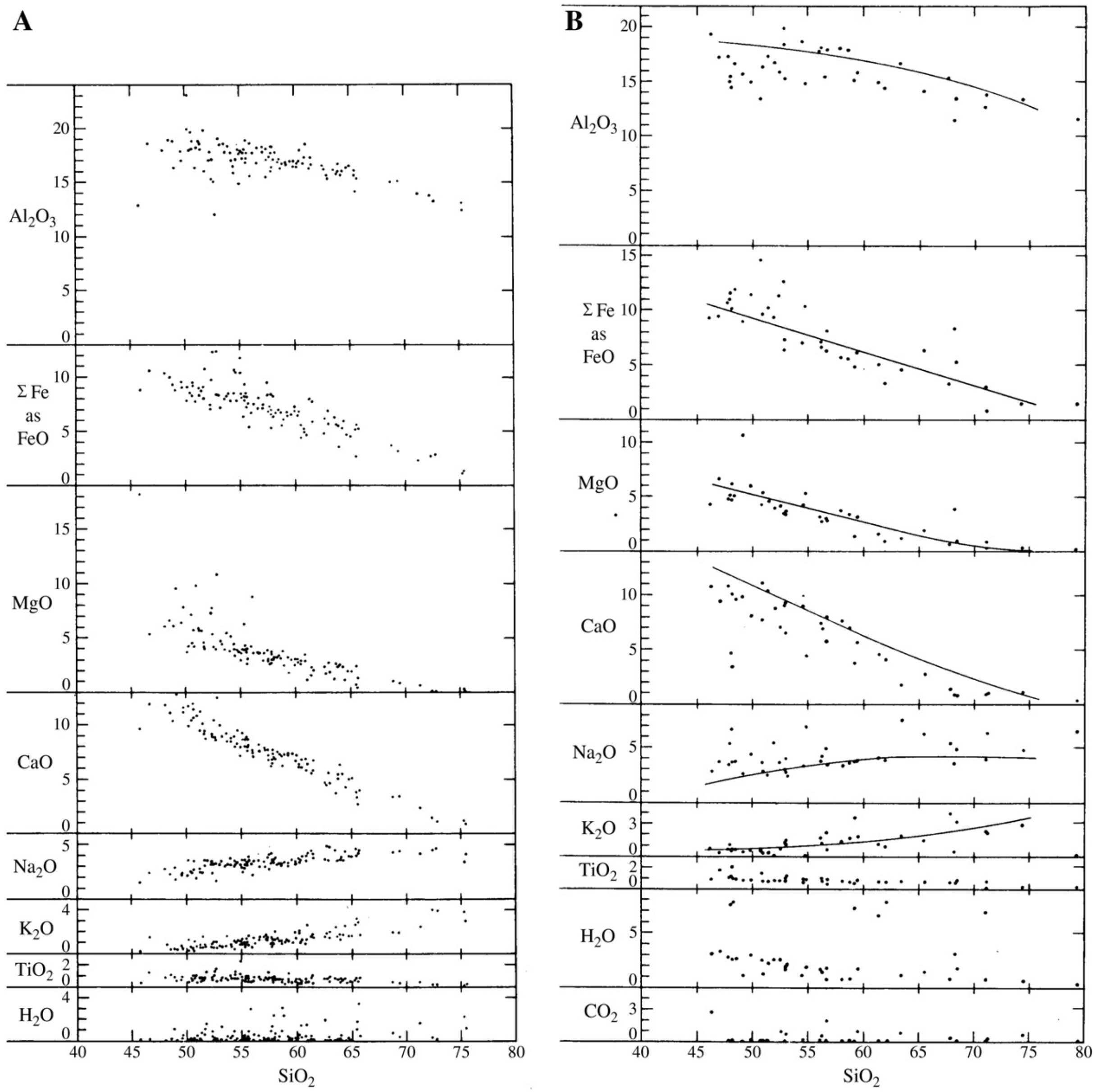

Fig. 2. Silica-variation diagrams of (A), subaerial volcanic rocks, and (B), submarine volcanic, volcaniclastic, and synvolcanic-intrusive rocks, of the Aleutian island arc. The lines in B summarize the systematic variations in A, unadjusted for volatile components. Most rocks are calc-alkaline. The subaerial rocks show systematic co-variations, and have a broad frequency-distribution peak from 50 to 65% SiO_2, a short low-silica tail, and a longer high-silica one. The submarine rocks are mostly altered at low greenschist facies (note contents of H_2O and CO_2). Interaction with hot seawater is shown particularly by erratic decrease in CaO below magmatic values, and corresponding erratic increase in Na_2O; most other elements retain magmatic co-variations.
After Hamilton (1963, Figs. 65 and 66), which see for sources of analyses.

melts are generated by intracrustal fractionation, secondary melting, and other reactions, and that felsic magmas represent materials previously within the crust, either from earlier mafic magmatism (Kohistan and Talkeetna) or from earlier continental sources (Ivrea). Seismic structure of the immature active Bonin island arc indicates its lower half, by volume, to be of mafic rocks (Taira et al., 1998). The distinctive volcanic arc rocks are generated in the crust, and should not be used, as commonly they are, to infer deep sources. In each of the three exposed arcs, the Mohorovičić discontinuity is a self-perpetuating density filter produced by fractionation of melabasaltic melts rising from the mantle, and is not a fossil boundary. Seismic-refraction studies commonly show Phanerozoic, and most Proterozoic, deep lower crust to be dominantly mafic, whereas Archean crust commonly has intermediate and felsic rocks to its base (Durrheim and Mooney, 1994).

One common conspicuous contrast between upper-crustal oceanic-arc volcanic rocks and ocean-floor and ocean-island basalts is the low content in arc volcanics of high-field-strength elements (HFSE, which include Ti, Zr, and Y), and this provides much of the basis for the claim by geochemists (Section 4.3.1) that they can identify the setting and deep source of any ancient igneous rock sample merely with ratios of ratios of trace elements, regardless of how different from modern analogues the bulk composition and geologic setting of that rock may be. However, the deep-crustal mafic rocks of the Talkeetna arc section are rich in Ti, complementary to the low Ti of mafic volcanic rocks (Greene et al., 2006). HFSE readily enter melts but not aqueous solutions, which is the basis for common speculation that modern arc magmatism is due to dewatering of subducted oceanic crust and resultant fluxing of the overlying mantle wedge to produce low-Ti melts that enter the crust. Many Archean geochemists

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accordingly claim that Archean low-Ti mafic rocks require subduction. These conjectures are refuted by the Talkeetna data. Further evidence against dewatering conjecture is given by well-constrained seismic tomography of the active Japanese arc, which shows a hot medial channel rising obliquely arcward within the mantle wedge (a pullapart plate-bounding feature related to the sinking of subducting slabs at angles steeper than their dips), not the low-velocity sub-arc vertical channel predicted by dewatering speculation (references in Hamilton, 2007b).

Melts commonly have compositions and temperatures approximately equilibrated to their transient depths, not residual from their sources. Major elements of igneous rocks are products of phase-petrologic reactions and hence powerfully constrain magmatic evolution and equilibria. For example, olivine and plagioclase cannot coexist at magmatic temperature deeper than about 30 km, which, like the deep-crustal exposures, negates the conjecture, common in Precambrian geochemistry, that evolved calc-alkaline intermediate and felsic igneous rocks of island arcs are generated by partial melting of subducted slabs, or by melting in mantle wedges fluxed by volatile components released from slabs, followed by rise of unmodified melts through hot peridotite and into overlying crust. Conversely, any mafic melt erupted at the surface with olivine and plagioclase on its liquidus is a low-pressure equilibrate that cannot have been transported intact from a deep setting.

3.4. Aggregates of island arcs

Modern arcs are narrow, and migrate and aggregate by colliding with each other and with continents (e.g., Hamilton, 1978, 1979, 2007b). Dissimilar vast aggregates, to thousands of km wide, of island arcs commonly are invoked to explain Precambrian terrains, but their components and structures bear no similarity to modern arcs. More than the igneous arc rocks alone (Sections 3.2 and 3.3) are at issue.

Archean cratons commonly are exposed as granite-and-greenstone terrains, at erosional depths near 8 or 10 km. (Most Proterozoic orogens are eroded much more deeply.) The Klamath Mountains of northwest California and southwest Oregon comprise a much-studied aggregate, up to 150 km wide, of Ordovician to Jurassic arcs eroded typically to similar depths (Burchfiel, 1992; Burchfiel et al., 1992; Dickinson, 2008), so direct comparison is appropriate. The complex lies landward of, and structurally overlies, the latest Jurassic through Quaternary accretionary wedge, 100 km wide as exposed in front of the Klamaths, which tapers westward to the active Oregon trench and consists of broken formation and polymict mélange of disrupted oceanic crust, mantle, islands, and sediments and includes blueschist and abundant oceanic pelagic sediments. The Klamath arc aggregate itself contains about 10% ophiolite, as several large sheets, one of which is a complete crustal section from harzburgite tectonite to pillow basalt and pelagic sediments, and as variably disrupted lesser sheets, ophiolitic mélange, and blocks in mélange. Another 25% consists of sedimentary-matrix mélange, much of it dominated by deep-ocean materials, and subordinate blueschist. The rest consists mostly of mafic and mafic-intermediate arc-volcanic and volcaniclastic rocks plus much-subordinate plutonic rocks, mostly mafic and intermediate. Variations on this theme can be seen along much of the length of western North America (e.g., Burchfiel et al., 1992), but nothing remotely comparable is known in any pre-Neoproterozoic terrain.

4. Archean tectonics

Most Archean reports of the last 20 years present explanations dominated by island arcs and plumes, whereas I (Hamilton, 2007a and this report) see no sutures, rock assemblages, or other evidence suggesting that ancient island arcs existed, and further see much evidence that plumes do not operate in the modern Earth (Section 3.1) and no evidence for their operation in the ancient one. The voluminous mélanges, ophiolites, and blueschists that make sutures obvious in upper-crustal Phanerozoic assemblages (Section 3.4) have no pre-Neoproterozoic analogues. Claims for ancient ophiolites are spurious (Section 4.3.2). Assertions (e.g., Polat and Kerrich, 1999) that narrow synmetamorphic strike-slip shear zones of local rock types within Archean greenstones are oblique-subduction mélanges are incompatible with the character and dimensions of modern mélanges, with the fact that modern oblique-convergence accretionary wedges are imbricated in gravitational trench-normal directions (Hamilton, 2007b), and with the lack of contrasted complexes on opposite sides. The common postulates that Archean greenstone sections are stacks of thin bedding-parallel rootless thrust sheets, juxtaposed randomly from oceanic complexes scattered initially over vast distances and superimposed structurally on TTG arcs (e.g., Wyman et al., 2002, for the Abitibi region of the Superior craton), or steeply imbricated thick blocks of alternating “arc” and “plume” crust (e.g., Wyman and Kerrich, 2009, same region), is incompatible with mapping and dating showing supracrustal complexes to have coherent regional stratigraphy (Thurston et al., 2008, same region), with zircon-xenocrystic, isotopic, and trace-element evidence for continental-crustal inheritance (Ketchum et al., 2006; Pearce, 2008, same region), with the complete age overlap of upper-crustal granitic and volcanic rocks (Chown et al., 2002, same region), and with the known character of Phanerozoic arc aggregates (Section 3.4). The relatively few zircon dates from Abitibi lower crust, as raised in a Proterozoic block uplift, span upper-crustal ages and extend hundreds of millions of years older (Benn and Kamber, 2009). Other parts of the Superior craton, and other cratons, also are known to have regionally coherent supracrustal stratigraphy incompatible with imbrication (e.g., Maurice et al., 2009).

Field evidence, like that from petrology, further shows Archean supracrustal rocks to be ensialic, not ensimatic as commonly assumed. No mantle rocks have ever been seen beneath Archean supracrustal sections, whereas older continental TTG basement is seen in many places depositionally beneath them, including the typical mafic and ultramafic volcanic lavas (Section 4.3.2; other references and illustrations in Hamilton, 2007a).

4.1. An alternative model

I summarize here an alternative early Earth, following on the mantle discussion (Section 2) and updated from a long paper with abundant references (Hamilton, 2007a). Fractionation before 4.4 Ga of thick mafic protocrust from extremely depleted mantle is the key. The protocrust contained most of the material recycled and polycycled into both continental and oceanic crust of all subsequent ages. Incremental delamination and sinking of protocrust as it was densified by removal of TTG began the process of net re-enrichment of upper mantle that enabled, but exceeded, extractions of other partial mantle melts at decreasing temperatures throughout the post-4.4 Ga history of the Earth.

Surviving Archean crust commonly is dominated to its seismically defined base by TTG, in sum about 30 km thick, which experimental and phase petrology require to have been derived ultimately by partial melting of more voluminous pre-existing mafic, not ultramafic, rock or, less plausibly, by fractionation of hydrous mafic magma. Generation of TTG from protocrust began very early and proceeded intermittently throughout Archean time. TTG as old as 4.0 Ga is dated by zircons, recycled zircons as old as 4.2 Ga are known in TTG, and zircons of TTG type as old as 4.4 Ga are found in Archean clastic strata. Most of the tonalite has steeply fractionated rare-earth elements (REE), so garnet, retentive of heavy REE, was abundant in the residue. More evolved felsic plutonic rocks were derived by recycling TTG. Zircons dramatically older than overlying supracrustal assemblages are preserved primarily in lower-crust gneisses, which commonly

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represent wetter and cooler melts, hence lower zircon solubilities, than do hotter, dryer upper-crustal granites.

Direct support for protocrustal control of this early history was provided by Kemp et al. (2010), who integrated U–Pb and Lu–Hf systematics of 4.4–3.8 Ga detrital zircons in Archean clastic strata of southwest Australia to demonstrate that felsic plutonic rocks from which the grains came were derived by partial melting of mafic crust that separated from the mantle before 4.4 Ga. This is incompatible with the common conjecture that incremental additions of mafic deep crust from whence came TTG, or of direct TTG, came from gradually depleting mantle throughout Archean time.

Sm–Nd "model ages" are widely misused to distinguish Precambrian felsic igneous rocks either as juvenile or as reworked from older continental crust (Section 2). Sm/Nd ratios of Archean mantle are unknown, but measured ratios are approximately chondritic in Archean basalts and komatiites, so in my terms, the "juvenile" ages of many Precambrian rocks approximately date, at best, extraction from mafic protocrust separated very early in Earth history from extremely depleted mantle. Melts generated in the mantle since initial fractionation of protocrust record primarily recycling of sunken crustal materials that have progressively re-enriched the upper mantle.

Archean cratons are exposed mostly as upper-crustal granite-and-greenstone assemblages, wherein domiform batholiths rose slowly as initially continuous supracrustal sections sank in intervening synforms (Fig. 4). Deformation and metamorphism decrease inward in synforms, from strong (Fig. 3) to, often, negligible. Local geologic studies that confirm granite-up, supracrustals-down shear along single sides of greenstone belts are sometimes claimed, wrongly, to indicate regional pre-batholithic thrusting. Widely variable synbatholithic shearing, either dominantly strike-slip or recording moderate elongation parallel to regional strike and shortening across it, disrupted the evolving assemblages (Fig. 4). As discussed for one region in Section 4.3.2, the only basement ever seen beneath Archean greenstone belts is older TTG; no Archean volcanic rocks are proved ensimatic; and there is no proof of an Archean continent/ocean dichotomy. Archean volcanic rocks are dominantly bimodal, with intercalated mafic and felsic rocks, the latter commonly increasing stratigraphically upward, and subordinate ultramafic and intermediate rocks. Ultramafic lavas, including komatiites, and sills were erupted at up to at least 1600 °C, indicating upper-mantle temperatures perhaps 300 °C hotter ca. 3.5 Ga than now. The felsic volcanic rocks were erupted from rising batholiths of TTG and its reworked derivatives and share their distinctive compositions. Supracrustal sections commonly end upward with marine and nonmarine clastic strata derived from breaching batholiths. "Greenstone belts" of supracrustal rocks record disruption of supracrustal rocks, not eruptions in linear arrays, for well mapped and dated sections have subregional stratigraphy. Preserved supracrustal cycles were inaugurated at different times, from 3.6 to 2.7 Ga, in different regions, and in some places two or even three cycles are superimposed, with batholithic doming and marginal shearing decreasing with decreasing age. Full cratonization of those parts of Archean terrains that otherwise survived severe Proterozoic reworking was not achieved until after 2.5 Ga. Late-continuing rise of batholithic basement diapirs affected the well-preserved regional sheets of late Neoarchean sedimentary and volcanic rocks of the Witwatersrand Basin in South Africa, and of the Hamersley Basin and its Pilbara outliers in Western Australia. Many plate-tectonics advocates postulate that Archean TTG formed in island arcs, despite the lack of modern analogues, and that the volcanic rocks were thrust over them in multiple thin sheets from diverse sources and in turn were overthrust by more TTG, but relevant structures have not been documented beyond, at best, vague invocations of local or hidden shear zones.

Archean middle crust, and the upper part of the lower crust in garnet-amphibolite or garnet-granulite facies, are exposed mostly where raised, and deeply eroded, in post-Archean block and rift-shoulder uplifts. Lower crust in places retains more than a billion years of history of high-temperature deformation and magmatism, including vast ductile to syn-intrusive mixing and intershearing of components originated in diverse deep to shallow settings. Polyphase TTG gneisses are dominant, but dismembered dikes and deep-sunken supracrustals are common, and metasomatized protocrust may be intersheared with TTG and thus preserved. Upper crust synbatholithic strike-slip shearing, mostly under low amphibolite to low greenschist facies conditions, records mostly-decoupled deformation ("clutch tectonics") of upper crust floating on mobile deeper crust. Prolonged doming by some batholiths, documented by decreasing-dip unconformities in flanking synclines, also shows prolonged lower-crustal mobility. Throughout Archean time, the crust was too mobile internally to support great local topography on either the surface or the Mohorovičić discontinuity (Moho). Rigid plates did not exist.

Dense degranitized garnetiferous and pyroxenic restites within protocrust intermittently delaminated and sank into hot low-density dunitic upper mantle. Some delaminated masses sank through what is now preserved as cratonic lithosphere, whereas others were arrested within it. Displaced hot mantle rose and partly melted remaining fertile protocrust, or reached and recycled pre-existing felsic crust to form more evolved granites. Komatiites, basalts, and the high-Mg

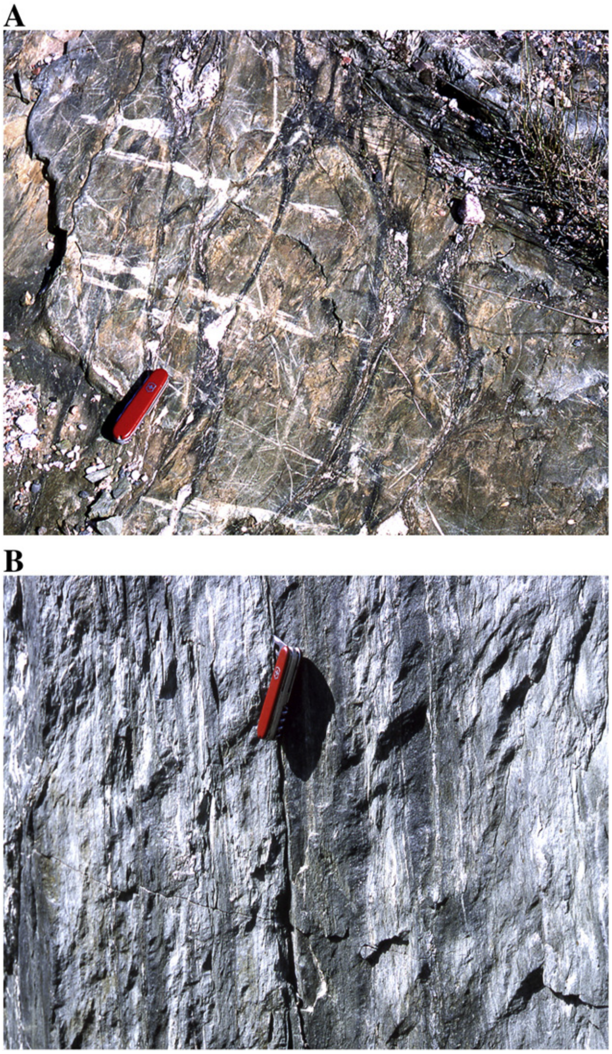

Fig. 3. Downdip stretching of greenschist-facies pillow basalt, near batholith in dome-and-keel setting. (A), horizontal surface, showing modest flattening. (B), vertical surface, perpendicular to extreme flattening and parallel to strong stretching lineation, same outcrop. Superior craton, near Foleyet, Ontario.

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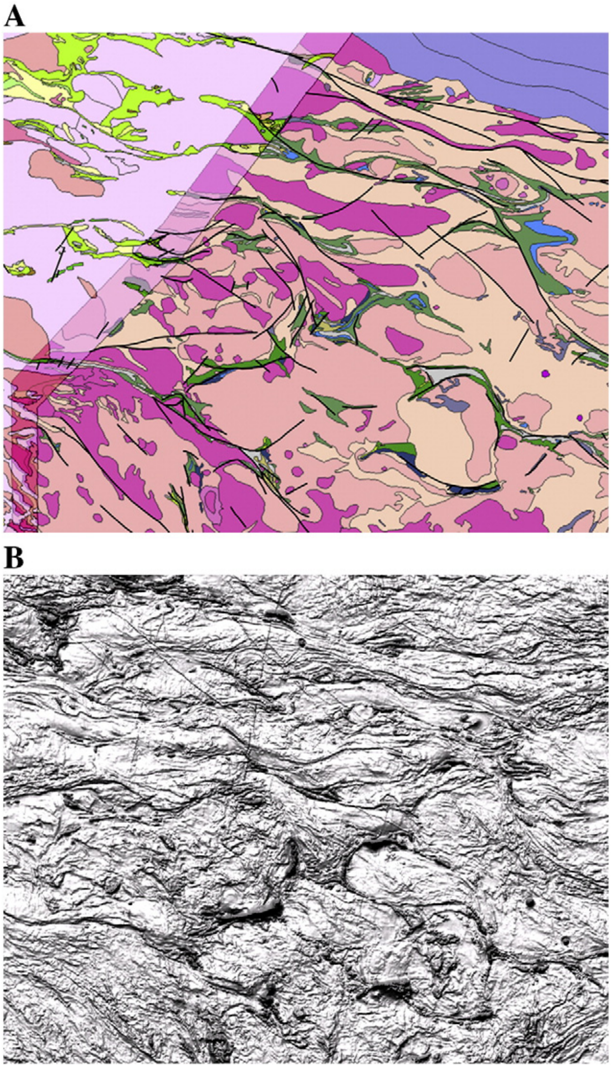

Fig. 4. Maps of part of northwestern Superior Craton. Area is ~500 km wide and centered near 93°W, 53.6°N. (A), geologic map; pinks, granites and gneisses; greens, supracrustal rocks, mostly metavolcanic; purple, Phanerozoic strata of Hudson Bay lowland; colors change at Manitoba–Ontario border. (B), shaded relief map of total magnetic field. Southeastern and south-central region shows dome-and-keel geology, with batholiths elongated in stretching direction; rest of area displays long-continuing synchronous diapirism and mostly dextral strike-slip deformation (e.g., Parmenter et al., 2006).
Maps by Geological Survey of Canada.

basalts that abundantly bridge between them record varying inputs from re-enriched mantle, sunken degranitized protocrust, and protocrust, not melting of extremely depleted pre-4.4 Ga mantle. Only after ca. 3.6 Ga was the felsic crust cool and dense enough to permit mafic and ultramafic melts to rise to the surface and erupt, but the crystallized mafic and ultramafic volcanic rocks were denser than the warm felsic crust, and sank into that crust as it rose in complementary fashion to form diapiric batholiths. The deep felsic crust frequently, if not continuously, flowed at ductile to near-solidus conditions, and the upper crust rode along, stretching and developing lateral shear zones with minor vertical components of offset (Fig. 4). Apparent global pulses of magmatism, defined by frequency distributions of zircon ages and commonly attributed to pulsing mantle circulation, may record instead both threshold stages in lithosphere development and the loss of most of the primary record of more random and continuous variations.

Impact history of the Moon presumably transfers to Earth. Accretion of large bolides ended on the Moon ca. 3.9 Ga with formation of Imbrium basin, as dated by Apollo samples (undated Orientale may be slightly younger). Lunar crustal-rock zircons go back to 4.4 Ga with erratically increasing abundance (Pidgeon et al., 2010), so the Moon, like Earth, then had almost its present size. I presume the low-pressure fractionates that contain the zircons to record primarily crystallization of impact-generated lava lakes, whereas conventional models assume long-continuing endogenic magmatism. Presumably declining terrestrial impacts similarly summed to surface saturation during the 4.4–3.9 Ga era of formation of early TTG. Impacts may be responsible for part of the extremely chaotic mixing of lithologies shown in lower-crustal exposures wherein zircon ages span substantial parts of that range (e.g., Hamilton, 2007a, Figs. 5 and 7). Impact-melt lakes must have formed from major terrestrial impacts, and the low pressure(?) calcic anorthosites smeared by ductile flow into many lower-crustal Archean TTG gneisses may include some of their fractionates. Impacts blasted large holes in developing terrestrial crust and redistributed surface loads, presumably enabling some of the gravitational spreading of mobile TTG crust. Long-continuing regional flow of Archean felsic lower crust may also record spreading toward and over regions of global protocrust either thinned by more thorough delamination, or subject to less development of TTG.

The oldest well-dated mafic dikes in TTG crust, mafic and ultramafic lavas erupted on such crust, and waterlaid sediments and pillow basalts are all 3.6 or 3.5 Ga. Local claims for ages to 3.8 or 3.9 Ga are poorly documented (Section 4.3.2). Popular models postulate a hydrosphere as soon as Earth had a solid crust, but Earth may instead have had until ca. 3.6 Ga a supercritical and supergreenhouse atmosphere of ~300 bars of, mostly, water and CO_2 that kept felsic crust too hot, and low in density, to permit rise and eruption of mafic melts.

4.2. Archean crust

Archean crust is unique in its typical seismic and compositional structure, low-relief Moho, and erosion levels that are shallow considering its age. It does not resemble Phanerozoic Kohistan, Talkeetna, and Ivrea, or most Proterozoic crust, and its features are not compatible with plate-tectonic models. All Archean cratons studied seismically have continuous felsic crust beneath greenstone belts, and felsic or intermediate crust typically extends to the Moho. High-resolution study of South African Kaapvaal crust (Nair et al., 2006; Niu and James, 2002) shows felsic basal crust ending at a sharp, flat Moho. Nair et al. recognized that this crust had been generated from subjacent mafic material, the residual part of which sank before present lithospheric mantle was stabilized. Thompson et al. (2010) presented similar results for Rae Craton, Canada, and recognized them also as precluding plate-tectonic analogies. The flat, sharp Moho, seen also in reflection and refraction studies of Archean crust in other cratons, shows that lower crust commonly was too mobile to support large topographic loads, and accords with known prolonged lateral and diapiric mobility.

Vibroseis reflection profiles have been made across parts of the Yilgarn craton of Australia, Kaapvaal of South Africa, and Superior and others of Canada. The erratic, and commonly steep, dips of shallow granite-and-greenstone complexes are not imaged, so most profiles are semitransparent in their upper few seconds. The distance range plotted as apparent middle crust often appears chaotic, with intersecting, crossing, and inconsistent reflectors that must include both out-of-plane reflectors and artifacts. Reflectors that appear visually to be in the lower crust commonly are undulating or subhorizontal, but this simplicity may be illusory because complex folds could not be imaged at that distance (Ji and Long, 2006). Subhorizontal Mohorovičić discontinuities typically display as abrupt lower limits of apparent crustal reflectors at depths of 30 or 40 km.

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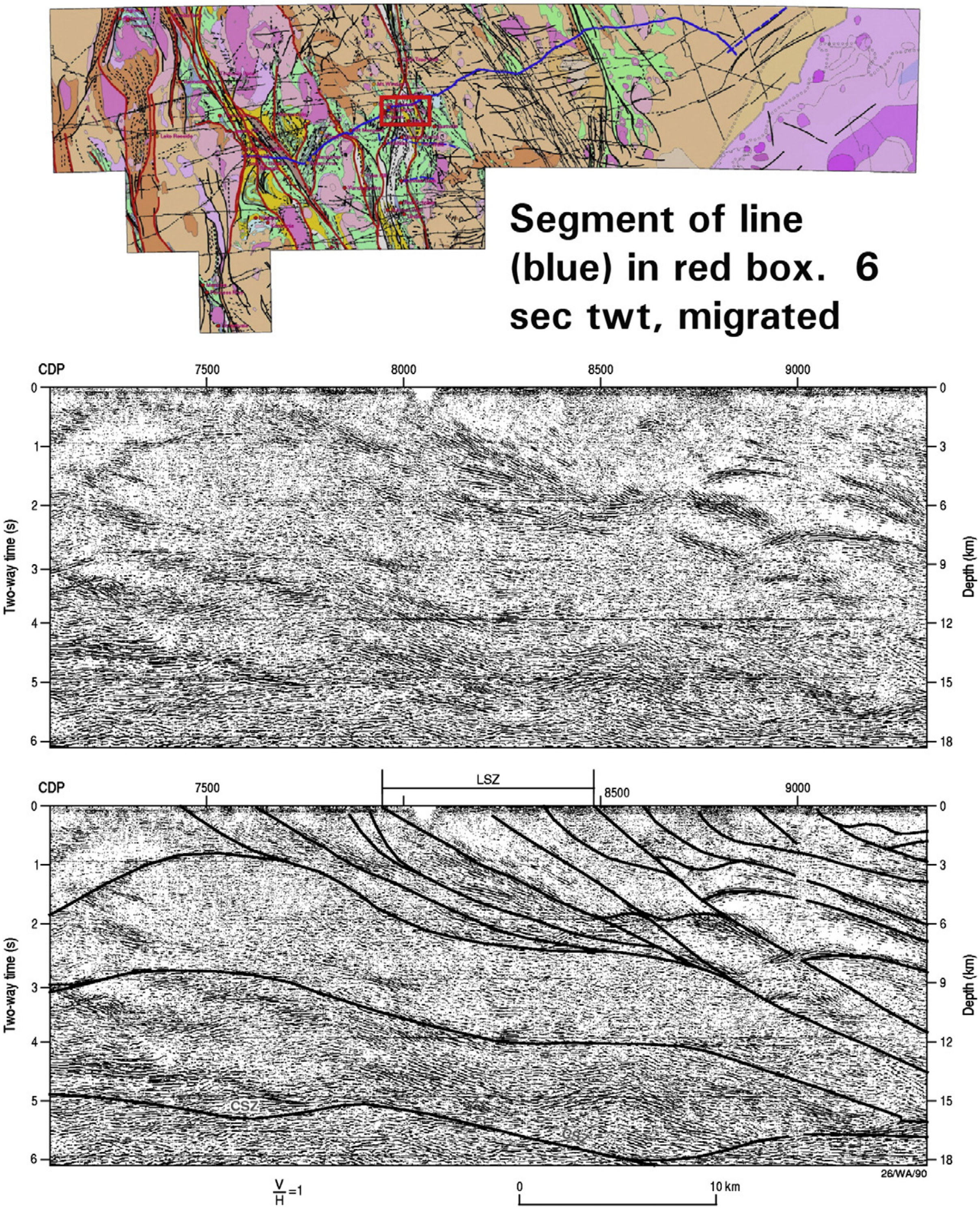

Fig. 5. Part of Vibroseis reflection profile, with extreme overinterpretation that assumes all apparent and artifact reflectors to be in vertical plane, across granite-and-greenstone terrain in eastern Yilgarn Craton, Australia. Approximate location is shown by the part of the blue line within red rectangle on geologic map, which shows Archean granitic and gneissic rocks in orange and lavender, mostly mafic metavolcanic rocks in green, mostly metasedimentary rocks in yellow, and thick Proterozoic dikes as thin black lines mostly trending ENE.
Profile and interpretation from Goleby et al. (2003, p. 101, Fig. 11).

Isolated profiles are necessarily ambiguous because no processing can discriminate in-plane from out-of-plane reflections in 2-D stacks, which are 3-D responses to broad swaths, and complex patterns generated by out-of-plane reflections can be mistaken for in-plane structure (Drummond et al., 2004; Hobbs et al., 2006). The common interpretation of these Archean profiles as showing only geologic structure vertically beneath the tracks incorporates the false assumption that all reflectors are either horizontal or strike perpendicular to the irregular traverses. Further visually misleading effects are added by processing to produce signal coherence that may be illusory, filtration to favor specific ranges of apparent dips, and migration in time to eliminate crossing events while assuming absence of both out-

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of-plane reflectors and abrupt lateral velocity changes. The most conspicuous potential planar reflectors in some profiled Archean regions are subvertical Proterozoic mafic dikes, which seldom are mentioned in interpretations. Archean-craton profiles commonly have been extremely overinterpreted to depict crustal-scale thrusting and extension within planes of sections, with disregard for surface geology except that speculative inclined apparent reflectors at depth often are projected to known steep shear zones at the surface.

Thus, a profile, about 400 km long across granite-and-greenstone Yilgarn craton is accepted as showing alternating convergent and extensional plate tectonics. Seismic theory, processing, and interpretation all assumed apparent reflectors to be in the plane of section (Goleby et al., 2003). The irregular traverse trended mostly near 070°. The east half of the profile (Fig. 5) crossed granitic and supracrustal rocks with irregular strikes and dips, exposed poorly through veneers of younger strata and regolith. The few mapped steep shear zones trend near 165° and could not have been imaged, and the erratic orientations of supracrustal rocks require that most reflections recorded at apparent shallow depths came from out of plane, though this was not considered. Many long, steep Proterozoic gabbro dikes strike between ~055° and 085° within the seismically visible 40 km or so on each side of the traverse. Major dikes are shown on the generalized geologic map with the displays (Fig. 5; p. 101 of Goleby et al., 2003), and more are shown on magnetic maps and on the Yilgarn craton map of Whitaker and Bastrakova (2002).

That apparent gently inclined reflectors in the profile must include such dikes was not considered in the Goleby et al. papers, which interpreted the ambiguous profile in terms of dip-slip structures within the plane of section (Fig. 5). Listric dip-slip faults were drawn although shear zones defined by field studies are mostly steep and strike-slip. Interpretation was specified to be of through-the-crust thrust-imbricating shear zones recording hypothetical plate-accretion processes, alternating in time with extension whereby thrust surfaces were re-used as normal faults that reversed thrust offsets to account for the lack of change of crustal levels in surface geology. No such re-use of crustal-scale thrusts and normal faults has been documented here or elsewhere in rocks of any age. Further, deep-crustal listric extensional faults, although often conjectured, have not been proved to exist anywhere within continuous crust, including the Basin and Range region of North America, although they are common on continental shelves and slopes where sliding is toward deepwater free edges. Contrarians Groenewald et al. (2003) recognized that the basis for Yilgarn plate-tectonic explanations is weak and non-actualistic, and that speculation that some shear zones are regional boundary structures between distinct "terranes" is disproved by geologic mapping.

4.3. Archean rocks

Archean rock compositions are incompatible with the common assumption that they record plate settings, particularly island arcs, like modern ones. Phanerozoic island-arc crust is dominantly mafic, yet mostly felsic Archean crust is popularly assigned to island arcs. Archean TTG dominates the crust of entire cratons whereas Phanerozoic arc rocks occur in narrow belts. Modern arc volcanic rocks are unimodal whereas Archean volcanic rocks are sharply bimodal. The dominant basalts of Archean greenstone assemblages are tholeiites, commonly assumed to be ocean-floor or oceanic-arc basalts although they do not resemble any modern basalt suites in either bulk compositions or their frequent interlayering with komatiites and high-Mg basalts that also lack modern analogues. Archean tholeiites commonly have markedly higher Fe/Mg, and lower Al/(Fe + Mg), than either arc tholeiites or N-MORB (Condie, 1981, 2005; N-MORB, "normal MORB" is a misleadingly named model-based selection of MORB analyses). The magnesian rocks commonly are attributed to plumes that switched abruptly on and off to produce abundant thin intercalations, a long extrapolation from obsolete conjectures (Section 3.1). Sinking delaminated protocrust provides obvious alternative access to then-greater mantle heat. Subordinate Archean andesites also differ markedly from modern arc andesites. Most Archean tonalite is much less magnesian and calcic, and more silicic, sodic, and potassic, than Phanerozoic tonalite, and generally has much steeper rare-earth patterns and higher transition-group elements (Condie, 1981; Martin, 1987).

4.3.1. Chemotectonics

Geology and bulk compositions of Archean rocks do not support analogy with modern plate tectonics, so trace-element geochemistry of Archean mafic igneous rocks commonly is claimed to be alternative evidence. Selected REE and HFSE are favored. When ratios, or ratios of ratios, of trace elements in ancient rocks are found to be similar to those in otherwise very different modern rocks of known tectonic settings, the ancient rocks are assigned to those settings on this basis alone. The preferred discriminants misclassify 20% to 40% of modern volcanic rocks and mis-assign obvious craton-covering Neoarchean flood lavas to oceanic arcs (Hamilton, 2007a), but nevertheless are applied rigidly to ancient rocks quite different from the modern ones. Condie (2005) exemplified the procedural logic. He acknowledged the lack of geologic and petrologic evidence for Archean plate interactions but assumed nevertheless that plates and plumes must have operated. He selected a number of analyses of Archean tholeiites as "non-arc" on the basis of their major-element chemistry, and found their Nb/Y vs. Zr/Y and Zr/Nb vs. Nb/Th to scatter mostly in fields typical of modern arc and oceanic-plateau basalts. He had screened the analyses to be non-arc, so he assumed them all to represent oceanic plateaus, and therefore, following obsolete assumptions (Sections 2 and 3.1), as formed atop plumes from deep mantle.

Most recent Archean reports omit qualifications and assert that selected trace-element plots uniquely define diverse plate-tectonic and plume settings. Rocks thinly intercalated in conformable stratigraphic sections are assigned to widely varying paleotectonic settings on the sole basis of these ratios. When, as is often the case, no ratios in ancient rocks approximate ratios typical of some modern setting, combinations of plume and plate settings with no possible modern analogues are deduced with arithmetic calculations (references in Hamilton, 2007a). Note that ratios cannot be averaged or treated with ordinary statistics, and that ratios of ratios completely obscure quantities and can generate spurious correlations when both ratios have the same denominator.

Almost all erupted magmas have mineralogic and chemical compositions indicative of equilibration at low pressure. They never reach the surface as superheated pristine melts from deep sources. The basic chemotectonic assumption that final-rock trace-element ratios were produced by batch melting of deep source rocks and preserved without change in composition or heat during transport through varying P–T–x regimes (e.g., Rollinson, 2008; Wyman and Kerrich, 2009) overlooks the requirement that partitioning of each element into initial and subsequently evolving melt and mineral phases must vary with P–T–x as melts change in relative and absolute volume and in composition by exothermically crystallizing locally refractory components and endothermically breaking down and assimilating locally fusible ones, thereby losing heat and differentially gaining and losing elements and changing their ratios as they migrate through fields of stepped and gradational phase equilibria. Initial batch-melting ratios are dependent on degree of melting as well as P–T–x, but this is merely the first stage for "incompatible" as well as other elements. O'Hara (1995) discussed just the partial-melting complications for major-element phases alone. Sample empirical evidence that the discriminants are products of magmatic processes: the volcanic rocks high in the Jurassic Talkeetna arc (Section 3.3) show typical island-arc-basalt low contents of Ti, the major HFSE — but the 10-km-thick layered gabbronorite low in the crustal section is enriched in Ti complementary to those shallow rocks (Greene et al., 2006), so Ti in the high-level rocks is a function of magmatic differentiation and secondary melting, not of direct transport from mantle fluxed by slab dewatering as commonly assumed by chemotectonicists.

Most trace-element discriminants applied to Archean igneous rocks are based on work with modern volcanic rocks by Julian Pearce and associates. Pearce (2008) himself showed that not only are the most-used of his discriminants in Archean reports inapplicable to the compositionally different ancient rocks, but the trace elements of most reputedly oceanic Archean mafic and ultramafic volcanic rocks require continental-crustal contamination. Furnes et al. (2009, Figs. 11 and 13) nevertheless used Pearce discriminant Th/Yb vs. Nb/Yb to assign Greenland rocks to an oceanic "island-arc ophiolite" (Section 4.3.2). Pearce (2008) emphasized that the distribution of these analyses on this plot (his Fig. 11c) was characteristic of modern basalts contaminated by continental crust (his Fig. 4a–e), that this contamination was typical of Archean mafic and ultramafic sections (his Figs. 10a–f and 11a–f), and that the positions and orientations of the Archean arrays distinguished them from modern island arcs. Furnes et al. (2009) dismissed all this with the implausible assertion that Archean midocean subduction was of continental crust.

Many Archean mafic rocks are mislabeled with petrologic or genetic names of modern rocks, of quite different compositions, which connote plate-tectonic settings, on the inappropriate basis of trace-element ratios alone, and the ancient rocks are then claimed to require the settings implied by the misused names. Jenner et al. (2009) termed some Greenland Archean mafic rocks "arc-like metabasalts" on the basis of ratios of ratios of a few trace elements, and rationalized away the severe misfit of REE and large-ion lithophile elements to that analogy. They did not mention that the rocks differ profoundly from modern arc basalts in being very low to extremely low in Al, and high to extremely high in Mg and Fe, and have the composition of komatiitic basalt, which commonly is interbedded with other exclusively Archean mafic and ultramafic rock types such as Jenner et al. asserted require plume origins. Ordóñez-Calderón et al. (2009, p. 113) assigned one suite of Archean amphibolites to N-MORB and another to oceanic island-arc tholeiite because "their trace element patterns are comparable" to modern rocks with those designations — but on their Th/Yb vs. Nb/Yb plot (their Fig. 12A), the ancient-suite fields do not even overlap those of purported modern analogues plotted by Pearce (2008), whose discriminant this is. Archean lavas misdesignated "arc picrites" by Ordóñez-Calderón et al. (2009) differ greatly from modern picrites, rare as arc rocks, in Fe, Al, and Ti, are misnamed on the irrelevant basis of La/Yb, and are claimed by their mislabel to indicate arc origins. The rare modern-arc rock boninite is plagioclase-free lava, low in Ca and Al and high in Si and Mg, unknown in the Archean. Many chemotectonicists misassign the name to Archean rocks that wholly lack these defining characteristics, on the inapplicable basis of selected trace-element ratios (review by Smithies et al., 2004), and then assert the misused name to require Archean subduction because it comes from arc rocks (e.g., Furnes et al., 2009; Nutman et al., 2009; Ordóñez-Calderón et al., 2009; Polat and Kerrich, 2004; and even Smithies et al.).

Adakites are uncommon rocks in modern island arcs. The term was defined for intermediate and felsic Aleutian rocks with steeply fractionated REE and other trace-element characteristics indicative of high-pressure partial melting from mafic rocks in a garnet stability field, and also, speculation inappropriate in a definition, as melted from subducted oceanic crust. Abundant Archean tonalites fit some of the trace-element parameters, and many geochemists (e.g., Polat and Kerrich, 2004; Rollinson, 2008; Wyman and Kerrich, 2009) claim their "adakite" label to require slab melting — a process not demonstrated in modern subduction systems, and precluded as a direct generator of tonalite melt by phase petrology because such melt could not survive rise through hot mantle-wedge peridotite. Convincing geologic evidence for generation of adakites instead from lower-crustal garnetiferous mafic rock exposed in a New Zealand Cretaceous island arc was presented by Stevenson et al. (2005), and accords with derivation of Archean tonalites from thick mafic non-arc protocrust, as advocated here.

4.3.2. No Archean ophiolite

Ophiolites, sections of oceanic crust and uppermost mantle, are caught in many Phanerozoic subduction sutures (Section 3.4). No ophiolites have been shown to be obducted, thrust onto overriding plates in the sense opposite to subduction, as claimed by the widely misused term. Thick, complete sections are capped by pillow basalts, commonly of arc or back-arc affinities. They show variable crustal stratigraphy of products of related magma types, increasingly mafic downward, and bottom in crustal-cumulate ultramafic rocks above pre-crustal tectonized harzburgite, indicating oceanic origins. Abundant scraps of MORB and oceanic-island crust and mantle occur in polymict mélange in accretionary wedges. Claims for pre-Neoproterozoic ophiolites fail scrutiny.

Many Archean greenstone sections contain interbedded mafic and ultramafic lavas and sills, which many authors misname "ophiolitic" despite lack of reqired crustal stratigraphy and rock types. The most specific of such claims is by Furnes et al. (2007a,b, 2009), who assumed that some tectonically flattened layered rocks in Greenland Isua supracrustals were initially sheeted dikes, that these had fed nearby pillow basalts, and that "dikes" and "basalts" plus metagabbro and serpentinite elsewhere in the greenstone section sum to a disrupted ophiolite. Their assertion that rough similarities in several trace-element ratios "strongly suggest that the pillow lavas and the dikes are cogenetic" is incompatible with their own many chemical analyses. Their nine subuniform analyses of "dikes" show them to have the distinctive composition of clinopyroxenitic komatiite, an Archean ultramafic rock type known elsewhere as thin lava flows easily mistaken for dikes when flattened. Their five subuniform analyses of pillow lavas are of utterly different ferroan andesite, an Archean rock type abundant in some greenstone sections and also in Neoarchean flood lavas that cover much of the Pilbara craton, where its trace-element ratios are those asserted by Furnes et al. to require oceanic-arc origins of the Isua rocks. I (Hamilton, 2007c) argued that this contrast precludes derivation of the lavas from the purported dikes. Furnes et al. (2007b) responded that major elements in Archean rocks are secondary and irrelevant for tectonic analysis (although Furnes et al., 2009, used selected major-element ratios elsewhere to bolster similarities with modern analogues), and they dismissed as also irrelevant the occurrence in voluminous continental-platformal Archean flood lavas of the same trace-element ratios which they claimed to uniquely require oceanic origins.

Powerful geologic evidence, beyond Pearce's analysis (Section 4.3.1), shows the Isua supracrustal section, and others in its region, to be ensialic, and their mafic and ultramafic rocks to be <3.1 Ga and deposited on older TTG crust, not >3.8 Ga and oceanic as commonly asserted. The Isua elliptical ring of steep-dipping supracrustals is flanked, inside and out, by old gneiss complexes in which the dominant zircon ages are ~3.6–3.8 Ga (Neoarchean granites are also present), and detrital zircons in Isua sedimentary rocks have those same ancient ages plus sparse younger ones (Nutman et al., 2009). The characteristic style of Archean upper-crust assemblages worldwide, where not disrupted by regional shearing, is of domiform batholiths, of diapiric older TTG crust plus younger magmatic granites, that rose while young, dense volcanic rocks sank between them as synclines. Some are shown on Fig. 4. Geologic maps (Chadwick and Coe, 1987; Garde, 1988) of the Isua region show four such typical granite-and-greenstone domes, Isua being northernmost, each 20 to 40 km long in the northeasterly elongation direction and outlined by supracrustal rocks. The three southern domes meet in a typical triple-junction synform of supracrustal rocks. Metamorphism and

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deformation are greatest close to the batholiths, and shearing is granite-side-up where studied, confirming dome-and-keel analogy, not regional thrusting. Beech and Chadwick (1980) and Chadwick and Nutman (1979) recognized the supracrustal sections to lie with locally preserved depositional contacts on ancient gneiss. Some of the best-studied sections of supracrustal rocks have a consistent stratigraphy. Thin, discontinuous quartzite and other metasedimentary rocks lie directly on TTG basement and are overlain by intercalated mafic and ultramafic volcanic rocks, overlain in turn by mostly clastic rocks interbedded with what major-element chemistry suggests to be felsic volcanic rocks. This is classic granite and ensialic-greenstone stratigraphy (examples in Hamilton, 2007a). Zircon U–Pb determinations of ages of hundreds of detrital igneous grains in metasandstones in these assemblages show diverse ages, but numerous detrital grains in all samples are younger than 3.1 Ga, and igneous zircons in felsic volcanic rocks in the successions also are younger than 3.1 Ga (Hollis et al., 2005, 2006; Knudsen et al., 2007; Nutman and Friend, 2007; Nutman et al., 2004, 2007). The detrital ages are similar to those of nearby granites and gneisses, except that late Neoarchean granites are younger than the sediments. Some sandstones contain clastic zircons spanning a billion years of Archean history, as do flanking plutonic complexes. Despite this clear evidence for post-3.1 Ga deposition of supracrustal rocks on TTG basement, Furnes et al. (2007a), Ordóñez-Calderón et al. (2009), and other Greenland researchers assert that there is no evidence for ensialic volcanism. Such misstatements may reflect unique-to-Greenland assumptions that supracrustal and plutonic rocks are randomly intersliced from unknown sources by invisible megastructures, and that their typical-Archean ensialic stratigraphy and dome-and-keel geology are irrelevant.

4.3.3. No blueschist

No Archean blueschist is known, but claims have been made for moderate-temperature high-pressure rocks as requiring "warm subduction". Thus, Moyen et al. (2006) claimed that minerals in cm-sized boudins in Archean quartzofeldspathic gneiss in the Kaapvaal Craton crystallized at 12–15 kb and 600–650 °C, and that the indicated thermal gradient, although too high for blueschist, requires subduction. Their reported mineralogy is a common skarn assemblage with a wide stability field. Their *P*/*T* calculations were based on mineral compositions determined by semiquantitative energy dispersion, not by quantitative wave dispersion, that are proved inaccurate by their requirement for impossible 8-fold coordination of ferric iron and 4-fold coordination of Al. Their *P*/*T* determination depends on calculation from these poor data of implausible significant almandine in a grossular-andradite garnet, and further depends critically on precise values assumed for water activity and oxygen fugacity which in fact have large uncertainties.

5. Paleoproterozoic and Mesoproterozoic tectonics

Networks of Paleoproterozoic orogens separate little-modified tracts of previously larger Archean cratons, but the assumption (Cawood et al., 2006; Hoffman, 1988) that this preservation requires Phanerozoic-style plate tectonics is dubious. Separation of cratons by seafloor spreading, followed ultimately by collisions as the resulting oceans were subducted beneath numerous island and Andean arcs, is commonly inferred, although no products of such processes are proved older than Neoproterozoic. There are no proved Paleoproterozoic or Mesoproterozoic ophiolites, accretionary wedges, blueschists, oceanic or continental magmatic arcs, or lithospheric continent/ocean dichotomies. Continental thinning and separation, and reconvergence, likely occurred, but formation of broad oceanic gaps by seafloor spreading is unproved. Paleoproterozoic sedimentary and volcanic stratal wedges lapped on to margins of otherwise-stable cratonic fragments, and thickened into deeply filled basins, after many of those margins had been raised, eroded deeply, and subsided, but no Andean subduction beneath those margins is proved by sutures or magmatic arcs.

The subduction-driven collision now ponderously underway between Australia and China, with Melanesian, Indonesian, and Philippine island arcs crunched in the complexly narrowing gap (Hamilton, 1979), is often cited as the analogue for collisions of Archean cratons with Proterozoic arcs squeezed between them. The island-arc assemblages in the Australia–Asia gap, however, resemble the Phanerozoic ones of the Klamath Mountains (Section 3.4), not only in their magmatic-arc rocks but in the voluminous associated mélanges, ophiolites, etc., and do not resemble the utterly different rocks and assemblages of Proterozoic orogens. Further, continental-arc rocks – Mesozoic in east Asia, Tertiary in medial New Guinea – are abundant on the converging continents, and have no analogues in the Archean cratons flanking Proterozoic orogens.

Although a sizeable minority of investigators is challenging plate-tectonic interpretations of some Paleoproterozoic and Mesoproterozoic orogens, recent literature is dominated by plate-tectonic speculations based on trace-element chemotectonics and on the assumption, shown by reliance on Nd and Hf T_{DM} calculations: Section 2, that upper mantle has been progressively depleted and continuously stirred throughout geologic time. Evaluation is hindered because many recent reports and maps depict primarily genetic assumptions rather than rocks. Thus, Whitmeyer and Karlstrom (2007) only occasionally used even general rock terms in their broad plate-tectonic interpretation of Proterozoic evolution of North America, instead characterizing rock assemblages only as, for example, "juvenile [oceanic] arc" on the basis of mostly unspecified assumptions. The Proterozoic rocks, although mostly unlike Archean ones, also are quite unlike claimed modern products of plate tectonics, and they display no convincing geologic evidence for either subduction or seafloor spreading. Distinctive features of most Proterozoic terrains include dominantly bimodal igneous rocks, voluminous richly potassic volcanic and granitic rocks (Fig. 6), and large tracts of nonvolcanic terrigenous sediments from continental sources, all of which are essentially unknown in Phanerozoic island arcs as exposed at any erosional depth. Island arcs nevertheless are widely invoked as the dominant producers of Proterozoic crust.

Granite-and-greenstone assemblages of Archean type, with limited dome-and-keel development, continued to form on some cratons in the early Paleoproterozoic, but Paleoproterozoic and Mesoproterozoic orogens otherwise differ greatly from both Archean and Phanerozoic ones and may be largely developed on pre-existing continental crust. Paleoproterozoic orgens may primarily record basins on Archean crust that were filled by sedimentary and volcanic

Fig. 6. High-potassium granite, 1.7 Ga, northwest Arizona. Potassic-silicic rocks are voluminous in the commonly bimodal igneous assemblages of Paleoproterozoic and Mesoproterozoic orogens but are very rare in the unimodal assemblages of modern narrow oceanic island arcs commonly assumed analogous.

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rocks, thickened tectonically, metamorphosed, and intruded by voluminous granitic rocks derived mostly from basin fills and pre-existing crustal rocks. Mesoproterozoic orogens in turn may mostly be products of basins superimposed on Paleoproterozoic complexes. Proterozoic orogens expose broad regions of igneous and metamorphic rocks formed at depths of 15 to 35 km that still have thick crust. Large exposures of Archean basement are proved beneath many deeply eroded orogens, widespread recycling of Archean crust into igneous rocks is proved even in their interiors, and other granites are known to represent partial melting of basinal sedimentary and volcanic rocks. The cratonic Mesoproterozoic Belt — Purcell(-Udzha?) basin (Sears et al., 2004), with 15 or 20 km of fill, provides an example that did not progress to complete collapse, inversion, and plutonism. Plumes are invoked by relatively few Proterozoic interpreters.

Most recently published reports infer that plate tectonics produced Paleoproterozoic and Mesoproterozoic orogens by closing oceans full of island arcs. The thought processes that lead to reliance on trace-element chemotectonics, and dismissal of voluminous contrary evidence, to reach plate-tectonic explanations are clear in another paper by Condie (1986), on volcanic rocks of the Paleoproterozoic terrain, 1500 km wide across strike, of southwestern United States and northern Mexico. Condie acknowledged that petrology and geology provide no evidence for Phanerozoic-style plate tectonics: the volcanic rocks are sharply bimodal, with voluminous felsic rocks and few intermediate ones; few of the mafic rocks, and only half of the felsic ones, are calc-alkaline; chemistry of many igneous rocks requires involvement of evolved crust; there is a huge tract of non-arc-like metapelites and quartzites; there is no evidence for sutures; and the region is far too broad for arc analogies. He nevertheless assumed that plate tectonics must have operated, and appealed to trace-element chemotectonics to define diverse oceanic and continental arc and back-arc settings in which were produced rocks and assemblages without modern petrologic analogues or geologic relationships. Most subsequent investigators of this region have omitted mention of the lack of geologic and petrologic evidence and have gone directly to assertions of plate processes.

Evidence for older continental basement within this particular orogen is accumulating nevertheless. Strong new evidence comes from an extensive study of detrital zircons in sediments of the thickly filled, and highly metamorphosed and deformed, middle Paleoproterozoic Vishnu basin in the central part, northern Arizona, of the vast orogen. The basin is filled by terrigenous clastic sediments derived mostly from 2.8 to 2.4 Ga rocks, not from Proterozoic island arcs as assumed previously, which likely occurred in large nearby exposures (Shufeldt et al., 2010) that, in my terms, were part of the Archean basement for the orogen. Other evidence for recycling of ancient crust comes from less extensive studies, from southeast Idaho to northwest Sonora, showing in various places isotopic and zircon-xenocryst evidence for reworking of Archean basement (references in Shufeldt et al., 2010; Whitmeyer and Karlstrom, 2007). A large subregion, of late Paleoproterozoic rocks in Colorado and vicinity, displays similar evidence for reworking of earlier Paleoproterozoic continental rocks (Bickford and Hill, 2007; they recognized that non-plate models should be considered).

Evidence for extensive ancient basement beneath Proterozoic orogens elsewhere is accumulating rapidly where extensive zircon dating is done. Paleoproterozoic orogens, 10 to 600 km wide, define the margins of the Archean Superior craton of North America and separate it from other cratons. Both sides of each circum-Superior sector commonly display onlapping stratal wedges dominated by clastic sediments from Archean sources, with intercalated 2.0–1.9 Ga basaltic and ultramafic sills and dikes, some of them large and internally fractionated, which are proved ensialic by correlative dikes in underlying Archean basement (Heaman et al., 2009). These shelf assemblages are variably deformed and metamorphosed. Rare claims of “ophiolites” within them are implausible. The several mafic and ultramafic sheets and dikes that comprise the “Purtuniq ophiolite” of Quebec (Scott et al., 1992) occur in the clastic-shelf sequence and show no ophiolitic crustal stratigraphy. The “Jormua ophiolite” of Finland (Lahtinen et al., 2010) is a small cluster of similar age, lithology, ensialic setting, and lack of crustal stratigraphy. The “Payson ophiolite” of Arizona intrudes older granodiorite (Dann, 2004) and cannot be oceanic. Onlapping shelves also typify contacts elsewhere between Paleoproterozoic orogens and Archean cratons, and nowhere have Proterozoic sutures been demonstrated, nor Andean arcs found on the adjacent cratons.

The mineral-rich Saskatchewan and Manitoba sector of the circum-Superior Paleoproterozoic is 600 km wide between flanking clastic shelves on Archean cratons and has been much studied. A major chemotectonic paper by Lucas et al. (1996) postulated ocean floors, islands, plateaus, variably rifted juvenile and evolved island arcs with unusual components, and assorted oceanic basins, all scrambled together in a small area by unidentified structures. Purported oceanic arc rocks are sharply bimodal (DeWolfe et al., 2009) and richly potassic granites are present. Most subsequent authors followed the approach of Lucas et al., and many papers convey little objective information. Nevertheless, Archean basement is proved in many windows eroded through basinal Proterozoic paragneisses (e.g., Bickford et al., 2005; Whalen et al., 2008), many Proterozoic plutons show obvious contamination by Archean crust or derivation from basin sediments, and quartzite and other terrigenous sediments, even in the purportedly once-midocean interior, have dominantly Archean detrital zircons. White (2005, p. 707) recognized that an origin as a supracrustal basin, filled very thickly by volcanic and terrigenous-sedimentary rocks, further thickened tectonically to “~40 km, consistent with present-day thickness estimates and erosional levels, is capable of producing enough crustal heating to melt the base of the sedimentary pile, advect heat to shallower crustal levels, and produce the observed *P*–*T* conditions.” Whitmeyer and Karlstrom (2007) recognized that the circum-Superior Paleoproterozoic orogens represent primarily “1.9–1.8 Ga reworked Archean crust”, but did not apply this knowledge to question interpretations of other similar American Proterozoic orogens, including that of southwestern North America, as of oceanic origins. Deeply eroded Paleoproterozoic orogens in Greenland expose Archean orthogneisses heavily reworked beneath Paleoproterozoic metasedimentary and metavolcanic rocks (e.g., Nutman et al., 2008).

Archean basement is widely exposed across the deeply eroded Paleoproterozoic Limpopo Belt, 250 km wide, which separates Kaapvaal and Zimbabwe Archean cratons in southern Africa (e.g., Buick et al., 2003; Rollinson and Blenkinsop, 1995; Zeh et al., 2010). Deeply eroded shoulder uplifts of flanking-craton Mesoarchean TTG and Neoarchean granite and greenstone border the orogen. The interior has been eroded 20–35 km into complexly polymetamorphic Archean complexes plus Paleoproterozoic metasediments at uppermost amphibolite and granulite facies. Variably recycled 3.35–3.15 Ga basement rocks (Fig. 7), some of which were derived by partial melting of more ancient crust, were interdeformed at high temperature with Neoarchean granites, Paleoproterozoic sediments including quartzites with detrital zircons spanning 3.9–2.1 Ga, and Paleoproterozoic granitic rocks ca. 2.1–2.0 Ga.

Australia's Paleoproterozoic and Mesoproterozoic orogens were long regarded on geologic grounds as derived from cratonic basins, and new evidence confirms this view despite 1990s assignments of oceanic plate-tectonic explanations to most of them. That highly deformed, metamorphosed, and intruded northern Australian Paleoproterozoic rocks were generated in such basins is shown by windows into the Archean floor, and by extensive dating of detrital zircons showing basin-filling sediments to have been derived in substantial part from Archean sources (Hollis et al., 2009). Two large windows of Archean rocks are exposed beneath high-grade Paleoproterozoic and

Fig. 7. Polymetamorphic Archean basement Sand River Gneiss with steeply plunging sheath folds, central zone, Limpopo mobile belt, South Africa. Published geochronology from this vicinity indicates initial crystallization of magmas, from still older crustal sources, ca. 3.3 Ga, followed by further plutonism and high-grade deformation ca. 2.6 Ga, deep burial by Proterozoic supracrustal rocks, and final plutonism and deformation ca. 2.0 Ga.

Fig. 8. Mesoproterozoic lower-crustal anorthosite over metagabbro, Naerøfjord arm of Sognefjord, western Norway. Exposure ~250 m high.

Mesoproterozoic basinal rocks of the Gawler orogen of South Australia (Fraser et al., 2010), and U/Pb and Hf isotopes in zircons require that Proterozoic granitic rocks formed mostly by reworking of underlying Archean crust (Belousova et al., 2009). Payne et al. (2010) demonstrated with Nd isotopes, REE patterns, and major elements that southern Australian Paleoproterozoic potassic–silicic granites were derived by partial melting of pre-existing Archean tonalite, despite chemotectonic trace-element assignment to subduction complexes. McLaren et al. (2005), like White (2005) in Canada, proposed that the often high content of heat-producing isotopes in Australian Proterozoic sediments enabled metamorphism and generation of voluminous felsic magmas in deep basins.

The basin concept appears broadly applicable to Paleoproterozoic and Mesoproterozoic orogens, but non-actualistic plate-tectonic conjectures nevertheless dominate interpretations. For example, Gower and Krogh (2002) made these implausible plate-tectonic interpretations within the Paleoproterozoic and Mesoproterozoic Grenville orogen of Quebec and Labrador: an oceanic island arc dominated by high-K granites; a subduction-accretionary wedge of high-*T*, low-*P* gneisses; and flat subduction of a “tongue” of spreading oceanic lithosphere that continued to spread, from a nearly fixed subcontinental center, for 200 m.y. after subduction.

A distinctive feature of many Mesoproterozoic and late Paleoproterozoic tracts, providing further evidence for time-varying processes unlike those of the present, are massif-type anorthosites (intermediate plagioclase, An_{35-65}, unlike highly calcic Archean anorthosites; Fig. 8), often associated with cumulate mafic and ultramafic rocks that include high-pressure aluminous orthopyroxene, and with high-temperature granites (ternary feldspars and accessory pyroxene: Fig. 9). These complexes are abundant in the Grenville orogen, where they range from 1.6 to 1.0 Ga (Bédard, 2010). Opinions regarding origin vary widely, but experimental petrology can be taken to indicate primary crystallization of typical anorthositic and cumulate rocks mostly at depths of 30 or 40 km, from partial melts of pre-existing mafic crust, followed by hot injection to their often shallower final emplacement sites (Longhi, 2005). Seismic *Vp* and *Vp*/*Vs* study indicates plagioclase-bearing mafic crust about 20 km thick to underlie deep-seated Grenville anorthosite and other lower and lower-middle crustal rocks (Musacchio and Mooney, 2002). Various datasets show the hot granites associated with the anorthosites, the similar-occurring classic rapakivi granites of Scandinavia (partly derived by amphibolite-facies exsolution from high-*T* ternary-feldspar granites?), and the widespread Mesoproterozoic potassic granites intruded into the United States Paleoproterozoic, to be crustal melts. These Mesoproterozoic complexes lack Phanerozoic equivalents, so conjectures assigning them to either convergent or divergent plate magmatism are non-actualistic (Bédard, 2010). Perhaps late-stage melting of ancient mafic protocrust, decreasing ambient temperatures and increasing refertilization of upper mantle, and deep roots of continental crust were jointly optimal to produce voluminous Mesoproterozoic mafic melts.

“Gray gneisses” in both Paleoproterozoic and Mesoproterozoic systems more resemble Archean TTG, and like them may be partial melts of then-extant ancient protocrust, whereas widespread potassic granites record variously partial melting of basinal metasedimentary and metavolcanic rocks and recycling of older Precambrian basement rocks. Perhaps the gray gneisses formed in places where Archean TTG crust, but not hotter underlying protocrust, had been sundered by rifting so that melting products of protocrust could rise as new crustal material without severe contamination by felsic crust.

Great deformation and transposition are widely shown in deeply eroded parts of Proterozoic orogens, and outward thrusting typifies marginal sectors (Fig. 10). The conventional assumption that thrusting requires plate collisions above subduction systems overlooks the diverse settings of active and late Phanerozoic thrust

Fig. 9. Mesoproterozoic high-temperature crustal-melt granite associated with anorthosite. Orthopyroxene is interstitial to large ovoidal ternary feldspars, now mesoperthite. Grenville orogen, near Tupper Lake, Adirondack Mountains, New York; coin diameter 1.8 cm.

Please cite this article as: Hamilton, W.B., Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated, Lithos (2011), doi:10.1016/j.lithos.2010.12.007

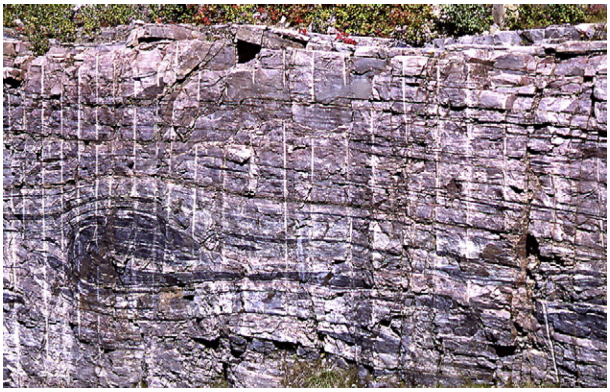

Fig. 10. Deep-crustal Paleoproterozoic or Mesoproterozoic mylonite gneiss. Pink garnet-rich quartzofeldspathic gneiss, light gray quartzite, and dark amphibolite show severe top-to-left (northwest) shear. Grenville orogen, near overthrust northwest margin, east–southeast of Huntsville, Ontario. Roadcut about 8 m high; vertical lines are drillholes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

systems, which record gravitational spreading in response to lithostatic heads of uncommonly high mountain regions formed by diverse processes. The uplands that drive modern south New Guinea thrusting, and eastward crustal flow from Tibet, indeed are collisional, but those that produced Cretaceous foreland thrusting in western United States, and modern Bolivian foreland thrusting, are noncollisional and may record primarily crustal thickening due to the mantle component of continental-arc magmatism (which in those cases does require subduction). Compressional collapse and inversion of regions of thick, hot crust may have been an important Proterozoic process.

The key to much Proterozoic crustal evolution presumably lies in its lithospheric mantle of ancient extremely depleted dunite re-enriched by sunken materials (Section 2). Continuity of this mantle with that beneath Archean cratons accords with continuity of Archean crust beneath Proterozoic orogens. I attribute the enriching materials primarily to sinking of delaminated ancient protocrust, densified by removal of Archean melts and, to the extent that some protocrust remained in place, to further delamination during Proterozoic time. The sunken material was variably melted, and recycled upward, as one of the processes by which the high upper mantle cooled about 100 °C per billion years. This cooling greatly raised viscosity, ultimately enabling plate tectonics.

Relative movements between Archean cratonic plates resulting from separations and convergences recorded in Proterozoic orogens likely will be defined by future paleomagnetic and other tests, but available paleomagnetic data are very sparse relative to the vast temporal and geographic span of Precambrian rocks, and are rendered ambiguous by major inconsistencies and by uncertainties of polarities and ages of magnetization. The data as yet provide little coherent support for the popular concept of plate-tectonic aggregation of a Rodinia supercontinent late in Mesoproterozoic time on an Earth that had less continental material than the present one.

6. Neoproterozoic beginning of plate tectonics

The full array of indicators of modern-style subduction, including complete ophiolite sections, lawsonite eclogites, voluminous accretionary-wedge polymict and broken-formation mélange, rock assemblages comparable to modern ones, and ultra-high-pressure domains of subducted and exhumed continental crust, is obvious only from Ordovician time forward. The Neoproterozoic record younger than ca. 850 Ma apparently contains the poorly understood transition into modern style plate tectonics, although evaluation of recent Neoproterozoic geologic literature is hindered, as for all of the Precambrian, by frequent minimization of description of rocks and structures and maximization of speculation based on chemotectonic and mantle-evolution assumptions. Stern (2005, 2008) is among the few who also see no pre-Neoproterozoic plate tectonics.

Blueschists, lacking earlier, are sparsely present in the Neoproterozoic, in far less than their Ordovician abundance (Maruyama et al., 1996). "Ophiolites" are too often claimed on the inconclusive basis of presence of serpentine or gabbro, but credible accounts of serpentinite-matrix melanges that contain most of the expected components of complete ophiolites include Johnson et al. (2004) and Stern et al. (2004) for 850–700 Ma Arabian and Nubian examples, and Khain et al. (2003) for 670–550 Ma Central Asian and Polar Urals examples. Belts of such likely dismembered ophiolites separate possible Arabian island arcs, ~850–620 Ma, which are dominated by basalt and andesite similar in both major and minor element compositions to modern arcs, with the notable exception that most suites are moderately bimodal, with subordinate rhyodacite peaks (Cole, 1993; Roobol et al., 1983). This precludes full analogy with modern arcs, as do the broad widths of tracts of such rocks as presently defined. Moroccan polymict mélange, with both serpentinite and sedimentary matrices, 10 km wide, includes exotic clasts of possible ophiolite and of metavolcanic rocks of greenschist, amphibolite, and, most significantly, blueschist facies; dated components are ~750–650 Ma (Hefferan et al., 2002). I presume the extensive late Neoproterozoic "olistostromes" (submarine landslides) reported by Khain et al. (2003) with serpentinite mélanges to include sedimentary-matrix accretionary-wedge mélanges, but Neoproterozoic mélanges elsewhere have been generally mistaken for stratigraphic units if they are common. (Phanerozoic accretionary wedges often are poorly exposed, and are still often misinterpreted as stratigraphic, not tectonic, complexes.) The best-mapped large region of Neoproterozoic orogenic rocks is the well-exposed Arabian shield, but I know of no sedimentary-matrix mélanges or blueschists yet recognized there.

Complete ophiolitic sections of oceanic crust and attached mantle in Phanerozoic subduction aggregates are of arc and back-arc affinity, and represent basal near-arc parts of overriding plates ramped on to mélanges on either oceanic or continental plates. I know of none for which a MORB origin is proved. By contrast, oceanic scraps in accretionary wedges appear to be dominated by seafloor and island materials, and I wonder if this is the case also for the fragments of oceanic crust found in the Neoproterozoic. Rigorous analysis is needed.

7. Conclusions

Evolution of continental crust and cooling upper mantle must be interrelated. I argue in this essay that the best reading of empirical information is that the upper mantle was extremely depleted before 4.4 Ga, by which time most material ever to be present in continental and oceanic crust was in a thick, global mafic protocrust, and that upper mantle has been progressively re-enriched, by sinking of delaminated and subducted bits of protocrust and its complexly polycyclic derivatives. Re-enrichment has exceeded removal of mafic melts to form new crust throughout the rest of cooling-mantle Earth history.

Surviving Archean cratons record extraction of a large fraction of potential TTG from mafic protocrust, yet TTG crust now ends abruptly above extremely depleted low-density mantle. Lower crust and subjacent mantle were highly mobile, not yet lithosphere, during most of the Archean, and flowed gravitationally to minimize crustal-thickness variations. Uneven fractionation of TTG from protocrust, uneven delamination of protocrust, and large bolide impacts are among processes that might have produced lower-standing regions toward which crust flowed. Perhaps rotational momentum was transferred gyroscopically between weakly coupled layers, as must now happen between mantle and core. Surviving intact TTG crust is

Please cite this article as: Hamilton, W.B., Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated, Lithos (2011), doi:10.1016/j.lithos.2010.12.007

that which was kept stabilized in thickness until subjacent buoyant mantle cooled to lithosphere, so Archean cratons owe their preservation to delamination of almost all intervening residual protocrust while that mantle was still so hot and weak that most delaminated material sank through it and accumulated lower in the upper mantle.

Paleoproterozoic and Mesoproterozoic orogens formed from networked basins filled deeply by sedimentary and bimodal-volcanic rocks and then highly deformed and plutonized. The pre-plate-tectonics concept of geosynclinal control of orogeny may have some applicability here. Thick mafic lower crust commonly intervenes between these materials and high upper mantle that is markedly more re-enriched, and less buoyant, than that beneath surviving Archean cratons, and that was stiff enough to isostatically support major crustal relief. Felsic basement, 0.2 to 2 billion years older than basin fills, has been recognized within many basinal Proterozoic orogens, but large uncertainties remain. To what extent were basins controlled by vertical density changes as opposed to lateral extension, to what was extension due, and how much rupturing of pre-existing continental crust accompanied it? How much deep mafic Proterozoic crust was generated locally from surviving protocrust, and how much came from partial melts of protocrust that had sunk into the mantle, including that which sank through initially shallow dunite? Were lithospheric oceans present? If surviving cratons converged as basins were inverted and plutonized, what drove them?

Seafloor spreading and subduction have operated in modern plate-tectonic mode only since late Cambrian or early Ordovician time. It may not be a coincidence that complex animals evolved slowly, but at eratically increasing rate, during late Neoproterozoic and Cambrian time, and then diversified rapidly and greatly during the Ordovician. The mafic melts that left the upper mantle to become oceanic crust, islands, plateaus, and island arcs, and to become the thick mafic underplate of continental magmatic arcs and also a major component of flood basalts, could not have come from ancient extremely depleted mantle, and were derived by partial melting of sunken delaminated and subducted crustal derivatives. Some sunken materials preserved general coherence as they sank into, or through, and so displaced upward, the initial extremely depleted magnesian upper-mantle rocks, and much partial melt from other sunken material had metasomatically re-enriched old mantle. How did processes evolve during the late Neoproterozoic, and when and how did the ocean/continent dichotomy develop?

Acknowledgments

I have been privileged to see a disproportionate share of the world's geology of all ages, often in the company of local experts. I have learned much, relevant to this essay, on broad topics of geophysics, earth evolution, mineral physics, petrology, and geodynamics from extensive discussions with D.L. Anderson, G.R. Foulger, T. D. Hoisch, J.A. McCreary, J.H. Natland, R.J. Stern, E.L. Winterer, and many others. The manuscript was much improved in response to comments by J.H. Bédard, M.E. Bickford, Andrew Hynes, and J.B. Murphy.

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Please cite this article as: Hamilton, W.B., Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated, Lithos (2011), doi:10.1016/j.lithos.2010.12.007

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Please cite this article as: Hamilton, W.B., Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated, Lithos (2011), doi:10.1016/j.lithos.2010.12.007

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Please cite this article as: Hamilton, W.B., Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated, Lithos (2011), doi:10.1016/j.lithos.2010.12.007