Tectonophysics xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Tectonophysics

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

Review Article

Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust

Warren B. Hamilton *

Department of Geophysics, Colorado School of Mines, Golden, CO 80401, USA

ARTICLE INFO

Article history:
Received 22 March 2013
Received in revised form 18 July 2013
Accepted 5 August 2013
Available online xxxx

Keywords:
Archean
Crustal mobility
Hadean
Mantle fractionation
Moho
Plate tectonics

ABSTRACT

This review evaluates and rejects the currently dominant dogmas of geodynamics and geochemistry, which are based on 1950s–1970s assumptions of a slowly differentiating Earth. Evidence is presented for evolution of mantle, crust, and early Moho that began with fractionation of most crustal components, synchronously with planetary accretion, into mafic protocrust by ~4.5 Ga. We know little about Hadean crustal geology (>3.9 Ga) except that felsic rocks were then forming, but analogy with Venus, and dating from the Moon, indicate great shallow disruption by large and small impact structures, including huge fractionated impact-melt constructs, throughout that era.

The mantle sample and Archean (<3.9 Ga) crustal geology integrate well. The shallow mantle was extremely depleted by early removal of thick mafic protocrust, which was the primary source of the tonalite, trondhjemite, and granodiorite (TTG) that dominate preserved Archean crust to its base, and of the thick mafic volcanic rocks erupted on that crust. Lower TTG crust, kept mobile by its high radioactivity and by insulating upper crust, rose diapirically into the upper crust as dense volcanic rocks sagged synformally. The mobile lower crust simultaneously flowed laterally to maintain subhorizontal base and surface, and dragged overlying brittler granite-and-greenstone upper crust. Petrologically required garnet-rich residual protocrust incrementally delaminated, sank through low-density high-mantle magnesian dunite, and progressively re-enriched upper mantle, mostly metasomatically. Archean and earliest Proterozoic craton stabilization and development of final Mohos followed regionally complete early delamination of residual protocrust, variously between ~2.9 and 2.2 Ga. Where some protocrust remained, Proterozoic basins, filled thickly by sedimentary and volcanic rocks, developed on Archean crust, beneath which delamination of later residual protocrust continued top-down enrichment of upper mantle. That reenrichment enabled modern-style plate tectonics after ~600 Ma, with a transition regime beginning ~850 Ma.

Contents

* Tel.: +1 3032793704.
E-mail address: whamilto@mines.edu.

0040-1951/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.tecto.2013.08.009

1. Introduction

A paradigm shift regarding Earth's evolution and geodynamics is decades overdue. Current dogmas are based on 1950s–1970s speculations that the lower mantle is still mostly unfractionated, the upper mantle has been only partly depleted by progressive removal of crust, and the entire mantle circulates together via plumes and deep subduction. These conjectures are contrary to data from all fields early claimed to provide support for them, yet are still widely asserted as facts. Stringent evaluation of assumptions and evidence is imperative for progress, but our science has much inertia because we all seek support for our preconceptions and resist contrary evidence, a failing termed "bias confirmation" by psychologists. The proposals made here can be broadly correct only if popular models are mostly false, so much of this essay is devoted to negatively evaluating those models and the assumptions on which they are based. The admonition, "you must not fool yourself—and you are the easiest person to fool" (Feynman, 1974), is fundamental to good science. Most of the papers I single out as exemplifying dubious science are representative of many uncited others, and appear to me to be products of what Feynman regarded as self-deception, and George Orwell termed Groupthink.

Formalization of prolonged-fractionation speculation by renowned isotope chemist Urey (1951) made the big step toward present dogma. He postulated that Earth accreted to full size with some volatilization and loss of low-melting components but without significant silicate fractionation; large iron cores of pre-fractionated planetesimals sank through to Earth's growing core, but most accreted metal remained dispersed with silicates; and very slow heating by radioactivity and by gravitational separation of the core, and progressive segregation of the core and fractionation of silicates, are still far from complete. By the late 1970s, it was recognized that the core had formed early, and gradualism was modified most of the way to its currently accepted form by, particularly, geochemists Wasserburg and DePaolo (e.g., 1979; Wasserburg was a Urey student, DePaolo a Wasserburg one). They speculated that Earth's lower mantle is still "primitive" and unfractionated except for loss of metal, whereas the upper mantle has been slowly depleted by separation of continental crust. Many geochemical concepts now applied widely as though they were fundamental principles—isotopic model ages, depleted-mantle ages, epsilons, juvenile melts, progressive growth of continents, and more—are merely extrapolations of those conjectures. Armstrong (1991) recognized these as circular rationales, but made few converts among geochemists. Modern geodynamics is dominated by extrapolations from the chemists' assumptions.

The current situation is analogous to that in the late 1950s through middle 1960s, when the then-standard model of global stabilism was taught as dogma even though it had already been disproved. I was then an actively writing and lecturing continental drifter. The evidence for rifting, drifting, colliding, and strike-slipping of continents was overwhelming, but the great majority of northern hemisphere geoscientists knew that mobility was impossible and hence that all purported evidence could be disregarded. The present equivalent is the acceptance of another standard model and dismissal of contrary evidence. I did not see plate tectonics coming, and the mechanisms I then vaguely imagined were wholly invalid, but the reality of the motions we drifters recognized were further confirmed by the ocean-floor behavior demonstrated by new data from marine geophysics in the late 1960s. Global mobility, in the expanded form of plate tectonics, was at last quickly accepted by those who were paying attention, although rearguard actions were fought by traditionalists for another decade or two. My participant's view of some of this history was presented in Hamilton (2002), which also contains a discussion of the stultifying enforcement of conformity by the peer-review system. I note that proved plate tectonics consists of a geometric description of relative motions of parts of Earth's outer shell, whereas most popularly appended speculations of framework, mechanism, and 3-dimensional behavior, subjects of the present essay, are false, and incorporate gross misconceptions of the proved relative motions.

Evidence is here presented for synaccretionary fractionation of Earth into core, severely depleted mantle, and thick mafic protocrust; for subsequent downward re-enrichment of only the upper mantle by sinking and recycling of derivatives of that protocrust; for formation of subsequent crust, both oceanic and continental, from protocrust and its derivatives, and for the evolution of the Mohorovičić discontinuity (Moho) beneath Archean cratons. I am confident that I am on the right track in opposing popular dogma and in supporting early fractionation, but of course am aware that I cannot have all the details correct.

These discussions combine newer information with, and modify, my earlier syntheses of tectonic and petrologic crustal and mantle evolution through time. I argued (Hamilton, 2011) that all claims for the operation of plate tectonics, and for the existence of lithospheric oceans, before ~850 Ma, are mistaken. That age limit had moved forward in time in my sequential papers on the subject, which began in 1998, as both relevant data and my comprehension increased. I am in a small minority but of course am not alone.

2. Early fractionation of Earth and lack of whole-mantle circulation

2.1. Thermodynamics

The fundamental assumption on which popular geodynamic and geochemical models are based is that the lower mantle is still "primitive" and has lost little of its components that partition into melts. If this hypothetical *lower mantle existed even now, its radioactivity would vaporize Earth. Early fractionation is required.*

Synaccretionary fractionation of Earth accords with thermodynamics, the mantle sample, the very early crusts of planetary neighbors, and much more. Opposition comes from decades-old conjectures, to which popular conclusions are force-fit, that the mantle is still mostly unfractionated and is only slowly yielding new crust. Heat enables Earth's dynamic and magmatic evolution, yet thermodynamics is overlooked in most global geophysics, and false assumptions commonly are substituted for both principles and data to provide illusory support for delayed fractionation. An important fraction of the high-quality experimental and theoretical thermodynamic work on Earth's interior during the last 20 years has been done by Anne Hofmeister and her associates. This section is based in substantial part on their work, and some of the broadest of their papers are cited. I am indebted to Hofmeister also for many discussions, but I may have introduced errors in the following elaboration.

Earth's heat loss is a critical factor in geodynamics. Popular models are built on false assumptions of the heat loss, so I begin with analysis of that factor. Heat flow is universally recognized to vary with crustal age in both oceanic and continental settings, and integration of measurements and age increments indicates a global heat loss of about 30 TW (terawatts, 10^{12} W). This was recognized 40 years ago, when relatively few measurements were available, and has been abundantly confirmed by the increasingly dense measurements made since (Hofmeister, 2010; Hofmeister and Criss, 2005, 2013). Nevertheless, a value of about 45 TW, 50% above measurements, has been widely assumed in the mainline literature of the last 35 years, to accord with model-based speculations. The large discrepancy illustrates the dominance of conjecture over facts in popular geodynamics.

Thermal conductivity has long been known to vary with temperature, but this is disregarded in mainline literature because it is incompatible with the standard model. Voluminous experimental data demonstrate that conductivity of both continental and oceanic crustal and lithospheric-mantle rocks decreases by about half as temperature increases from ~0° to 500 °C, decreases a little more to minima commonly near 1000 °C, and changes little, or increases modestly, at still higher temperatures. Gibert et al. (2003) cited papers from 1968 onward demonstrating this; newer and much more comprehensive work includes that by Hofmeister and Criss (2005, 2013), Merriman et al. (2013), and Whittington et al. (2009). Specific conductivities and falloffs with increasing temperature vary with composition, and are higher for mafic and ultramafic lithosphere than for felsic continental crust. Integration of this conductivity decrease validates the measurement-based 30 TW of global heat loss, disproves the standard model's speculative 45 TW, shows the average unit-area heat losses of oceans and continents to be similar, and precludes retention of primordial heat. As emphasized in subsequent sections, this temperature dependency also disproves the common assertion that plumes from deep mantle are needed to carry extra heat to shallow depths, and it accounts for the strong contrast in behavior of Archean upper and lower felsic crust. At high pressures and temperatures, conductivity increases with incompressibility (Hofmeister, 2010), which affects lower-mantle calculations.

The temperature dependence of shallow thermal conductivity is disregarded in conventional work because its incorporation disproves popular assumptions of basal-lithosphere temperatures and of abundant primordial heat. Measured heat flows, integrated with crustal age, are used, properly, in popular work to define heat loss through continental crust and through oceanic crust older than 50 or 60 Ma. Heat flow increases markedly with decreasing age in oceanic crust younger than that, and integration of abundant measurements with age of young oceanic crust yields the global heat loss of ~30 TW noted above. The global power of ~45 TW preferred by modelers is deduced by more than doubling the measured heat flows from young oceanic crust to fit a hypothetical curve calculated from assumptions including the disproved one that conductivity is constant through the lithosphere at its high cold-surface value. After Hofmeister and Criss (2005) emphasized that experimental data by them and many others falsify this assumption, they were challenged by three papers claiming, in effect, that the extra-heat method was better because it produced theoretically desired results. Hofmeister and Criss responded to two of those. All five discussions are cited in Hamilton (2007b), and the reader who looks them up can evaluate the conflict between data and entrenched assumptions.

Most mainline writers since have ignored the data and re-asserted the conventional assumptions as though facts. Evaluation of the recent report by Hasterok (2013), which re-derived the traditional value of ~45 TW from a much larger dataset than was available to his predecessors, illustrates the continuing dominance of speculation over data. Like his predecessors, Hasterok correctly used age-integrated measured heatflows from continents and old oceanic crust—and, also like them, he substituted assumptions for measurements in oceanic crust younger than 50 Ma. He discarded low determinations outright, and made large age-varying additions to higher ones to bring them up to a hypothetical curve calculated with constant thermal conductivity and other assumptions. He justified this use of false constant conductivity by misleadingly citing Gibert et al. (2003) as showing "uncertainties" in relationships between conductivity and temperature, without mentioning that both the data newly reported by them and the 9 prior studies they plotted (as well as the more thorough uncited studies by others published after 2003) *all* demonstrated a decrease of thermal diffusivity of upper-mantle materials by >50% with a temperature increase from ~0° to ~500 °C; nor did he mention that the ~45 TW he sought required calculation with constant conductivity and other model-based assumptions. He justified his great additions to heatflow measurements with the assertion that circulating sea water removes all of the desired but undetected heat from young oceanic lithosphere; not only is there no evidence for this on the scale postulated, but if it were happening, at age-varying rates throughout the youngest third of oceanic crust, a great many drillholes would have encountered the hypothetical constantly departing hot water and have registered high heat flows. Hasterok's speculative curve goes to infinite heat loss at zero age, and he truncated his integration beneath the curve at 2 Ma, where the desired 45 TW was reached.

Use of this 50% overstatement of global heat loss is a critical component of geodynamic modeling by advocates of whole-mantle convection. The data-based global heat loss of ~30 TW indicates global heat loss to be approximately equal to current radioactive heat production by U, Th, and ^{40}K, and precludes a major contribution from retained primordial heat (Hofmeister and Criss, 2005, 2013). Modelers postulate great primordial heat still in core and mantle to enable calculation (with incorporation also of false assumptions of physical properties: Section 2.4.1) of the vigorous mantle activity they seek, and accordingly use the hypothetical 45 TW. Thus, Korenaga's (2008, 2013) review papers chained elaborate speculations about planetary behavior and evolution from assumptions that Earth's heat loss is 46 TW, that there is no radial variation of heat-producing elements within the mantle, and that 80% of Earth's mantle heat loss (which is exclusive of crustal loss) is of primordial heat.

The radial distribution of heat must be a function primarily of the distribution of thermal conductivity and the main radioactive heat-producing elements, U, Th, and ^{40}K, and secular cooling is due primarily to decreasing radioactivity, which early was rapid because of the short half lives of ^{235}U and ^{40}K but now is slow (Hofmeister and Criss, 2013). U, Th, and K all partition into melts, so radial distribution of heat depends on mantle fractionation and melt migration, which is mostly omitted from conventional modeling. The more evenly dispersed the radioactivity, the hotter the mantle and the slower it cools, whereas the more concentrated upward the radioactivity, the cooler the mantle and the faster Earth loses heat. The magnitude of these effects was far greater in the early Earth than now. The major concentration of radioactive heating is now in continental crust, from which heat leaks directly to space. Earth would be vaporized even by current radioactivity if the lower mantle were still "primitive". The widely accepted conjecture that a hot core separated early, taking heat down with it, invokes impossible thermodynamics, including violation of the Second Law; nor is separation possible without concurrent silicate fractionation (Hofmeister and Criss, 2013).

If the whole mantle now had uniform radioactivity, and the core none, mantle temperature would increase downward to the core–mantle boundary at a rate decreasing with depth, and the core would be isothermal inside the boundary. Core–mantle boundary temperatures thus calculated for uniform mantle and crust distribution of 30 TW of present radioactive heat generation are absurdly high, about 22,000 and 16,000 K for plausible conductivities of 4.5 and 6 W/m K (Watts per meter per Kelvin), respectively, and vary from 35,000 K for an unreasonably low conductivity of 3 W/m K to 10,000 K for an unreasonably high conductivity of 10 W/m K (Hofmeister and Criss, 2013). Extrapolation of heat generation by uniformly distributed U, Th, and K back in time from the present 30 TW, for example to ~100 TW at 4 Ga, leads to much higher impossible temperatures. Instead, the mantle must have been severely and irreversibly fractionated concurrently with accretion, and the standard model of still-primitive lower mantle is false. On the other hand, if all radioactivity is now in the upper mantle, the lower mantle and core are approximately isothermal at a temperature controlled by the depth distribution of the radioactivity in the upper mantle, and this misfits the plausible requirement for a core–mantle boundary hotter than the temperature at the discontinuity near 660 km. A uniformly radioactive present upper mantle and crust that generates 30 TW would provide an isothermal lower mantle at about 3700 or 4800 K for conductivities of 6 or 4.5 W/m K, respectively, 100 TW at 4 Ga would have kept lower mantle and core about 500 K hotter than that.

What has been the distribution through time of upper-mantle radioactivity? Seismicity and high-amplitude seismic tomography show many subducting slabs to be plated down on the great seismic discontinuity about 660 km deep, so downward recycling and mixing obviously now extend to that depth. No evidence stronger than weakly permissive suggests that material crosses through the 660 either downward or upward (Section 2.4.2). The major radioactive isotopes will always tend to migrate upward with partial melts, but early concentration of most radioactivity into synaccretionary protocrust, followed by progressively increasing downward recycling into upper mantle of solid components of that protocrust as radioactivity diminishes, would operate to decrease secular change in lower-mantle temperature.

Calculations with more complex radial arrays of radioactivity—a present concentration in continental crust, graded or layered values in the upper mantle, and small allowances for the lower mantle—will be helpful for visualizing options, although major uncertainties cloud mantle conditions. Commonly inferred current temperatures at various depths are based on unconfirmed answers to fundamental questions. The bulk composition of the silicate Earth is known only within rather broad limits, and there is little reason to accept the assumption that it is either a contrived "pyrolitic" peridotite or a "chondritic" mix of the refractory components of one specific carbonaceous meteorite. Did the average composition of accreting material vary with time? Is the great seismic discontinuity a pressure-phase boundary, or a change in composition (Section 2.4.2)? Are basal-mantle low velocities due to high temperatures, as assumed by most modelers, or to high iron contents, as better fits seismic parameters? What are the light elements with iron in the core, and how do they affect phase relationships? Is the geodynamo dependent on thermal convection, or something quite different, such as gyrosopic transfer of momentum between mantle, outer core, and inner core? Given the need for synaccretionary fractionation, how did it actually operate (Section 2.5)? And so on.

Core separation could not have generated much gravitational-potential heat, and accretionary impact heating was shallow and hence quickly dissipated (Elkins-Tanton, 2012; Hofmeister and Criss, 2013). Plumologists, however, want strong basal heating to generate their hypothetical narrow plumes from deep mantle, and commonly claim the core to have been an inexhaustible source of heat, at temperatures far hotter than the mantle, throughout geologic time. The source of such heat is deemed either primordial (accumulated during accretion, in defiance of the Second Law of thermodynamics, and retained ever since despite high heat loss assumed to have driven constant vigorous mantle convection), or as generated by latent heat of crystallization (which cannot raise temperature, but can be released only in response to cooling and immediate removal of heat). The local concentration of core heat along the core–mantle boundary, invoked by plumologists to inaugurate the narrow plumes they desire, is another violation of the Second Law. Plumologists further add intense but dimensionless internal mantle heat to enable the mantle to convect with the desired patterns and vigor, and disregard the great effects of pressure on strength and thermal expansivity because those preclude desired results (Section 2.4.1).

Formation of the Moon by a giant impact, the currently popular explanation, would have melted the entire Earth, and could account for the Moon's much lower contents of low-condensation-temperature elements and iron than those of Earth. Hofmeister and Criss (2013) argue that such a collision is incompatible with Earth's nearly circular orbit and upright spin, and that the compositional differences accord with co-accretion of a planetoid with much smaller size and gravity.

The experimentally determined downward halving of thermal conductivity with increasing temperature in both oceanic and continental crust and lithospheric mantle also has great significance for tectonics and magmatism. The decrease in conductivity is mostly complete by ~500 °C, which approximates the brittle–ductile transition at slow strain rates in both continental and oceanic rocks. Oceanic lithosphere, and the entire continental crust in low heat flow areas, or the upper continental crust where heat flow is high, are thermal insulators that retard passage of deeper heat. This requires that modern asthenosphere be hotter by ~200 °C than is calculated with the constant conductivity wrongly used in conventional work, and obviates the rationale that plumes are needed to import heat. Large amounts of melt can accumulate beneath the insulating lid, which accounts for rapid, voluminous eruptions of large igneous provinces, also with no need for plumes. Much partial melting of uppermost mantle or lower crust is to be expected from heat generated within continental crust or introduced beneath it. These attributes are applied in subsequent crustal-evolution sections.

2.2. Isotopic constraints

Recent work on short-lived radionuclides helps define stages of accretion from the Solar System nebula that are compatible with the conclusion that Earth fractionated concurrently with accretion. Review papers include Caro (2011), Caro and Kleine (2011), Kleine and Rudge (2011), and Wood (2011), although these authors minimize conflict with popular dogma by invoking only modest early fractionation, followed by subsequent slow fractionation. Particularly useful data regard the long-extinct mother–daughter isotope pairs ^{26}Al–^{26}Mg, half-life 0.7 m.y., both lithophile elements but with quite different chemical behaviors; ^{182}Hf–^{182}W, 9 m.y., the Hf highly lithophile, W highly siderophile; and ^{146}Sm–^{142}Nd, 103 m.y., both highly lithophile rare earths, but Sm slightly enriched in residues, Nd in melts. Condensation of the solar nebula had begun by ~4567 Ma, the best U–Pb age of its oldest dated components—"CAI" inclusions rich in Ca and Al, in the Allende carbonaceous chondrite, which formed when ^{26}Al was still very much alive, hence soon after the pre-nebula supernova(?) nucleosynthesis of the ^{26}Al. Chondrules, flash-melted droplets of accreted dust, are indicated by ^{26}Mg data to have formed shortly after the CAIs. The ^{182}Hf–^{182}W pair is critical for constraining differentiation of both

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

meteorites and the Earth. Metallic meteorites fractionated in small planets soon after CAIs formed. Hf–W data show that both accretion of the Earth and separation of its core also were rapid, and were perhaps 90% complete within 30 m.y. of the start of Solar System condensation. Although the complex mixtures of highly processed high-temperature components with low-temperature unprocessed ones in comets and many meteorites indicate that many features of main accretion are not yet understood, accretion and fractionation rates apparently were far faster than long assumed (Hofmeister and Criss, 2013).

The Moon, hence presumably the Earth, had essentially its present size and a fractionated crust by ~4.46 Ga, the ^{147}Sm–^{143}Nd isochron age of the oldest lunar rocks yet dated. A date as early as ~4.52 Ga can be fit to lunar and terrestrial tungsten isotopic data, or even 4.537 Ga with integration of pressure-phase considerations of silicate/metal fractionation (Yu and Jacobsen, 2011). That both Venus and Mars also had thick mafic crusts before most of the impacts registered on their surfaces is consistent with the compositional information available from them.

Concordance of zircon U/Pb ages—calculation of approximately the same age from the ratios of ^{238}U/^{206}Pb and ^{235}U/^{207}Pb, which have very different half lives—is normally taken to establish an absolute age of crystallization. Many isotopic and petrologic calculations and deductions are anchored to ancient ages thus defined, which indeed appear to be valid throughout younger geologic time, for which lead loss results in marked divergence from concordance. However, ancient lead loss in zircon, perceived today, approximately parallels concordia, and results in calculated ages that are too young, so concordance alone is not proof of absolute age in ancient materials, and many derivative interpretations may be spurious (Vervoort, 2012; Vervoort et al., 2012).

2.3. Proposal

Our upper-mantle sample (Section 3) comes primarily from the lithosphere, and is as required by the severe early depletion advocated in Sections 2.1 and 2.2. The sample is of rocks that were extremely depleted early but progressively re-enriched subsequently in more fusible components. This accords with the concept of synaccretionary growth of a thick mafic protocrust, followed by progressive re-fertilization *from the top* through geologic time. By 4.5 Ga or soon thereafter, at least the high upper mantle was extremely depleted, and consisted mostly of extremely magnesian olivine. I presume the rest of the mantle to also have been severely depleted, although direct evidence for this is weak. As an end-member model, I suggest that a thick mafic protocrust that contained most components of all subsequent continental and oceanic crust was formed by syn-accretionary fractionation. Neither the primitive lower mantle rich in fusible components, nor the slowly depleting upper mantle, has ever existed, although both are presumed in most popular speculations of global geochemistry and geodynamics.

2.4. Further evaluation of the gradualistic standard model

The fundamental assumption of variants of the standard model is that any early fractionation of Earth was much subordinate to slow differentiation that is still far from complete. The derivative assumptions that the lower mantle is still mostly "primitive", and that the upper mantle is still unidirectionally fractionating crust, in turn form the basis for speculations of whole-mantle circulation, including deep subduction and deep-sourced plumes, which dominate current geodynamics and related geochemistry and petrology. Voluminous data falsify these dogmas, but most proponents, even those who have themselves generated much of the disproof, devise evasions by giving every example a unique explanation. Proponents currently postulate vigorous whole-mantle circulation throughout geologic time, which would long ago have obliterated the "primitive" character of the lower mantle they regard as driving the circulation.

2.4.1. Geodynamic modeling

Most newly-mobilist geodynamicists of the early plate-tectonics era accepted the geochemists' delayed-fractionation speculation, and, as have their subsequent followers, forced compliance on their models. The use of the fictitious global heat loss of ~45 TW is an aspect of this bias. Current modeling is mostly with dimensionless ideal-incompressible-fluid mechanics, which has little relevance for the solid Earth, but is used because it can be manipulated, via selection of unrealistic properties and of heat sources that "work" and exclusion of properties and interrelationships that preclude desired results, to provide visual aids for conventional speculations that are mistaken for evidence by unwary observers.

The real mantle consists of compressible solid, not incompressible liquid. Thermal expansivity, and hence thermal buoyancy, decrease with deep-mantle pressure to about one-quarter of their shallow values (Chopelas, 1996). Desired mobility could not be illustrated were this incorporated, so pressure effects are omitted from, or minimized by, conventional models. Solid strength also increases with pressure, and solid strain is a power-law function of stress. Preconceived narrow plumes and whole-mantle circulation are impossible in realistic lower mantle, wherein any motions would be broad and sluggish. Real properties are interdependent, but in popular modeling properties are treated as independent so that arbitrary values can be assigned individual parameters to enable calculation of desired results. If liquid viscosity is increased in the deep part of the model, heat input and thermal conductivity are increased to keep everything moving as desired. The wanted motions can be activated only with very strong bottom heating, so inexhaustible heat from a core far hotter than the mantle, and its local concentration into plume bases at the core–mantle boundary, are assumed. The barrier of the 660-km discontinuity commonly is ignored (Section 2.4.2). The models based on these chained assumptions vary widely in sophistication but generate approximately fixed vertical boundaries between convecting cells, and are wrongly asserted to show how plate tectonics works (e.g., Korenaga, 2013; Tackley, 2012). Actualistic plate tectonics (almost all plate boundaries move relative to all others, and change shapes, lengths, configurations, and interactions in accord with surface-plate constraints) is disregarded. Geodynamic models postulate rapid turnover and vigorous mixing and heat loss, yet require what are assumed to be permanent compositional contrasts and heat sources.

2.4.2. The uncrossable 660-km discontinuity

The prominent seismic discontinuity at a depth of 660 $\pm$ 20 km is now commonly taken as the boundary between upper mantle, with its other discontinuities, varying velocity/depth gradients, and large horizontal velocity variations, and the lower mantle, wherein discontinuities are subtle, horizontal variations are small except near the bottom, and velocity/depth gradients are mostly smooth. The 660 marks a profound change in dimensions, patterns, and amplitudes of velocity anomalies, consistent with its being a complete barrier to material transport (Gu et al., 2001). That it is a barrier is compatible with its being either a compositional boundary or the usually-assumed pressure-phase boundary.

Integration of experimental petrology with seismic properties approximately fits the conventional explanation that the 660 km discontinuity is dominated by a density-phase change in mineralogy and crystal structure of the composition represented in the shallow mantle by olivine (Frost, 2008; Helffrich, 2000). Most metamorphic phase changes occur across positive pressure/temperature (Clapeyron) slopes, whereby increasing pressure favors the dense phase, and increasing temperature the lighter one. The gain or loss of latent heat in crossing a positive-slope boundary warms rising hot material and cools sinking cool material, expediting both transits. The presumed 660 km phase boundary has an unusual negative P/T slope, although experimental and theoretical ambiguity clouds its precise P/T slope and position. An increase in either P or T favors the dense phase, so rising hot material must cool to cross the boundary, and sinking cold material must warm, thus eliminating or decreasing the positive or negative buoyancy needed for transit.

The transition zone is the lower part of the upper mantle, and by definition extends from the 660 upward to the discontinuity at 410 ± 20 km. The 410 marks another major phase change, this one with a positive P/T slope that expedites transits. Consistent with these opposed senses of P/T slope, the 410 rises where slabs subduct directly through it, whereas the 660 is broadly depressed where slabs, identified by robust high-amplitude seismic tomography, are plated down on it as subduction hinges roll back. See Niu et al. (2005) for an example of contrasted 410 and 660 behavior, and Hamilton (2007b) for illustrations, references, and discussions of the kinematics and general tomography. The 410 and 660 km discontinuities do not broadly anti-correlate (e.g., Gu et al., 1998), which indicates that subducted slabs laid down on the 660 fill only the lower part of the transition zone (Niu et al., 2005), and are not greatly thickened by crumpling such as is assumed by those who postulate subduction to be a process of injection rather than of gravitational sinking from retreating hinges. Note that the inclinations of slabs subducting through the upper mantle, as demonstrated by zones of seismicity and by high-amplitude seismic tomography, define transient positions of slabs sinking more steeply than they dip, and not trajectories down fixed slots.

Alternatively, the 660 may be a compositional boundary. Murakai et al. (2012) deduced from experimental and observed *S*-wave velocities that the Mg/Si ratio may change from a dominantly olivine composition (atomic Mg/Si of the pure phase = 2:1) above the discontinuity to a dominantly high-Mg silicate perovskite (Mg/Si = 1:1) below it. Hofmeister and Criss have argued in several papers that sub-660 compositions more like those of enstatite chondrites or CAI inclusions are likely. An enstatite–chondrite Earth, for example, would provide enough iron to make the core, and reasonable oxygen isotopes.

Seismic tomographic illustrations by proponents of whole-mantle circulation are often miscited as proof that slabs subduct through the 660 km discontinuity and on down to basal mantle, and that narrow plumes rise from deep mantle up to the asthenosphere or to Earth's surface. These illustrations are invalidated by problems of both sampling and methodology. See Dziewonski (2005) and Foulger et al. (2013) for discussions of what can, and cannot, be seen with seismic tomography.

Almost all published seismic-tomographic profiles across spreading ridges suggest hot material beneath the ridges to be confined to the upper part of the upper mantle. Dziewonski (2005, fig. 6) showed whole-mantle profiles through 6 body-wave *Vs* tomographic models by different expert tomographers in the same position across the central Mid-Atlantic Ridge. (Models are calculated in 3-D, but commonly are illustrated with vertical or horizontal slices through the models.) Five of the profiles, including the one by whole-mantle-circulation advocate Steven Grand, show the sub-ridge low-velocity anomaly to be confined to the upper part of the upper mantle, one shows it occupying the entire upper mantle, and none show the connectivity into the lower mantle postulated by whole-mantle convectors.

Surface-wave tomography better constrains upper-mantle structure within most of the oceans. North Atlantic surface-wave tomography, with excellent source and recorder coverage, found the robust low-velocity anomaly, d Vs = 4–7%, of the Mid-Atlantic Ridge, including Iceland (a must-have deep-mantle plume for plumologists), to be a narrow band centered on the ridge and confined to the upper 200 km of the mantle (Pilidou et al., 2004).

Some seismologists generate body-wave tomographic cross sections purported to show slabs subducting into the lower mantle, or, with completely different methods, plumes rising from deep mantle. Methods claimed to see one cannot image the other. Colors depicting divergence of assigned velocities from a 1-D radial-Earth reference model are saturated at very low values, giving the misleading impression that a dubiously calculated retardation such as 0.4% in the lower mantle is equivalent to a robust 6% retardation in the upper mantle. Published illustrative profiles are located to best depict desired features, and are truncated horizontally and downward to omit distractions inconsistent with desired interpretations. The only published profiles wherein the visual impression is given of a high-velocity slab subducting obliquely down through most of the mantle, from beneath northern Mexico to east of the SE United States (Grand et al., 1997), have been cited hundreds of times as showing the “Farallon slab”. (Tackley (2012), bases his geodynamic modeling of continuous vertical subduction from crust to core–mantle boundary throughout the past 4.5 b.y. on this.) The 6 profiles published by Dziewonski (2005) by diverse tomographers are along precisely the same line as those of Grand et al., but extend farther into both Pacific and Atlantic, and have colors saturated at non-misleading values higher than those of Grand et al. The broad lower-mantle region of calculated irregular and variably intersecting slightly high-velocity anomalies (including those in a revised 1999 model by Grand himself) can be inferred to contain a subducting slab only with high selectivity.

The unique purported deep slab of Grand et al. (1997) is unconstrained by the crossfire imperative for reliable tomography, and instead apparently represents the misassignment to the lower mantle of time advances gained by recorded rays from Andean earthquakes as they exited obliquely down through the Andean slab within the upper mantle. This is indicated by inspection of the global maps by Jeroen Ritsema (in Hamilton, 2011, fig. 1; reprinted in Foulger et al., 2013) of raypaths, color-coded for increments of travel-time anomalies, for all standard-catalog *S* and *SS* rays that have mid-mantle turning depths. These are major components of the tomographic models. The various other purported tomographic illustrations of lower-mantle slabs around the world have much less continuity and visual appeal than this “Farallon slab” artifact, but also are in places where misassignment of time advances from slab earthquakes appears probable.

Oft-cited pro-plume tomographers Montelli et al. (2004) and Wolfe et al. (2009) claimed to show narrow plumes of “hot” (relatively low-velocity) material rising through much of the lower mantle beneath isolated islands by use of a method now disavowed by its authors. The depictions of purported deep plumes applied derivatives of the “ACH method” of Aki et al. (1977), who postulated that lower-mantle velocity information could be derived from relative travel times of steeply rising rays without the usual tomographic constraints of crossing rays and absolute travel times. Half of these relative velocities are by definition slow, are assumed, a non sequitur, to have come along hotter paths (paths through iron-rich basal mantle fully suffice), and their relative slowness is partitioned to any desired parts of the rising raypaths with arbitrary assumptions. Surviving ACH authors Christoffersson and Husebye (2011) acknowledged that their 1977 assumptions, data, and calculations were all incorrect. Plume-skeptic seismologists have long recognized the method as merely illustrating arbitrary assumptions. (I am indebted to D.L. Anderson for this analysis.)

The “Yellowstone hotspot” is a must-have fixed plume for plumologists because its temporal progression and direction are unique in North America in being approximately compatible with a hypothetical fixed Hawaii in plate-motion calculations. Tomography with surface waves and both *S* and *P* body waves, constrained by the close-spaced seismometers of both the U.S. Transportable Array and the High Lava Plains Experiment, demonstrated that low seismic velocities are limited to the upper mantle, and that hypothetical connection to the lower mantle is blocked by a subducted slab plated down within the transition zone (James et al., 2011; Wagner et al., 2010).

2.4.3. Plumes do not operate

Speculations that plumes—variously as narrow pipes, upward-expanding mushrooms, balloons, or tadpoles, and broad upwellings—carry silicate melt or mobile solid from basal mantle to or near the surface are extrapolated from conjectures that the lower mantle is unfractionated and strongly heated by the core. (Any mass that rises or sinks by positive or negative thermal or compositional buoyancy can be termed a "plume", but I use the word here in accord with its common geodynamic and geochemical usage for a hypothetical hot mass rising through almost the entire mantle.) Early corollaries were that fixed plumes make volcanoes or volcanic provinces in overpassing plates and define a "hotspot reference frame" of absolute plate motions, and that plume volcanoes can be recognized by chemical, isotopic, and physical criteria. A widely popular additional rationale, that excess heat is needed to make a volcano, is falsified by the 200 °C temperature increase due to the insulation by crust and lithosphere that is ignored by plumologists (Section 2.1), and further incorporates many false assumptions regarding the thermal and mechanical variations and properties of the lower mantle.

All of the physical, chemical, and isotopic features early claimed to indicate the presence of plumes—*all* predictions in the initially tidy concepts—also have been abundantly falsified. Hypothetical plumes do not define the fixed framework once presumed, and they have no physical or chemical attributes by which they can be identified. For extensive evaluation, see Foulger's (2010) book. She demonstrated that the strong preponderence of evidence of all types disproves the plume concept and requires controls by plate-tectonic processes in the upper mantle. (Plumes and plate tectonics are unrelated concepts, and the former is hypothetical whereas the latter is a proved description of relative motions, but not of absolute motions or mechanism.) Arguments by skeptics and advocates can be compared directly in the many articles in the thick compendia edited by Foulger and Jurdy (2007) and Foulger et al. (2005), and in the many papers and commentaries posted at www.mantleplumes.org. The thick volume edited by Foulger and Jurdy is particularly good for this purpose: Foulger is a skeptic, Jurdy an advocate, and the papers are half-and-half. Many of the papers have attached discussions, rebuttals, and discussions of discussions (15 in one case!), to which many outside pro and con experts, as well as other participants in the symposium, contributed. Authoritarian bluff and rote science would be far less prevalent were this procedure more often followed. Recent short anti-plume reviews include Anderson (2011, 2012), Hamilton (2011), and Presnall and Gudfinnsson (2011). Anderson noted that all seismological predictions for Hawaii, type example of a purported plume, have been falsified—low absolute velocities, a depressed 410-km discontinuity and a raised 660 with ponding beneath it, specific geometries of anisotropy and shear-wave splitting, a dragged and sheared plume head extending to the NW. Plume proponents (e.g., Collins et al., 2012) have given a different ad hoc evasion for each such failure, thus acknowledging the concept to contain no testable predictions and claiming it to be immunized against scientific testing. Among Anderson's geophysical and kinematic demonstrations is that no local addition of deep-mantle heat is needed to account for effects commonly attributed to plumes. Presnall and Gudfinnsson integrated phase petrology and geophysics to show that the overlapping compositions of oceanic island and spreading-ridge basalts are as required by their derivations from different depths in the normal low-velocity zone, and that plumes are precluded. Plate tectonics is enabled by mantle heat but is driven by density inversions due to top-down cooling of oceanic lithosphere, and circulation likely is confined to the upper mantle (Hamilton, 2007b).

Even many plume proponents now knowingly disprove the features that they and others earlier claimed to require the operation of plumes—but instead of considering alternative explanations, they give each misfit a rationalization that invalidates the purported reason for its initial designation as a plume, and thereby claim the properties and behavior of plumes to be whatever inconsistent features are observed or imagined wherever plumes are postulated.

The deep-mantle-plume concept arose as a 1970s conjecture, by Jason Morgan as an extrapolation of a suggestion by Tuzo Wilson, for the demonstrated younging of the volcanoes of the great Emperor–Hawaii chain of seamounts and islands across part of the Pacific plate. The volcanoes become progressively younger SSE along the Emperor seamounts, from the Kamchatka–Aleutian corner, currently dated as ~80 Ma, to an abrupt change in direction, ~47 Ma, to ESE along the Hawaiian seamounts and islands to the very active volcanoes of Hawaii island and Loihi seamount at the end. Morgan proposed that the Pacific plate had traveled NNW above a fixed narrow vertical plume from deep mantle from 80 to 47 Ma, abruptly changed course, and has since moved WNW over the plume, the volcanoes having been built as the plate passed over the plume. (The 60° change in direction is at the crossing of the great Mendocino transform fault, which at 47 Ma marked a huge change in thickness and properties of oceanic lithosphere that requires a shallow cause for the inflection; and the continuity of magnetic anomalies throughout the Pacific plate, from long before until long after 47 Ma, precludes the conjectural great Eocene reorganization of plate motions.) Morgan predicted that other then-undated chains of Pacific-plate islands and seamounts would show trends and age progressions concordant with the same plate motions, as would whatever volcanic features, such as Yellowstone (Section 2.4.2), on other plates that were selected, while ignoring the abundant misfits, because they might be compatible with a fixed framework of absolute plate motions if such were defined by Hawaii.

This tidy conjecture, still widely miscited as fact in textbooks and research papers, has been thoroughly disproved. Plume advocates have provided much of the disproof, and have devised variably conflicting evasions, often unique to each example, as to why none fit the hypothetical fixed framework that provided the basis for the concept. Advocates Tarduno et al. (2009) demonstrated that even the Emperor half of the Emperor–Hawaii chain grossly misfits the fixed-plume concept, and speculated that "mantle winds", for which no other justification exists, blow this and all other errant plumes to wherever their erupted products are seen. (That the Hawaiian half of the chain still fits a fixed-source conjecture is merely a restatement of the assumption that absolute motion of the Pacific plate is defined by the Hawaiian progression.) The other Pacific island and seamount chains predicted to have age progressions and bends concordant with a fixed Emperor–Hawaii source have been shown by extensive subsequent work to lack both (Clouard and Bonneville, 2005). Morgan and Morgan (2005; the first author was the major developer of 1970s speculations) argued that the mismatches show volcanoes to squirt up in any temporal and spatial order from plumes that tunnel thousands of km horizontally in the asthenosphere, and thereby acknowledged the original basis for the concept to be false. Proponents Tosi and Yuen (2011) conjectured that vast horizontal tunneling is instead beneath the 660 km discontinuity, although there is no evidence tunneling at either depth. Advocates Koppers et al. (2007) speculated that Gilbert Ridge and Tokelau Seamounts lack the predicted age progressions and bend correlations because "jerky" motions of the Pacific plate made their plumes misbehave. There are many more examples of ad hoc evasions of geometric requirements of the initial theory, although providing illusory visual aids for the falsified early prediction of fixed vertical plumes remains the major goal of most geodynamic modelers (Section 2.4.1).

Plumes were early postulated to be recognizable by their heads, tails, early uplifts and large igneous provinces, and other distinctive characteristics. The purported examples of these also have been abundantly disproved, by advocates (e.g., Ali et al., 2010) as well as by skeptics. The response by plumologists here too has been to claim the behavior of plumes to be highly variable because it consists of whatever is observed or imagined wherever a plume is postulated.

Isotopic and trace-element features were early claimed to characterize plume products, and many of them to require origins in the lower mantle, some even in the core. Skeptics have long argued against these criteria, which are based on chained assumptions and numerology that disregard phase petrology, behavior of minor elements, thermodynamics, and statistics, and are so riddled with inconsistencies and "paradoxes" as to be meaningless. The broader plume-advocating geochemists also now recognize all of the early generalizations to be false. Thus, White's (2010) major review demonstrated that none of the

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

widely accepted chemical and isotopic criteria can be diagnostic of either plumes or deep sources—but he maintained his career-long enthusiasm for plumes by arguing that their products are whatever is observed wherever plumes are imagined.

Despite such disproofs of all fundamental concepts of plumology, most concerned geochemists nevertheless continue to assert, in the ever-increasing plumological literature, that trace elements in surface lavas are inherited from basal-mantle melts. Example: the lavas of Mauna Kea and Mauna Loa, 40 km apart and the two largest volcanoes on the island of Hawaii, differ in Nd, Pb, and Sr isotopes. To explain this contrast as due to sources in unfractionated deep mantle, without mention that the upper mantle source region is known to contain diverse lithologies, Weis et al. (2011) postulated that two narrow fixed plumes, originating thousands of km apart in basal mantle, have long risen obliquely through the deep mantle as fixed plumes, merged precisely at a fixed upper-mantle point, and jointly fed a fixed shallow vertical Hawaiian plume, within which the two streams maintain their separate identities as they rise together to the surface.

The many mutually incompatible ad hoc speculations with which plumologists evade disproofs of the existence of plumes are united only by their assumption that the plume concept is immune to scientific test, and thereby demonstrate the evolution of plumology from scientific hypothesis to mere mythology.

2.4.4. Plumes have never operated

The disproved geochemical assumptions regarding deep origins of hypothetical modern plumes are still accepted and rigidly applied to Precambrian rocks by many geochemists. They claim to identify plume products intercalated in stratigraphic sections of ancient volcanic rocks just from ratios of ratios of a few selected trace elements, based on the false early assumptions of compositions of conjectural modern plumes. Further, many Precambrian geologists casually invoke megaplumes merely to bring heated material to shallow levels, unneeded given insulating lids and high ancient radioactivity (Section 2.1). Hundreds of published reports assume that plumes were larger and more abundant in Precambrian time than even the most enthusiastic speculations for the modern Earth. For example, Bédard (2006), Bédard et al. (2013), Ivanic et al. (2012), Van Kranendonk et al. (2013), and Zhang et al. (2013) presented strong arguments against plate tectonics in some Archean terrains, with which I concur, but then postulated that giant plumes intermittently rose during Archean time, underplated the crust, and provided the mafic feedstock needed for episodic TTG formation.

The many fluid-dynamic modelers of Precambrian geodynamics (review by Gerya, in press), like those for modern Earth (Section 2.4.1) and Venus (Section 4.2.1), assume ideal-incompressible-liquid values for selected properties, wrongly treated as independent variables, that allow depiction of vigorous whole-mantle convection with plumes and subduction, and similarly disregard known properties, such as compressibility, that preclude these results. These modelers include a highly fertile lower mantle, either primordial or re-enriched by ancient whole-mantle subduction, and thereby also disregard thermodynamics (Section 2.1) and much else.

2.5. Differentiation of the mantle

Major syn-accretionary fractionation of the mantle is required by thermodynamics (Section 2.1), and the contrary popular concept that the mantle is still mostly unfractionated is contradicted by evidence from many fields (Sections 2.2 to 2.4). The most tangible product of this differentiation is the 200 km or so of extremely magnesian and uniform ancient dunite that is held up by its buoyancy beneath ancient cratons (Section 3), and the rest of the lithospheric mantle sample can be accounted for by contamination of such dunite so it likely was a global layer. Fractionation of a mafic protocrust at least 100 km thick provides the likely source for the TTG that dominates Archean crust, and downward recycling of densified protocrust that had lost its more fusible components provides a plausible explanation for the evolution of the upper mantle (Sections 3, 5, and 6).

That short list can define, at best, only part of the fractionation and re-enrichment process, and the reality must have been much more complex. How did violent degassing, turbulence, and impacts, including a giant Moon-forming impact if such occurred, interact? What is the bulk composition of the mantle, did the average composition of accreting material change with time, and why is the 660-km discontinuity a barrier? What was the thickness of the evolving synaccretionary melt zone, and what pressure-phase boundaries and mineral compositions controlled melting and crystallization within it, and subsequent conversion to still denser phases? Were the magnesian dunite of the high upper mantle and the mafic protocrust paired differentiates, or did the early-crystallized or residual light olivine float in a denser melt, from which were precipitated pyroxene, garnet, and other dense minerals, or their still-denser higher-pressure equivalents, that remained below the dunite? In what form did the protocrust remain on top, and what was happening to it? The major radioactive elements could not have remained in the dunite, but to what extent did they go down with denser minerals, as opposed to going up with protocrust? How did the processes vary as Earth's size increased? Answers to these and many more fundamental questions are not obvious.

3. Progressive re-enrichment *from the top* of upper mantle

The present mixtures of upper mantle rocks that vary from extremely depleted to much enriched could not have formed together in equilibrium. Our mantle sample is almost entirely from the lithosphere, as exposures, and as abundant xenoliths and their mobile kimberlitic, carbonatic, or alkalic carriers. Increasing data accord with evolution by progressive re-enrichment throughout geologic time of an extremely depleted high-Mg ancient lithospheric mantle to produce the sampled mixtures of depleted rocks, metasomatically re-enriched ones, sunken rocks, and new magmatic rocks. There is an irregular increase in the proportion of fertile to depleted ultramafic rocks in the high upper mantle with decreasing age of overlying continental crust, and abundant re-enriched rocks are present also in oceanic mantle lithosphere. The array is incompatible with standard-model assumptions of progressive *depletion* of long-fertile upper mantle.

Knowledge of the ancient depleted rocks of the mantle sample is compatible with their being products of synaccretionary fractionation. Further, a now-vanished mafic protocrust as needed for generation of the voluminous felsic rocks that were forming before 4.4 Ga (Section 5). Subsequent continental evolution can be attributed to re-enrichment of early-depleted upper mantle by derivatives of protocrust that sank into the upper mantle, in substantial part to depths greater than those we primarily sample, and from which were mobilized the rising melts and fluids that accomplished the metasomatism and that, as kimberlites and other carriers, brought the mantle-xenolith sample to the surface.

The low-density lithospheric mantle now held by its buoyancy directly against Archean cratonic TTG crust, and also much lithospheric mantle under Proterozoic orogens, consists mostly of refractory dunite and harzburgite with extremely magnesian olivine, remarkably uniform in composition near $Fo_{92.6–92.9}$ (Bernstein et al., 2007; also Begg et al., 2009; Griffin et al., 2009). Little if any of even the magnesian orthopyroxene now in harzburgite could have formed in equilibrium with this high-temperature olivine. Fertile minerals in mantle peridotites, and all olivine less magnesian than ~Fo_{92}, likely record subsequently introduced material. The uniform composition of olivine in the unmetasomatized depleted rocks accords with formation at circumglobal subuniform temperature, but not as residuals from long-protracted incremental removals of partial melts under varying conditions. Add the thermodynamic requirement for synaccretionary fractionation, and the picture emerges of a zone-refining melt that migrated upward as Earth was enlarged by rapid accretion, most potential

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

crustal material thereby being removed upward. Anderson (2007) is among others who have advocated a magma ocean zone-refining its way outward during planetary accretion, but most authors, including Bernstein et al., stay as close as possible to 1970s assumptions and advocate instead protracted incremental removals of partial melts.

More fertile rocks bearing clinopyroxene, garnet, plagioclase, and spinel (lherzolite, pyroxenite, garnet peridotite, eclogite, and others), as well as less-magnesian olivine and probably even orthopyroxene, have compositions incompatible with formation in equilibrium with the dunite with which they are now intermixed, whether that dunite was initially a precipitate from a melt or a residue after removal of all else, and whether it floated or sank (Section 2.5). As many petrologists have documented in recent years (e.g., Agashev et al., 2013; Aulbach et al., 2004; Begg et al., 2009; Bernstein et al., 2007; Griffin et al., 2009; Lazarov et al., 2012; Malkovets et al., 2007; Wasch et al., 2009), many of the more fertile rocks were formed by variable metasomatism of high-Mg dunite by addition of Si, Fe, Al, Ca, and Cr, and suites of trace elements, all incompatible with primary crystallization with $Fo_{>92}$ olivine, commonly in conjunction with rise of volatile-rich kimberlitic melts. Thus, regarding minor elements, "the incoherent behavior 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). Other fertile rocks, including some eclogites, were introduced wholesale, but many of these also have been severely metasomatized and reconstituted (Greau et al., 2011; Huang et al., 2012). Ancient subduction has often been assumed for eclogites (e.g., Shirey et al., 2003), but the implicit predictions of composition are not met, even with allowance for metasomatism (Huang et al., 2012). Isotopic age determinations from subcratonic mantle xenoliths commonly are erratic because of long histories above closure temperatures, but typically are greater in dunite and harzburgite than in fertile rocks, and well-dated metasomatism was of kimberlite, not ancient, ages. Thermobarometry of mantle xenoliths is applicable, at best, to the times of entrainment in the magmas that carried them to the surface.

Those carrier melts also modified the mantle through which they rose. The xenolith sample is strongly biased by metasomatism by the melts that carried the xenoliths, and uniform high-Mg dunite and harzburgite likely strongly dominate upper mantle beneath Archean cratons away from these late melts. Seismic properties indicate subcratonic mantle to be generally more uniform and magnesian than the mixtures sampled by kimberlites, and metasomatized xenoliths are found mostly above the low-velocity-mantle margins of cratons (Artemieva, 2009; Griffin et al., 2009). Both seismic analysis and xenolith thermobarometry show the deeper upper mantle beneath buoyant sub-cratonic dunite to be more fertile (Artemieva, 2009; Yuan and Romanowicz, 2010), but there too the fertility is likely secondary.

Lithospheric mantle beneath Proterozoic orogens shows highly variable, and generally greater, enrichment of initially-depleted Archean mantle (Griffin et al., 2009, and many others), which is consistent with direct geologic evidence (Hamilton, 2011) that those orogens were built 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 many geochemical calculations. 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 (2006) for summary of compositions. Rampone and Hofmann (2012) and Warren et al. (2009) showed that the extreme isotopic and geochemical variability of oceanic peridotites cannot be reconciled with time-increasing depletion, and many of the Warren et al. samples retain compositions permissive of extreme depletion ~4.5 Ga. Obviously re-enriched ancient shallow depleted 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). The relative homogeneity of ocean-floor basalts in limited areas records mixing of melts from diverse sources and the requirements of phase petrology, not source uniformity.

Subducted slabs are widely plated down on the 660-km discontinuity (Hamilton, 2007b, 2011), so obviously the lower part of the upper mantle is also being re-enriched. This too accords with synaccretionary fractionation of thick mafic protocrust from depleted mantle, with re-enrichment of upper mantle by sunken derivatives of protocrust, and with derivation of all subsequent crust either directly from protocrust or from remobilized components of its sunken derivatives.

About half of the papers cited here as documenting progressive metasomatism of depleted mantle are from excellent petrologic work by the Macquarie University group. They (e.g., Griffin et al., 2012), however, opt for the standard model: the severely depleted dunite formed by removal of preserved Archean crust [mostly TTG, which cannot have come directly from the mantle, but only from mafic rocks] circa 3.5 Ga, and, although now scattered about the globe beyond its sub-cratonic sites of formation, the dunite does not, in those terms, record a synaccretionary process. I disagree. On a longer time scale also, the general temporal progression toward less depleted bulk upper mantle with time is commonly attributed to decreasing proportions of melts extracted and added to the crust with time (e.g., Lee et al., 2011). This overlooks the metasomatic enrichment of upper-mantle rocks, and claims that only previously hidden fresh mantle is partly melted to provide new increments of crust. Conventional variants add melts and fluids rising from deeper unfractionated mantle. I note again that Armstrong (1991) demonstrated that downward recycling can account for isotopic evidence commonly claimed to require progressive depletion of upper mantle. Most geochemists still do not consider this option.

Disappearance from beneath preserved crust of thick protocrust is required, and can account for the observed re-enrichment of the lithosphere. If, however, moderately enriched dense rocks formed beneath the extremely depleted dunites during synaccretionary fractionation (Section 2.5), then their partial melting or breakdown could also have furnished re-enriching materials.

4. Hadean bombardment, 4.5 to 3.9 Ga, and planetary Mohos

4.1. Limited terrestrial record

Earth's next 600 million years, after what has been argued here to have been rapid accretion and synchronous fractionation that included formation of a thick mafic protocrust, are poorly constrained by terrestrial data. The protocrust is needed as a source for the voluminous TTG of preserved Archean crust, and remnants of it may have been found but have received little analysis. Leucocratic components of polycyclic lower-crustal gneisses, initial melts for which could not have been generated in the mantle, have yielded igneous zircons at least as old as 4.0 Ga (Section 4.3), and xenocrystic and detrital zircons of poorly defined provenance, but presumably from felsic rocks, date back almost to 4.4 Ga. The dated in-situ ancient zircons are in crustal-melt granitoids, and in places range over 400 m.y. within small outcrops, indicating long-continued near-solidus crustal temperatures consistent with high mobility and high-temperature recycling.

Much or all of the 4.5–3.9 Ga era is, however, recorded in the ancient surfaces of the other terrestrial planets and the Moon as surface-saturating impact craters, small to enormous, and, particularly on Venus, huge impact-melt constructs, and Earth must have been similarly bombarded. Many papers from the impact community have emphasized this (examples: Barlow, 1990; Glikson, 1999; Grieve, 1980; Grieve et al., 1990), but it is overlooked by most earthbound geoscientists; thus Gerya's (in press) review paper puzzled about Earth's history in this interval without mention of planetary constraints.

Planetology has been heavily contaminated by the assumption that the other terrestrial planets must be internally active in the fashion assumed in the standard model for Earth, so again I digress, this time to argue against the extrapolation of terrestrial misconceptions to, particularly, Venus, which provides excellent analogs for the Hadean Earth when those obfuscating misconceptions are removed. Going outside Earth brings to mind two other false dogmas, now mostly extinct, whose undeserved longevities encourage me in my contrarian approach. When I came on the research scene, most observers knew that lunar craters and basins were products of internal magmatism; plumes, in current jargon. Ralph Baldwin of course was instead correct that they had impact origins, although this did not become obvious to all observers until close-up images were obtained from Ranger rockets in the 1960s. And Robert Dietz argued, correctly, for lonely decades that Earth's circular "cryptoexplosion" and "cryptovolcanic" structures were products of bolide impacts, not of plumes (again in current terminology). Dietz' lesson has still been learned only partially. In South Africa, where Vredefort was only recently accepted as the early Proterozoic impact structure it was proved to be much earlier, adjacent larger composite Bushveld has a melt sheet identical in age to Vredefort's and a floor now known to have large downward-injected "explosive brecias", but is still discussed in print exclusively as an unrelated plume product.

4.2. Venus, Mars, and Moon

Mars and Moon are accepted by all as preserving impact-dominated surfaces from this early era, and that of the Moon is known to date from the whole span, from 4.5 to 3.9 Ga. I contend that Venus does also, with many thousands of small to enormous circular structures with impact morphology, and many huge buildups of impact-generated melts, as described and illustrated briefly in Section 4.2.4 and more fully by Hamilton (2005, 2007c). Venus is only a little smaller than Earth in diameter and density, and Earth's protocrust must have been similarly bombarded, and its protocrust disrupted and, in many places, melted. Earth's crust, unlike that of Venus, may then have been independently mobile, although there is no clear evidence for this. Subsequent downward recycling of protocrust occurred only on Earth, enabling its evolving dynamics and tectonics throughout geologic time. Venus, Mars, and Moon show no plate tectonics, and little recent activity other than sparse small impact craters. They broadly preserve very ancient surface features, lack evidence for liquid cores and have no endogenic magnetic fields, and obviously have thermal structures and histories unlike the Earth's. Lillis et al. (2008) inferred from the surface-geologic distribution of locally preserved remanent magnetization on Mars that its dynamo was inactivated ~4.1 Ga.

Most planetologists, however, interpret the terrestrial planets in evolutionary terms as close as possible to the standard model, which I reject, for a slowly fractionating and plume-ridden Earth. Unchanging global "stagnant lids" are presumed to enclose mostly-unfractionated interiors kept forever active by primordial heat. Plumologists conjecture a still-hot core and active plumes even for little Mars. Venusian radar imagery shows many thousands of circular structures, of all diameters from 15 to 2500 km, many with obvious impact morphology and hundreds of them with cookie-cutter overlaps, but consideration of these as impact products is prohibited in mainline literature by adherence to dogma. Mainline Venusian interpretations have been completely dominated for 30 years, since before good imagery became available, by plumologists who assumed that preservation of an ancient surface on Venus is impossible, hence all large circular structures must be endogenic, and their conjectures have been accepted, without evaluation, by successive waves of diverse specialists.

Large rimmed circular structures were conspicuous even on low-resolution and incomplete 1970s radar imagery of mist-shrouded Venus, and contemporary interpreters (e.g., Masursky et al., 1980) recognized the morphology and size–frequency distribution expected of ancient impact basins dating from late-stage main planetary accretion, with which I concur. Modelers (e.g., Solomon and Head, 1982), who still dominate Venusian work, nevertheless insisted that the physical properties, evolution, and highly active internal dynamics they assumed, without evidence, for Venus, should be comparable to those they also assumed, mistakenly in my view, for Earth. They dismissed the possibility of an ancient moonlike surface, and argued that all large circular structures must be endogenic. Extrapolating far beyond plume speculations then in vogue for Earth, they conjectured these structures to have been formed by plumes from deep mantle. There were a few evidence-oriented holdouts for impact origins for a decade, but most Venusian investigators accepted a plume-ridden Venus as dogma before high-resolution radar imagery was received from Venus-orbiting spacecraft Magellan in 1990–1994. Allure accompanied the search for unique-to-Venus plumological processes, and unconstrained speculations, none of them resembling anything proposed by terrestrial plumologists, have completely dominated Magellan interpretations from first images to the present.

There are many thousands of small to gigantic circular structures obvious on Magellan imagery, but only small young ones can be impact structures according to popular dogma. One thousand of the youngest-looking small circular structures accordingly have been designated as impact structures. The hypothetical basis for selection as impact craters is that they be "pristine", any alteration being incompatible with the additional dogma that erosion and sedimentation could not have occurred since they formed. In fact, ~60% of the accepted "pristine" craters are conspicuously modified by variable burial of their ejecta blankets and crater fills (Herrick, 2006; plumologist Herrick is the current keeper of the official list of "pristine" impact craters). The distinction between "pristine" craters and plume constructs is inconsistent and arbitrary, as is shown by images of many craters on both sides of the purported boundary between impact and plume products in Hamilton (2005, 2007c).

All of the thousands of other, and mostly larger, circular structures on Venus are "non-pristine" and, by default, not analysis, are deemed endogenic in mainline literature. At least 3/4 of the visible "pre-pristine" circular structures are ignored and unmapped, but about a thousand, selected mostly from the highlands, are given plumological explanations. These interpretations are constrained only by the requirement that they must be endogenic and by limitations to imaginations, so speculations by different groups tend to be mutually incompatible, to the extent that one's rising plume can be another's sinking antiplume. The consistent circularity and impact morphology of the structures at all scales is obfuscated in words and maps; as, by drawing irregular blobs around single circular structures, or around clusters of circular structures with cookie-cutter overlaps, and interpreting the blobs while ignoring the circular structures. Intricate classifications of plume products are devised, of which diverse types of "coronae" are most numerous. Impact options are rarely mentioned, and then only to be dismissed without evaluation.

The assumption that the present landscape formed entirely under hot and anhydrous conditions like those now—the surface temperature of Venus, beneath its supergreenhouse 90-bar CO_2 atmosphere, varies inversely with altitude but averages about 460 °C—was also dogmatized before Magellan imagery was available, and the powerful evidence for fluvial features and oceanic sedimentation has yet to be acknowledged in conventional reports. Determination, in popular-dogma terms, of the maximum age of the craters mislabeled "pristine", and hence the hypothetical age of the plume-riddled topography, incorporates huge uncertainties of bolide flux and of disruptions of weak and small bolides in the superdense atmosphere, and can be rationalized as anything from ~0.3 to ~3.9 Ga. About 0.5 Ga is commonly cited, whereas I opt for an age closer to 3.9 Ga.

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

4.2.1. Thermodynamics and modeling

The Moon and terrestrial planets arguably all had thick synaccretionary protocrusts, although popular planetology seeks explanations as close as possible to the hypothetical slowly-fractionating Earth. Dated Apollo samples from the Moon, and meteorites from Mars, show both to have to have reached approximately full sizes, and to have had fractionated crusts, of unspecified thicknesses, by ~4.5 Ga. Partial semiquantitative chemical analyses by Soviet landers on Venus defined approximately basaltic compositions, dated only by interpretation of landscape age, mine being that the planetary surface is impact-saturated and thus goes back to synaccretionary fractionation of thick protocrust. All but Earth, which progressed subsequently through the stages of internally mobile crust and downward recycling, were arrested in protocrust stage, their radioactivity permanently concentrated at shallow depths, and they cooled rapidly and were soon inactivated (cf. Section 2.1). The Venusian atmosphere contains only about half as much absolute ^{40}Ar as does Earth's, which suggests a comparably lower content of ^{40}K and so markedly less early radiogenic heating. Further, as Hofmeister pointed out to me, blackbody radiation increases with the cube of temperature, so Venus has always lost heat faster than Earth because it is closer to the Sun, and its current super-greenhouse atmosphere holds its surface temperature more than 400 K above that of Earth. The high surface temperature also cancels the shallow insulating-lid conductivity effect that retards terrestrial heat loss, which further expedites cooling. Nevertheless, Venus and Mars are commonly assumed to have only thin crusts, like that Earth developed late in its unique history.

Ideal-liquid fluid-dynamic modeling is widely applied to modern Venus and Mars, to which it is even less relevant than to modern Earth (Section 2.4.1). As for Earth, selected physical properties, wrongly treated as independent variables, and heat sources are assumed to be whatever is needed to enable whole-mantle plumes, and properties such as compressibility, which preclude desired outcomes, are disregarded. Thus, Smrekar and Sotin (2012) modeled present Venusian mantle as an ideal incompressible adiabatic liquid, its viscosity unaffected by either pressure or temperature, and the core as a high-temperature heat source, and deduced Venusian mantle to be vastly hotter and weaker than Earth's. Hundreds of Venusian papers elaborate similar impossible properties, at scales varying from global to small geologic structures, constrained only to accord with the imagined processes and results.

4.2.2. Geoids, plumes, and Mohos

The preservation of ancient surfaces on our neighbors, and the relation between gravity and topography on each, provide powerful evidence for early inactivation and hence for shallow concentrations of radioactivity, cool mantles, and present inertness compatible with their appearances and other features noted above. Dominant speculation nevertheless presumes interior mobility continuing to the present, modest for Mars and extremely vigorous for Venus, which can be reconciled with the Venusian geoid only by implausible rationales.

Most of Earth's topography, at all scales down to ~400 km, is invisible in the geoid (Fig. 1A) because large positive and negative surface loads—continents, plateaus, mountain systems, and oceans and their ridges—are compensated isostatically at shallow depths, and the dipole moment of the density distribution requires that the geoid anomaly be very small for a surface mass compensated at shallow depth (Anderson, 1989, p. 242). The large anomalies in the terrestrial geoid indicate lateral density variations deeper in the upper mantle, of which subducted slabs plated down in the transition zone are most conspicuous.

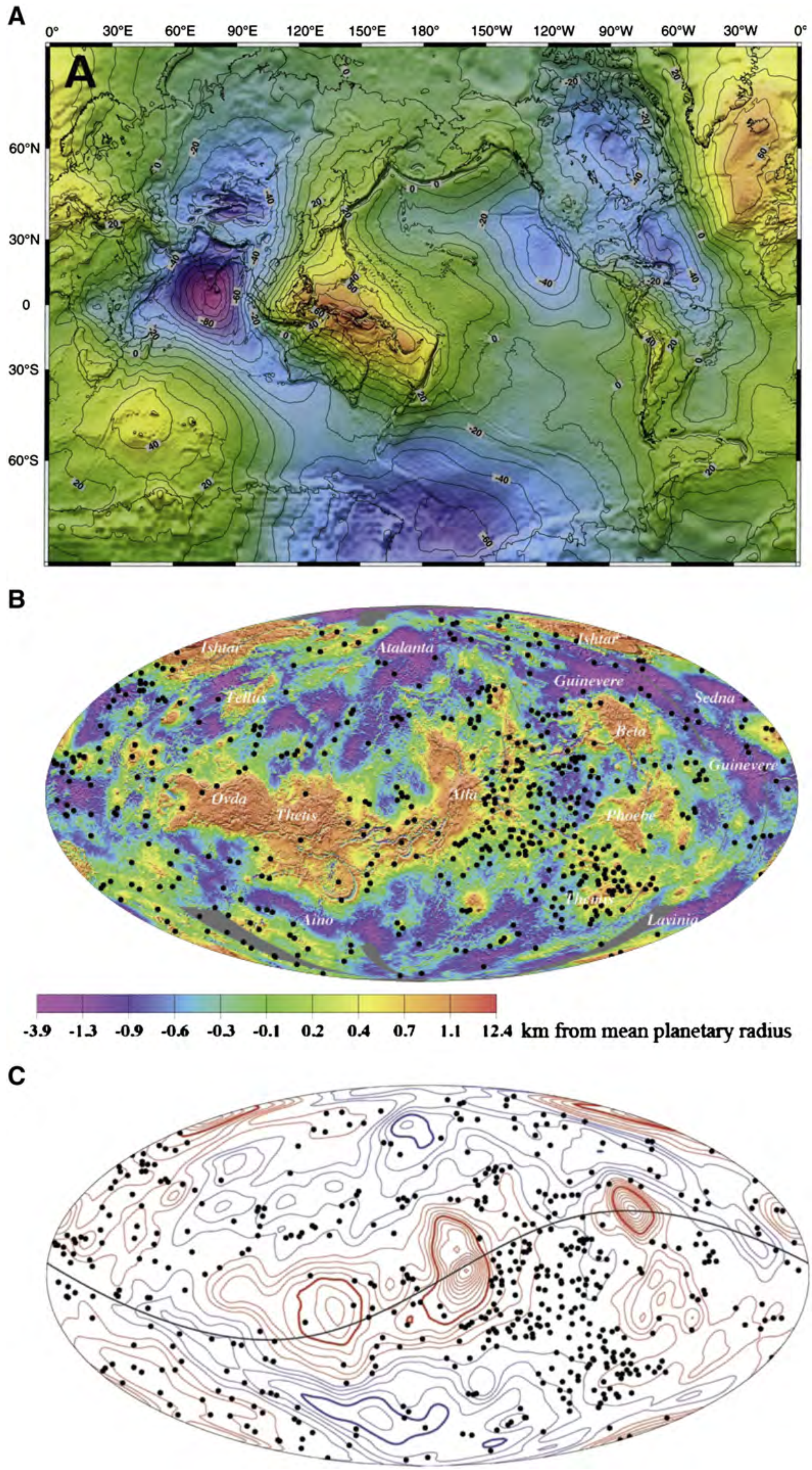
By contrast, Venusian geoid and topography correlate strongly and directly at all wavelengths between about 12,000 and 1500 km, and appreciable lateral density variations away from these are not apparent (Fig. 1B and C; Johnson and Richards, 2003; Steinberger et al., 2010; Wieczorek, 2009). The straightforward explanation is that Venusian topography is deeply compensated and has long been stable, the mantle is relatively rigid, and little prior mobility beyond very early fractionation and the topographic effects of impacts is recorded. Venusian upper mantle has been too cool and inert to visibly affect the surface since early in planetary history. Lower temperature accords with the solid Venusian core indicated by the lack of a magnetic field, and with the lack of surface deformation. Venus shows no evidence for plate tectonics, and its topography is unimodal, not bimodal as is Earth's present division into lithospheric oceans and continents.

Mainline Venusian specialists agree on the lack of Venusian plate tectonics but reject the rest of the preceding paragraph. They dismiss the geoid signal with the assertion that the strong correlation of geoid and topography "is a proxy for dynamic support of the crust" by upwelling and downwelling plumes. The quote is from James et al. (2010), and is based on the early-1980s unconstrained assumption that Venus is still intensely active in a plume-dominated mode, which in turn was merely extrapolated from since-disproved terrestrial speculations (Section 2). Other recent elaborations of the assumptions that major Venusian topography was formed, and is still supported dynamically, by plumes and anti-plumes include Basilevsky and Head (2007), Dombard et al. (2007), Herrick et al. (2005), Steinberger et al. (2010), and Wieczorek (2009). They and others explain the existing topography as produced by rising and sinking plumes at a time they assume to have been ~0.5 Ga (I see the topography as much older and as lacking any plume involvement: Section 4.2.4), and explain the current correlation of the geoid and that same topography as now maintained by up-pushing and down-pulling positive and negative plumes. *They thus postulate that the hypothetical plumes and antiplumes have maintained the same shapes, dimensions, and columnar configurations of densities, temperatures, and velocities from core to surface for a half-billion years, without producing any new visible effects*. Master geodesist William Kaula (1995) recognized an early version of this as "wishful thinking", but had no effect on the commitment to plumology by Venusian specialists. Acceptance of dynamic support frees Venusian interpreters to postulate any properties desired to explain hypothetical plume processes and products, as in the example noted in Section 4.2.1. Some Venusian modelers assume an unchanging stagnant lid to preserve an unchanging surface, whereas others assume plumes to have heated even exposed surface rocks to extreme weakness over much of the surface, and assume vast magma pools just below the surface.

Published crustal-thickness models for Venus combine dismissal of all or most of the huge geoid signal as dynamic with additional unconstrained chained assumptions: an unfractionated planet, shallow weak rheology and high temperature, thin continuous nondisrupted crust above a shallow Moho inverse to short-wavelength topography, simple Airy isostatic compensation with one density for crust and another for mantle, and a lack of any effects of impacts and sedimentation. Wieczorek (2009) evaluated moderately conflicting models within the dubious framework of acceptance of their cantilevered speculations, to which he has contributed. Similar exercises have been carried out for Mars and Moon.

4.2.3. Lunar dating of 4.5–3.9 Ga bombardment

Dating of Apollo samples from the Moon accords with the inference that an impact-saturated planetary surface can record large bolide impacts that span ages from ~4.5 Ga to 3.9 Ga. All of these lunar samples may have come from the great ejecta blanket from the Imbrium impact basin. Mare Imbrium, 1100 km in inner rim diameter and the youngest large impact structure on Moon's nearside, formed ~3.91 Ga (Grange et al., 2010). Undated multiring Orientale on the far side appears on geologic grounds to be of the same age or slightly younger, so 3.9 Ga approximately dates the end of accretion of large bolides on the Moon. The Moon's surface is saturated by pre-Imbrium impact craters and basins, one of them 2500 km in diameter and a number of others comparable to Imbrium, and is pocked by small post-Imbrium craters. An Sm/Nd whole rock and mineral isochron of 4.46 Ga presumably indicates the Moon to have reached essentially its full size, and to have had



Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

an evolved crust, by that time. The concept of a brief "late heavy bombardment" of the Moon, centered on 3.9 Ga, is popular but unproved (Chapman et al., 2007). Purported dates of this late bombardment are argon/argon analyses of shock-melted glass in impact breccias, and may represent only scatter in determinations of the Imbrium event. Morbidelli et al. (2012) deduced from other data a bombardment increase circa 4.1 Ga, with large impacts before as well as after, but no 3.9 Ga concentration.

Frequency distribution of U/Pb ages of Apollo zircons, mostly xenocrysts in shock breccias but partly crystals in situ in tiny fragments of, mostly, norite and granophyre, defines a very erratic falloff in abundance from 4.4 to 3.9 Ga (Pidgeon et al., 2010). Although these ages are commonly assumed to define fractionates of a slowly growing endogenic crust, to preserve parallelism with the slow-differentiation standard model for Earth, the rock types are low-pressure differentiates of types to be expected from impact lakes such as Sudbury and Bushveld, and so the ages may instead reflect a general fall-off of large bolides with decreasing age.

4.2.4. Venusian analogs for pre-3.9 Ga bombardment of Earth

The preceding rejection of conventional plumology for Venus sets the stage for a look at some of the actual surface of that planet, which, dated by analogies with the Moon, likely illustrates what happened to the Hadean Earth.

Venus is almost as large and massive as Earth, so the impact effects of large bolides on its surface should provide reasonable analogs for those on Earth. Unlike the Moon, Venus shows voluminous melts associated with large impacts. The greater gravity of Venus and Earth resulted in impacts ~5 km/s faster than on the Moon (although velocities must have varied hugely as functions of the unknown pre-impact orbits of bolides around the Sun), so both shock and depressurization melting presumably were greater on the two planets than on the Moon. Weak and small bolides were, however, mostly fragmented and destroyed in the dense atmosphere of Venus, which greatly decreased the abundance of craters smaller than ~150 km in diameter.

The main imagery for interpretation of the Venusian surface consists of Magellan high-resolution synthetic-aperture slant-radar backscatter (reflectivity) and low-resolution nadir-radar altimetry. Both are commonly reproduced in grayscale, and backscatter brightness misleadingly resembles optical photography but is altogether different. Radar brightness is not albedo, but instead is a function of orientation of slope to look direction, surface roughness on approximately centimeter to meter scale (radar wavelength was 12.6 cm), and electrical conductivity. Cross-flightline map distance is proportional to travel time, not to optical angle, and images are projected onto low-resolution topographic models that yield confusing illusions in moderate or steep topography. Parts of Venus are covered by both west and east look directions, or by two look inclinations to the same side. Appearances can be dramatically different between these, to the extent that a feature conspicuous on one can be invisible on another, but some paired backscatter images can be viewed in informative optical stereo, despite topographic illusions, when dark and light are in the same ground positions. The altimetric images yield invaluable additional information invisible in backscatter, and often require very different conclusions than can be reached from backscatter alone; compare paired Fig. 3A and B. Most Venusian specialists study only backscatter images. When they do use the altimetry, it is often to produce pseudoperspective images with extreme vertical exaggerations, commonly 20:1 or more and usually unmentioned, that effectively prohibit rational structural and topographic analysis and leads instead to "unique to Venus" structural interpretations.

Evidence for my interpretation of the Venusian surface as recording ancient-impact saturation is primarily in the radar imagery, which the reader can evaluate for himself. More than 60 backscatter and altimetric images, illustrating Venusian impact features of diverse types and modifications at all scales from local to hemispheric, are presented in Hamilton (2005, 2007c). The conventional literature, although voluminous, lacks such comprehensive collections. Many of my images illustrate the complete gradation between "pristine" and extremely modified craters, and the lack of any distinction between products of "impacts" and "plumes". Among my favorites are images of Aramaiti "corona" (Hamilton, 2005, fig. 4), a crater with complete classic impact morphology (central uplift; circular rim 270 km in inside diameter, steep inside with terrace faults, gentle outside slope surrounded by a lobate ejecta apron), which has been singled out in the mainline literature for at least 3 mutually incompatible plumological explanations, without mention of impact. Cookie-cutter superpositions of circular structures, impossible with popular endogenic explanations, are shown in figures 2005-10 to 14, and 2007c-9 to 14, and several of those images contain many examples each. Numerous very large impact basins, to ~2500 km in diameter, are illustrated by 2005-13 to 15. Saturation of lowlands as well as highlands by overlapping small to large craters is shown by 2005-7 to 9, and 2007c-2, 13, and 14. Large impact-melt constructs, of all ages relative to surface-saturating lesser impact structures, are illustrated by 2005-1, 2, and 16 to 20.

I include here a few examples, with interpretations given mostly by the captions, of images composited by U.S. Geological Survey from the narrow Magellan flightstrips. Fig. 2 shows a crater-saturated plains region. Although perhaps half of old highland probable-impact structures are mapped and considered in the conventional literature, as plume products with blob boundaries that obfuscate strikingly circular morphologies, something like 90% of the circular structures in the more extensive lowlands, as in Figs. 2 and 3, are omitted from maps and ignored—and this false contrast between highland and lowland abundances is then asserted to require origins by megaplumes that pushed up the highlands.

The paired images of Fig. 3 show a plains region saturated with impact craters; water-eroded and variably bombarded remnants of impact-melt constructs; and sediments compacted into craters. Much critical information invisible in reflectivity (A) is shown by altimetry (B), but only reflectivity is considered in most Venusian work, wherein nearly all of these obvious structures are ignored. Any mention of the possibility of fluvial erosion or fluvial or marine sedimentation, both probably seen here, is forbidden in mainline work by adherence to dogma that the landscape developed entirely under anhydrous conditions. The area shown is almost as large as the conterminous United States.

Fig. 4 illustrates what I regard as an impact-generated melt inside an obvious impact basin, complete with rim, isostatic moat, and surrounding ejecta blanket. The large, low melt pancake is unlike any terrestrial volcano, but mainline Venusians term it a "corona–volcano hybrid" of plume origin. This large construct plus impact basin and ejecta has been minimally pocked by later bolides, so lunar analogy suggests an age near 3.9 Ga. Older impact basins, up to ~500 km in inside rim

Fig. 1. Contrasted geoids show Earth to have thin, weak lithosphere and a highly mobile and variable upper mantle, and Venus to have far more strength and vastly less internal mobility. (A) Terrestrial geoid, 10 m contours, blue and pink low, green–yellow–brown high. Long- and moderate-wavelength topography is compensated isostatically at shallow depths, and, as required by geoid construction, thus shows almost no correlation with geoid. (B) Venusian topography and (C) geoid correlate directly over a broad range of wavelengths because topography is supported deeply. (C) Venusian geoid, height shown by 10 m contours, 0 not shown, red positive, blue negative. Spherical harmonic degrees 2–30 are fully retained, but, because reliability falls off at higher degrees and because truncation would cause artifacts, a Gaussian roll-off is applied to degrees 30–60. Venus maps are centered on the equator and longitude 180°. Arbitrarily selected backscatter-identified "coronae", which exclude many upland and almost all lowland circular structures here regarded as of impact origin, are marked by dots in (B) and (C).
Panel A provided by David Sandwell. Panels B and C, published originally by Johnson and Richards (2003), provided by Catherine Johnson, who also supplied the topographic scale, corrected from the erroneous one initially published.

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

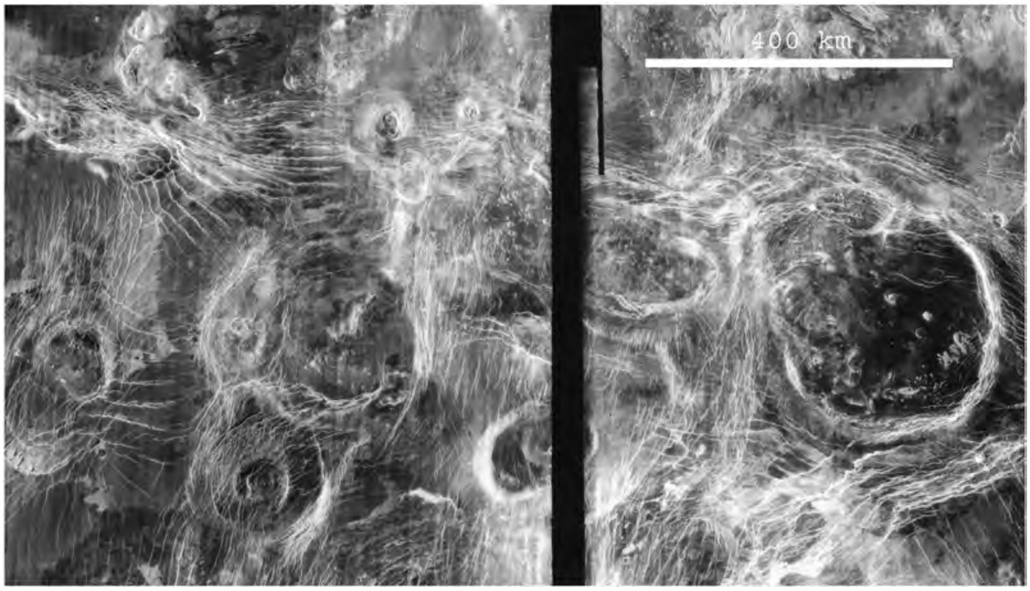


Fig. 2. Venusian plains region (Ganiki–Kawelu Planitae) saturated with impact craters with inner rim diameters of 15 to 300 km. All circular structures visible at this scale (there is one tiny "pristine" crater within the view) are to me ancient impact features. Most of these are ignored and unmapped in the conventional literature, and the few that are considered are claimed to be products of plumes. Note superpositions and varying degrees of preservation. The largest, Ki "corona" (far east, center) has a rim ~1 km high, steeper inside than outside, and is seen on larger-scale imagery to have a preserved lobate ejecta blanket to east and south; its rim is cut at north-center by a 65 km crater. East-looking backscatter image of area from 40° to 47°N, and centered on 222°E.

diameter, mark the surrounding region within the view. The area of this image is larger than the United States. Other well-preserved low Venusian "volcanoes" reach 1000 km in diameter, whereas remnants of still other "volcanoes" show all degrees of disruption by large and small impact craters and basins, hence record often-repeated similar events during prolonged Hadean bombardment. Many of these "volcanoes" contain very large but shallow crestal sags, with or without low scarps, commonly termed "calderas" with the implication of incrementally fed volcanoes, but actually requiring huge volumes and areas of melt just below the surface that are appropriate for impact-melt constructs but not for volcanoes.

Still larger melt constructs, "tessera plateaus", are huge quasicircular pancakes 1000 to 2500 km in diameter. It appears to me that one of them flowed out from a ruptured 1400-km impact basin wherein the melt formed (Fig. 5; the area of this image is comparable to that of Africa). The other "tessera plateaus" share the distinctive surface characteristics of this one, as conventional interpreters correctly emphasize, although they assign all of them, including this one, to plumes. The continuous flow and spreading structures and the large slump-outs show that each was sluggishly mobile throughout its extent when it formed (e.g., Hamilton, 2005, fig. 15), and I presume they all formed from impacts. The megapancakes include this and another large upland, minimally pocked by mostly "pristine" impact craters, a lesser 1000-km circular pancake, and abundant remnants that underwent widely varied amounts of bombardment by large bolides—two such remnants are in Fig. 3—so these constructs also formed throughout the Hadean bombardment and were variably recycled by it. Amount of melt is a function of impact velocity as well as bolide size, and other apparent large impact basins, 2000–2500 km in diameter, on Venus have only very low melt constructs.

This interpretation predicts fractionation of "tessera" primarily from melts of, mostly, thick mafic protocrust, and hence a more felsic composition for capping differentiates than for typical Venusian surface. This is tentatively confirmed by emissivity of the nightside surface of Venus, as measured through the atmospheric-absorption near-infrared window at 1.02 μm by the spectrometer aboard the European Venus Express orbiting satellite. The emissivity correlates primarily with altitude, and hence ground temperature, but apparently is lower for tessera than for plains when this is factored in (Haus and Arnold, 2010). As this emissivity should increase with content of ferrous iron in surface rocks, they interpret the data to suggest that tessera surfaces indeed are more felsic than the planetary average.

Venus displays a few "rift zones" with small-offset normal faults, commonly attributed to extension by arching by plumes and illustrated by cartoon domes with unmentioned vertical exaggerations of 100:1 or so because the actual extremely gentle slopes allow almost no extension by doming. These minor rifts, and the swarms of fractures visible in many places (as in Figs. 2 and 4), may be products of torques generated as Venus rotated through its axis to move transient mass equators, reflecting new generations of impact-melt constructs and other impact mass redistributions, closer to the spin equator. The mass equator is shown by the black line in Fig. 1C.

The Venusian surface is dominated by lowland plains, through which project many other features. Convention deems the plains to be floored with flood basalt despite the lack of vent areas, while simultaneously claiming that the plains are pulled down dynamically by great sinking cold anti-plumes. I see instead oceanic sediments. Optical-scanner images by four Soviet landers on the plains all show horizontal thinly-platy rocks (images reproduced in Hamilton, 2005, fig. 21), unlike any basalt lavas, which presumably are fine-grained sediments metamorphosed to greenschist facies by the hot atmosphere. The sediments in some regions are too thin to cover many of the impact structures (Fig. 2). In other regions, sediments mostly cover area-saturating large craters, which show primarily as depressions into which the sediments are compacted (Fig. 3), and in still others thick sediments mask most craters. Sedimentary structures are widely visible in large-scale imagery (Fig. 6). Distributary channels (Fig. 7), geometrically like submarine turbidite channels (as contrarians Jones and Pickering, 2003, recognized), carried sediments from the highlands. Valleys erode some highland areas (as in Fig. 3), and appear to be of fluvial origin where optical stereo is possible with paired high-resolution images. I know of no likely continental shelves or coastal deltas, but multiple recessional shorelines can be inferred from the radar-bright horizontal lines ringing some projecting impact rims, and I infer evaporating, not stable, oceans. Solidification of the Venusian core and consequent loss of a magnetosphere shield may have resulted in desiccation as water molecules were dissociated by the charged particles of the solar wind.

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

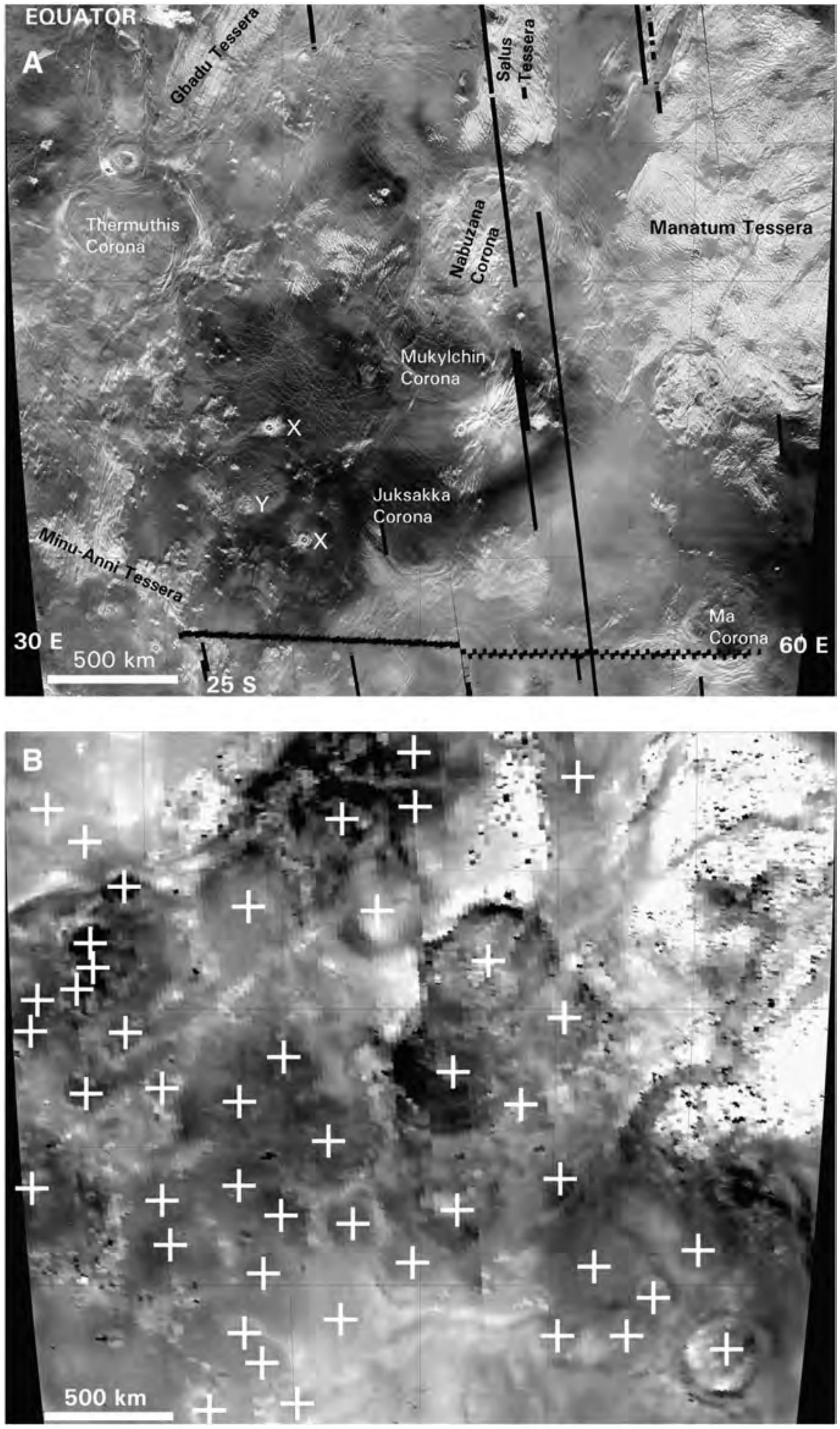


Fig. 3. Paired images of Venusian plains region saturated with impact craters, mostly overlain by thin sediments, and variably bombarded and eroded remnants of large impact-melt constructs. (A) Radar backscatter; (B) nadir radar altimetry, light = high, dark = low, total relief 4 km, but most of area is within 2 km. Many overlapping craters, maximum rim diameter 500 km, are marked by crosses in (B), but most are thinly covered by sediments compacted into them and are invisible in (A). The large conspicuous remnant of a "tessera plateau" (large impact-melt construct; compare with Fig. 5), light gray in northeast quadrants of both (A) and (B), is more sparsely pocked by craters than are plains, so was formed during the period recorded by all the craters marked by crosses; it is cut by sediment-floored river? valleys, most conspicuous in (B). A smaller "tessera" remnant (SW corner of A) is more heavily bombarded.

Polygonal faulting and low gentle-sided mud volcanoes are seen over vast areas (Fig. 6; also Hamilton, 2009). These dimensionally and geometrically resemble the polygonal faulting and mud volcanoes imaged in many marine sedimentary basins by modern close-spaced three-dimensional seismic-reflection surveys (e.g., Cartwright et al., 2007). Terrestrial and Venusian patterns of nested polygons within larger polygons are of similar sizes and shapes that are variously equidimensional, rectangular, linear, or curving. Terrestrial ones are due to compaction, fluid flow, and water expulsion in fine-grained sediments (Cartwright et al., 2007). Venusian dewatering presumably

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

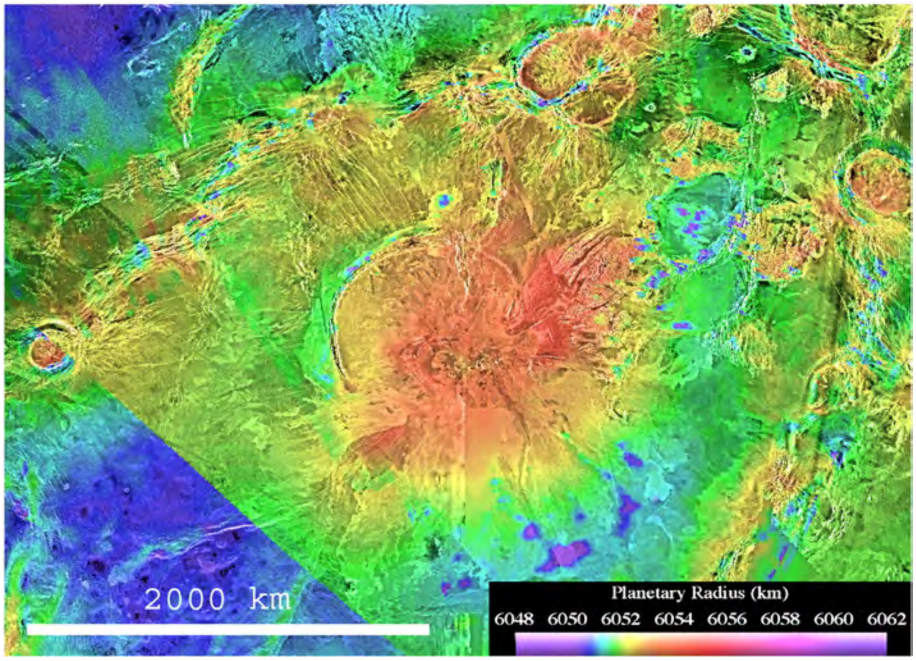


Fig. 4. Quetzalpetlatl impact basin and impact-melt "volcano", Venus. Sharp basin rim, 800 km in diameter, is exposed in west and northeast, and buried beneath outflow of the huge low melt construct elsewhere. The eccentric "volcano" rises a maximum of only 2.5 km above the rim, with slopes mostly <3°; a similarly eccentric ring syncline, ~1 km deep, is formed around the "volcano" and the west rim, and an ejecta apron is inferred to extend outward to a radius of ~1250 km from the center of the rimmed basin. Note the broad scale of the implied compensation by beam strength. The "volcano" shows no features suggestive of its terrestrial namesake, and appears both here and on detailed imagery to have spread as a single large mobile mass. Conventional Venusian specialists term this type of superposition of "volcano" and apparent impact basin a "volcano–corona hybrid", and infer plume origins for such pairs. Three "pristine" impact craters, 25 to 70 km in diameter, show as tiny bright rings, one just north of the main rim, the other 2 in the upper-right part of the view. All larger circular and quasi-circular features in view are conventionally attributed to plumes, whereas all appear to me to be impact structures and constructs. Color mismatch in lower left corner is a shift in datum and source. Altitude shown by color, radar backscatter brightness by shading. South-polar stereographic projection, 0° longitude vertical through center, north at top, center of image ~68°S.

records both lithostatic pressure and top-down heating after evaporation of standing water. Conventional reports consider liquid water impossible, and give conflicting endogenic explanations to the Venusian structures, assumed to be in basalt lavas, including columnar jointing 1000 to 10,000 times larger than in terrestrial lavas, and endogenic reheating by plumes. Conventional work designates the 100,000 or so small, round, low conical hills in the plains as "basaltic shield volcanoes", although they lack the dimensions, proportions, alignments, and other features expected of igneous origins, and are to me the mud volcanoes expected to accompany dewatering fine-grained sediments, which presumably were derived primarily from impact-comminuted debris.

No Venusian rocks have been dated. Analogy with the Moon, and with the analysis of Earth in Section 2, permits the inference that Venus had a thick mafic crust by ~4.5 Ga and that its heavily bombarded surface dates from about that time until ~3.9 Ga, after which only smaller bolides landed. Cratering and impact melting on the scale inferred here of course are incompatible with the undisturbed undulating shallow Moho assumed by conventional modelers (Section 4.2.2). Whether or not oceans existed before the last of the very large impacts is unclear, but hundreds of isolated small and midsize craters appear obviously water-worked (e.g., Fig. 6) and presumably record submarine impacts. Only a minority of these are on the official list of "pristine" impact structures so, in my terms, oceans were present long after 3.9 Ma. The existence of terrestrial seas is presently proved only after ~3.6 Ga, so perhaps Venus and Earth had analogous water-condensation histories. If the post-3.9 Ga falloff in small-bolide frequency was exponential (as can be argued for Earth from the abundance of impact spherules in Archean sections), then the Venusian oceans perhaps were gone by something like 3.0 or 2.5 Ga, and the small "pristine" impact craters are mostly younger than that.

4.3. Earth's crust, upper mantle, and Moho from 4.5 to 3.9 Ga

The Venusian history of deformation and magmatism by large bolides until ~3.9 Ga, as permissively dated by lunar analogy, should transfer to the Hadean Earth, the upper 100 km or more of which was in these terms broadly churned by large impacts, and underwent fractional crystallization in impact lakes up to ~2500 km in diameter, complexly superimposed on the products of primordial synaccretionary fractionation. The bombardment era is represented on Earth by U/Pb age determinations of inherited zircons in lower-crustal polycyclic gneisses and of detrital zircons in sediments presumably derived from them. The long post-3.9 Ga period of Archean near-solidus lower-crustal temperatures (Section 5.1) indicates the crust to have then been mobile internally, and presumably it was active also during the Hadean bombardment era, perhaps similarly generating capping TTG felsic crust while losing densified residual protocrust downward by delamination. Unlike Venus, flowage of terrestrial crust, both concurrent with and following the bombardment, tended to heal the great impact disruptions, and variably incorporated impact breccias and melt products. Some terrestrial Hadean zircons likely crystallized in impact fractionates, and others were reset by shock; future analyses presumably will examine options other than hypothetical plate tectonics. The static surfaces of less mobile Venus and Mars show that no such healing occurred on them, and they did not progress to the pervasive mobility and magmatism of Earth's Archean crust (Section 5) and, beyond that, ultimately to plate tectonics.

Much protocrustal material may have been lost to space by impact erosion (e.g., O'Neill and Palme, 2008), and much magmatic and physical remixing of crust and uppermost mantle presumably occurred, although the initial thickness of protocrust is unknown. Much of the mafic protocrust was still in place by 3.9 Ga (Section 5), and Earth's

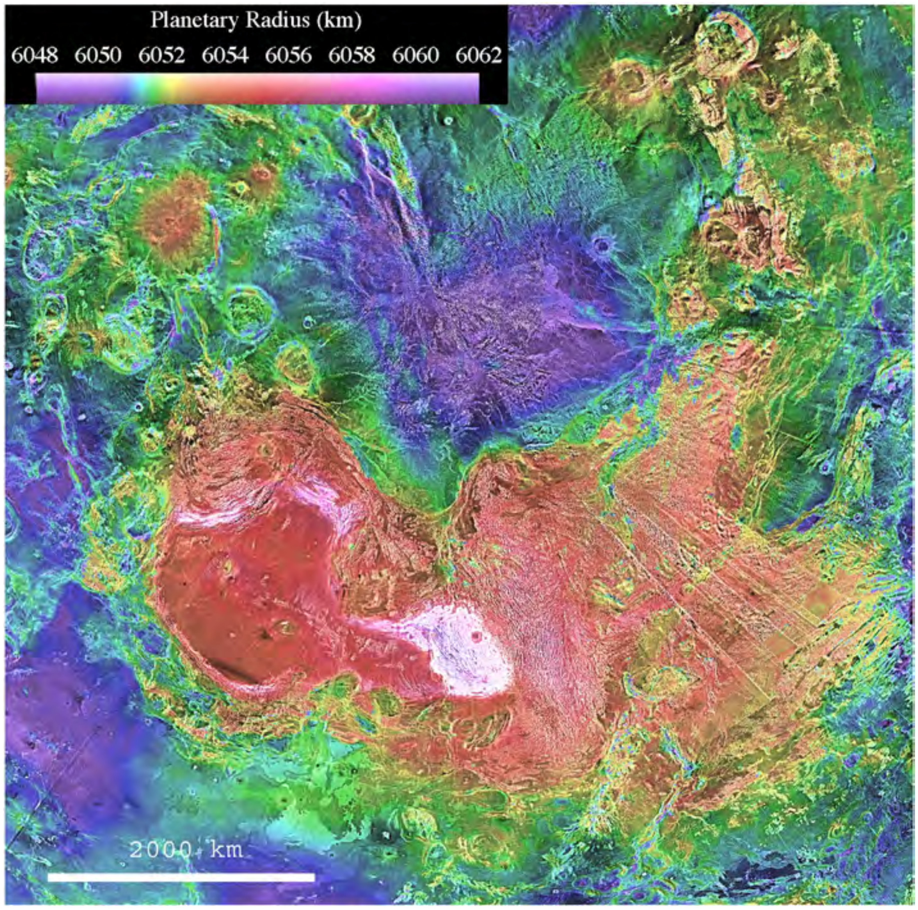


Fig. 5. Ishtar Terra upland, Venus, is a composite of three large "tessera plateaus" (uplands across lower half of image), which to me are large impact-melt constructs. The left one flowed out from a breached impact basin 1400 km in diameter. The basin rim contained the melt on the west and south, but melt broke out the north and east rims and formed great pancake flows, which show the characteristic viscous-flow structures of "tessera". The rim stands 2 km above the enclosed lava-filled interior remnant (dark red Lakshmi Planum) of the great melt lake. Many small "pristine" craters are within the view but mostly are invisible at this scale; the largest is in the blue-plain area toward the upper right from the center of the image. The many conspicuous larger circular structures, 100–500 km in diameter plus much larger Lakshmi, are to me impact craters and basins, but in mainline reports are all regarded as endogenic plume constructs. Altitude shown by color, backscatter brightness by shading. Radar-white area below center is Maxwell Montes, which reaches 11 km above mean planetary radius, the highest point on Venus; the large magma slump-out to the north of it may be related to its rise. North-polar stereographic projection; vertical midline is longitude 0° (bottom)–180° (top); north pole is 1/3 of way down from top of image. Radial streaks in right-central region mark flight strips.

Moho of that time no longer exists, for it was presumably at the base of the protocrust. The proto-Moho still had far to evolve to become the subhorizontal boundary we now see between cratonic TTG and dunite.

Large dated masses of quasi-uniform granitoid rocks go back only to ~3.8 Ga so far as I am aware. Older igneous zircons occur as xenocrysts in polycyclic gneisses with non-understood histories, and in small bits of crustal-melt products of undefined prior sources. Non-detrital pre-3.6 Ga zircons have come almost entirely from lower-crustal gneisses, wherein Zr saturation was better maintained than in the often hotter and dryer shallow melts. The problems that Hadean rocks present are illustrated by the outcrops shown in Fig. 8, from the Acasta Gneiss of northwest Canada, which yielded the first zircon U/Pb determinations of 4.0 Ga zircons, and subsequently yielded xenocrysts with apparent ages to 4.2 Ga. Diverse leucosomes in these multiply deformed rocks contain 400 m.y. of apparently igneous zircons, so this lower-crust terrain was continuously or repeatedly near solidus temperatures during that period. Whether those leucosomes were mobilized locally or were introduced, and if the latter how and whence, is unclear in these multiply deformed rocks. Note that plate tectonics could not have operated with such mobile crust.

Isotopic and inclusion information on ancient detrital zircons, with U/Pb ages spanning much of the Hadean 600 m.y., has been published in many papers by Mark Harrison and associates (e.g., Harrison, 2009; Hopkins et al., 2010, 2012), who argue that inclusions and isotopes in some of the zircons require water oceans and plate tectonics. Rasmussen et al. (2011, 2012) also studied the inclusions, and presented data indicating them to be products of subsequent low-grade metamorphism, and not of pre-3.9 Ga conditions of primary crystallization. Support for the Rasmussen argument, unmentioned by either group, is the fact that ancient lead loss in zircon concordia plots is now perceived as an offset down along concordia, and hence open-system alteration cannot be precluded just by apparent concordance in U/Pb ages (Section 2.2). Factors compatible with the Rasmussen opinion will be obvious also in other sections of this essay.

5. Evolution of Earth's Archean crust and Moho, 3.9–2.5 Ga

Misplaced faith in both uniformitarianism and mythology has led to a literature dominated by assumptions that a combination of plate tectonics and interacting plumes produced Archean crust. Arguments against the operation of deep-mantle plumes of any age on any terrestrial planet were a major topic of Sections 2 and 4. Much of the rest of this essay will stress the inapplicability of plate tectonics to any but the youngest of Precambrian rocks.

Archean crust was internally mobile throughout most of Archean time, which distinguishes it from Proterozoic and Phanerozoic crust and is alone enough to demonstrate that plate tectonics could not have then operated. The subhorizontal sharp Moho that characterizes

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

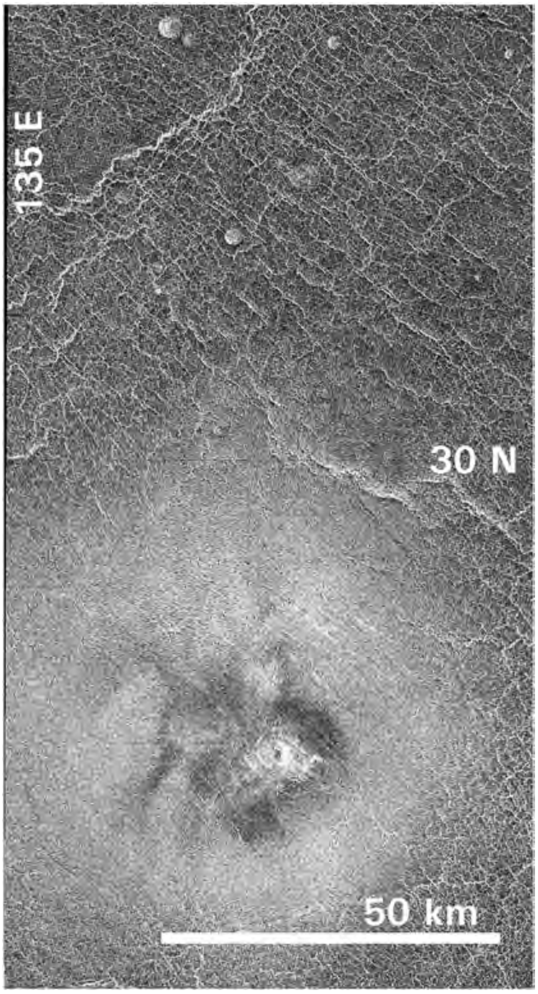


Fig. 6. Radar-backscatter image of ancient-ocean features of Venusian plains. Central-peak impact structure, rim diameter 35 km, in south was much reworked, and likely formed, underwater. Polygonal faults, formed by dewatering of smooth radar-dark sediments, overprint reworked impact apron as well as plains sediments. Scattered small circular structures in north are low gentle-slopes mud volcanoes, such as commonly accompany polygonal faulting on Earth.

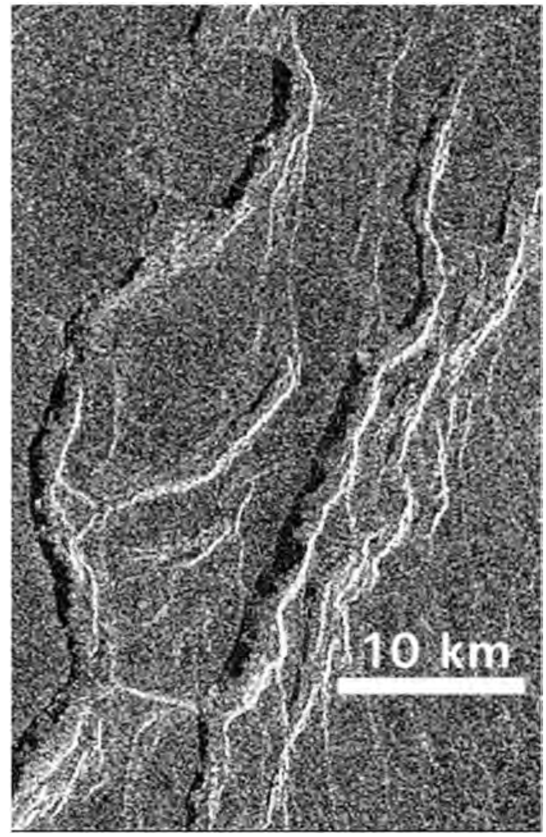


Fig. 7. Flat-floored submarine turbidite-distributary channels near distal end of set fanning northeast from Atla Regio upland, 130 km distant, into plains. Illuminated from west: east banks are bright lines, whereas shadows mark steep west banks. Younger anastomosing channels were cut progressively deeper. Center of image ~23.2°N, 198.3°E.

Archean cratons is a product of that crustal mobility. The following descriptions of Archean complexes are mostly abbreviated from prior papers (Hamilton, 2007a, 2011, and to a lesser extent earlier reports back to 1998) that contain many more details, discussions, illustrations, and references.

The Moho beneath nearly all Archean cratons—those regions whose crust has been minimally deformed and recycled during the past 2.5 b.y.—differs strikingly from that beneath crust stabilized subsequently. The excellent global review of the cratonic Moho by Abbott and Mooney in this volume provides documentation and references; Mooney and his associates have themselves made many of the seismologic determinations. (My explanation for evolution of this Moho differs greatly, however, from the plumology advocated by Abbott and Mooney, at least in the initially submitted draft of their paper.) The sub-Archean Moho is both much flatter and sharper than that beneath most subsequently stabilized crust, and its depth is mostly between 34 and 40 km. Archean crust commonly is dominated to its base by felsic rocks, known in outcrop to be typically tonalite, trondhjemite, and granodiorite (TTG) plus subordinate amphibolite, and in some lower crust their equivalents in granulite facies. The TTG are in seismically sharp contact with highly magnesian mantle rocks, dominantly the $Fo_{>92}$ dunites discussed in Section 3. Archean deep crust contains much less mafic material than does most younger continental crust, and lacks the thick mafic underplates also common in younger crust.

5.1. Geologic description

The present surface of most Archean cratons exposes granite and greenstone upper crust, and commonly records only 5 or 10 km of erosion even for tracts as old as 3.5 Ga. Deeper exposures occur primarily where post-Archean deformation led to deeper erosion, as at the extensional margins of Proterozoic orogenic terrains and Phanerozoic rifts. Archean lower crust is dominated by TTG gneisses. Extensive zircon dating shows that magmatic augmentation in gneisses in single areas often occurred over hundreds of millions of years, even a billion years, with continuous or frequent mobility demonstrated during those long periods. Igneous zircons in polycyclic TTG gneisses reach at least 4.0 Ga, and xenocrystic and detrital zircons of unproved provenance are known back to almost 4.4 Ga (Section 4.3).

The basic architecture of granite and greenstone terrains, in their simple vertical-tectonics regime, has long been recognized as consisting of granitoid domes that rose into supracrustal lavas and sediments as the supracrustal rocks sank in synforms between the domes (e.g., Hickman, 1983; Macgregor, 1951). The rising domes and sinking supracrustals righted the density inversions caused by crystallization of thick dense lavas above mobile TTG, and the domes consist of both ancient TTG gneisses and younger magmatic rocks, which include granodiorite and monzogranite melted from TTG. Much of the Neoarchean Zimbabwe craton, where the style was first documented by Macgregor, and the northeast Mesoarchean part of the Pilbara craton of Australia (Fig. 9), Hickman's classic area, exemplify nearly pure vertical tectonism, Domes of ancient rocks, as opposed to new magmatites, often took many millions of years to fully rise, in some cases even

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

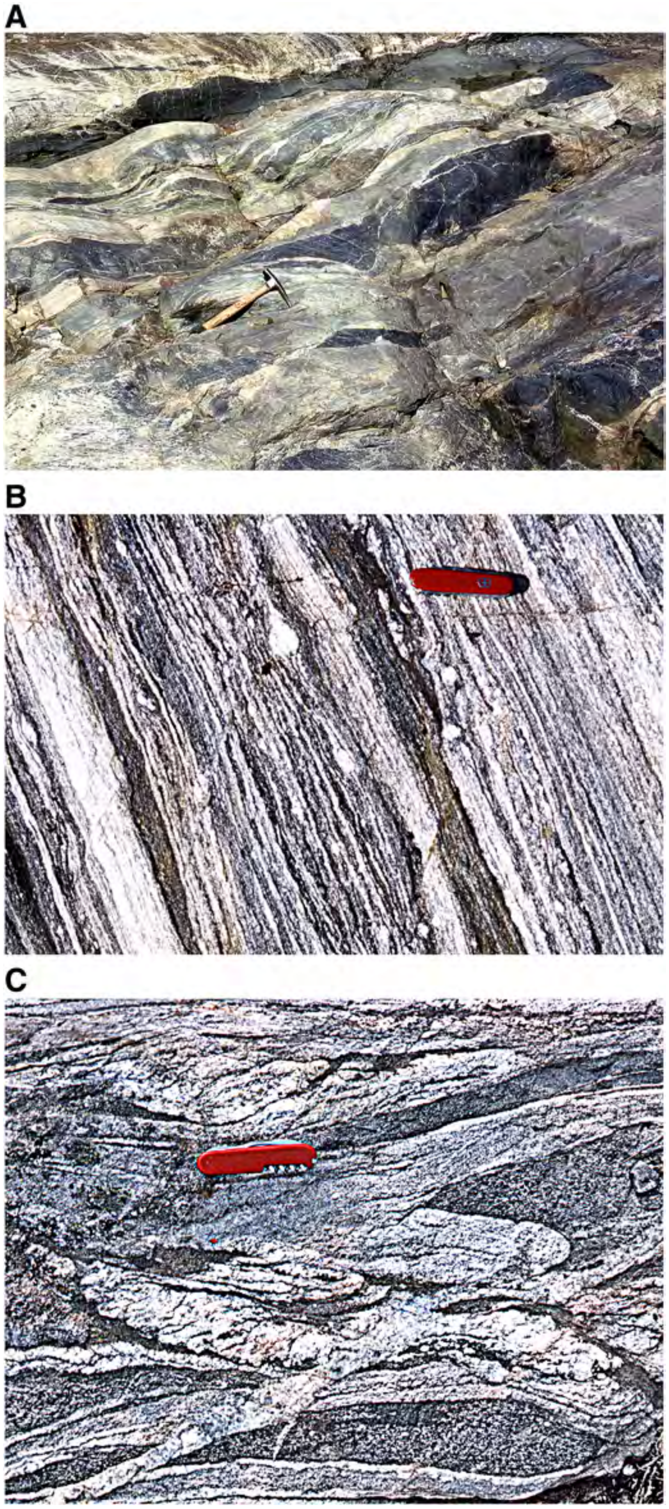


Fig. 8. Polycyclic gneisses with 3.6–4.0 Ga igneous zircons in leucosomes and rare 4.1–4.2 Ga xenocrysts, northwest border of Archean Slave Craton, Acasta River, Northwest Territories, Canada. (A) Multiply deformed tonalitic and amphibolitic gneisses. A mafic dike is isoclinally folded (hinge in upper right corner) and disrupted. (B) Amphibolite facies tonalitic and more mafic mylonitic gneiss, with feldspar porphyroclasts (Bowring's "porphyritic granodiorite gneiss"). (C) Contorted mylonitic gneiss, arrested in transposition toward new foliation. Age determinations by S.A. Bowring and associates (e.g., Bowring et al., 1989) and T. Iizuka and associates (e.g., Iizuka et al., 2007). Photographs by author.

several hundred million years, and the synformal sediments that sank between them display incremental to major unconformities spanning long periods of sedimentation, volcanism, and deformation, but domes of new magma must have risen quickly. The supracrustals formed as subregional sheets, often initially 8 or 10 km thick, wherever stratigraphy and geochronology have been worked out, and not as primary narrow "belts", but are preserved primarily in downfolds between domes. Supracrustals typically are moderately contact-metamorphosed, and moderately to severely deformed, close to the domes, but little deformed, and metamorphosed only at lower greenschist or prehnite–pumpellyite facies, in the interiors of broad synclines. Stretching lineations are dominantly down-dip. A new sheet-stratigraphic Neoarchean and Paleoproterozoic supracrustal section was deposited across the dome-and-keel terrain, and was itself involved in continued doming and sagging in the northern part of Fig. 9, but in the southern part is still coherent and little deformed; south of this view, the section is involved in limited doming. A correlative, and perhaps originally contiguous, regional sheet in South Africa is similarly in part preserved more or less intact, and in part deformed by domes.

All granite and greenstone terrains display rising domiform batholiths, but in most preserved cratons the vertical tectonism occurred simultaneously with subhorizontal spreading and extension of the lower crust even as it also supplied the rising domes between which the greenstones sank, and the proportions of vertical and horizontal deformation vary widely. The brittler upper crust was carried along, giving the rising domes a regional elongation or even shearing them apart, dragging out the rising domes and complexly disrupting the sinking supracrustals. Both subvertical dome-and-keel and subhorizontal stretching deformations are products of the high mobility of the lower crust, enabled by the shallow concentration of high radioactivity. The mostly-Neoarchean Yilgarn craton, and the northwest part of the Mesoarchean Pilbara craton, of Australia, and the mostly-Neoarchean Superior craton of Canada, are of this composite type. The paired geologic and magnetic maps of much of the Superior craton (Fig. 10) illustrate all gradations from dominantly vertical-tectonic domes-and-keels to severe horizontal disruption. The proportion of westward lower crustal flow apparently increased westward. Shoufa Lin and his associates (Lin and Beakhouse, 2013, and references therein) have been particularly productive of structural and petrologic studies demonstrating prolonged synchroneity and interaction of vertical doming and horizontal shearing and stretching in the Ontario part of the area illustrated. Domes elongated as they rose and enlarged, and the complementary downfolds of supracrustal rocks were sheared out by the less pervasive deformation of the upper crust above the more smoothly flowing lower crust. The sheared-out supracrustals commonly are referred to as "belts", which are features of deformation, not primary deposition, and the disrupted supracrustals also display subregional sheet stratigraphy where sequences have been resolved with detailed work. The northwest edge of the exposed craton is of lower-crustal Archean granulites, which produce a distinctive high-frequency magnetic pattern, exposed by erosion consequent on extension at the margin of the Paleoproterozoic Trans-Hudson orogen, which consists of metamorphosed sedimentary and volcanic rocks that lap on to Archean cratons on all sides. Trans-Hudson supracrustal rocks were at least in substantial part, and arguably entirely, deposited on top of deeply subsided Archean crust, and Trans-Hudson plutonic rocks were mobilized mostly from Paleoproteozoic metasedimentary rocks and Archean basement rocks.

The only depositional bases ever seen beneath Archean supracrustal successions anywhere are with older TTG or older granite-and-greenstone terrains. Clastic sediments derived from the older rocks always intervene, although they can vary in thickness from a few meters to several kilometers. All Archean stratigraphic sections that include mafic and ultramafic lavas, and whose original bases are exposed, depositionally overlie continental crust. No ophiolites, oceanic mafic igneous rocks erupted atop oceanic mantle, or other bits of oceanic mantle, have ever been found. Geochronologies show the basement TTGs, and detrital grains in the sediments lying directly on them, to be older than the overlying greenstone sections of basalt, komatiite, and other sediments. Although depositional contact have been widely obliterated

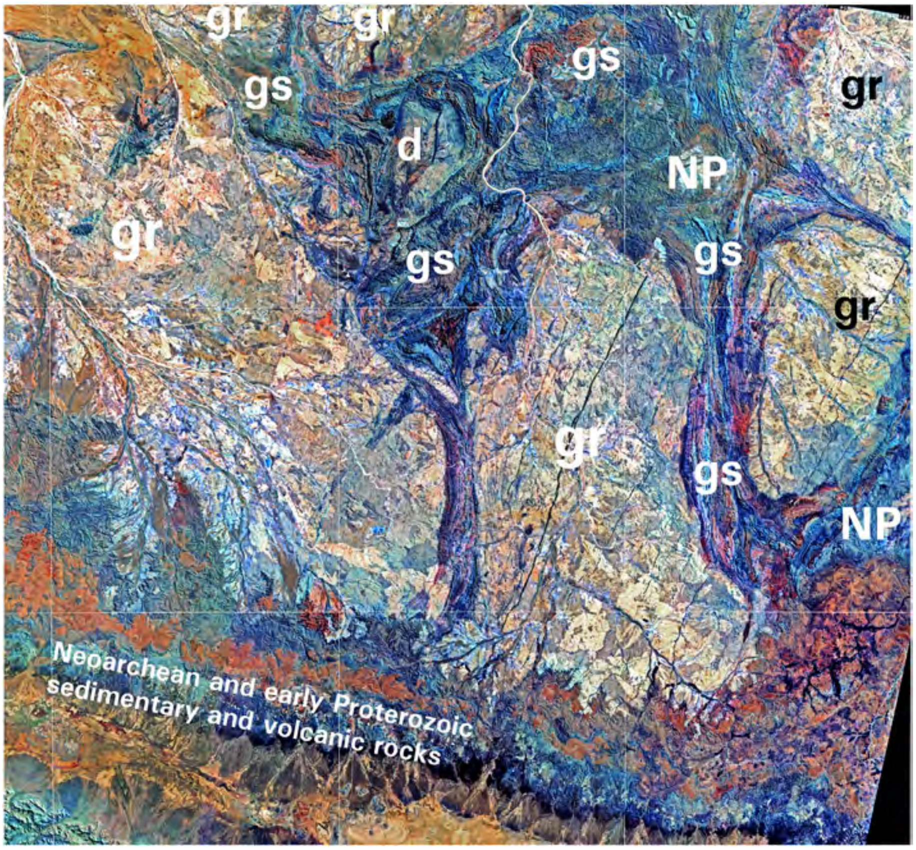


Fig. 9. Landsat satellite optical-scanner image of East Pilbara Archean craton, Western Australia. Northern two-thirds is granite-and-greenstone terrain, consisting of diapiric batholiths (pale yellow; gr; also small dome; d) of lower-crust TTG plus granite magmas that rose as supracrustal rocks (green, blue, and purple in image; mostly greenstones, 3.5–2.9 Ga, with regional sheet stratigraphy; gs) sank between them in synforms, recording density-driven vertical tectonics. Younger sedimentary and volcanic rocks, 2.8–2.2 Ga, the start of another greenstone cycle, maintain sheet stratigraphy and are little deformed in south of this scene, but participated in late-stage synclinal sinking in the north (NP); they also are disrupted by moderate diapiric doming south of this view. Diapiric rocks include gneisses at least as old as 3.7 Ga, and rose from ~3.4 to ~2.4 Ga. Area is approximately bounded by Latitudes 21.0 and 22.5 S, and Longitudes 118.4 and 120.0 E, and is about 150 km wide. False colors: blue is assigned to Band 2, visible green; green to 4, near infrared; and red to 7, mid-infrared.
Image provided by CRA Exploration Pty., Ltd.

where basement rocks have been remobilized as diapiric domes, there are, for example, at least four well-documented localities of TTG basement overlain depositionally by thin sections of derivative feldspathic and quartzose metasandstones and conglomerates, overlain in turn by thick sections of mafic lavas, in just the southwest part of the area of Fig. 10.

Supracrustal sections thus begin with clastic sediments, and are overlain by thick sections of submarine mafic lavas, which commonly are intercalated with subordinate ultramafic lavas and intrusive sheets (komatiites and their kin), all with compositions strikingly unlike modern igneous rocks. Higher sections typically are dominated by intercalated mafic and felsic extrusives, the latter erupted from rising batholithic domes. Often these supracrustals in turn are overlain unconformably by thick sections of clastic strata, eroded from emergent batholithic domes. The supracrustals range in age globally from 3.6 to 2.0 Ga (the style continued in some regions into the early Proterozoic), whereas TTG is preserved in outcrop as rocks at least as old as 4.0 Ga. Common assertions that Archean pillow basalts and komatiites are equivalent to ophiolites, and represent oceanic crust, are unsupported by evidence.

Lower-crustal gneisses are rarely mineralized and have received little structural study. One exception is in the Kapuskasing Paleoproterozoic crustal-scale thrust-fault uplift of Archean lower crustal rocks in the Superior craton, just east of the south part of Fig. 10. There, strong stretching lineations (Fig. 11) are parallel to the long dimensions of large diapiric domes in the upper crust, in accord with the inference that the upper-crust elongation is a product of lower-crust flow.

Another pair of magnetic and geologic maps (Hamilton, 2007a, fig. 22) illustrate vertically and horizontally disrupted upper-crustal granites and greenstones in part of the Yilgarn Craton of southwest Australia, at a larger scale than Fig. 10. The first-vertical-derivative magnetic map of this more detailed pair shows many individual stratal units within the highly deformed supracrustals, and also clearly depicts broadly gradational intensities of lateral shearing of the rising batholiths. The broad shear zones are schematically shown as faults by geologic mappers in this poorly exposed region.

Most Archean rocks are distinctly different in composition from Phanerozoic rocks that share the same broad rock names. Archean TTG is mostly higher in K, Na, and Si, and lower in Mg and Ca; has much steeper rare-earth-element patterns; and is lower in transition-group elements. Archean tholeiites differ from modern tholeiites in both arc and sea-floor settings in having higher Fe/Mg and lower Al/(Fe + Mg). And so on.

The oldest proved mafic dikes in, or mafic volcanic rocks erupted above, TTG are ~3.6 Ga. This is also the maximum proved age of waterlaid sedimentary or volcanic rocks. If this is the true age limit, and not an illusion from non-preservation or non-discovery, then there may have been no hydrosphere before 3.6 Ga, and instead a supergreenhouse atmosphere of $H_2O + CO_2$, and TTG gneisses formed before 3.6 Ga may have been so hot and low in density that mafic melts could not rise through them. Claims have been made for the presence of highly deformed and metamorphosed Archean supracrustals as old as 3.8 Ga, on the basis of lenses of mylonitized TTG now structurally concordant within them and assumed to have been intrusive, as in the

Isua supracrustals of Greenland and Nuvvuagittuq/Porpoise Cove supracrustals of Quebec. I have discussed (Hamilton, 2007a, 2011) such claims as likely misinterpreting as mylonitized intrusive dikes what are instead structural intercalations of basement TTG, known in those particular complexes to be present in adjacent domes, sheared into strongly deformed and metamorphosed stratigraphically low supracrustals, an option that has not been investigated in the field. If I am wrong, then the oldest known supracrustals are a little older than the 3.6 Ga I perceive.

Fig. 11. Flattened and lineated megacrystic anorthositic gabbro, in lower crust of Superior Craton, raised in Paleoroterozoic Kapuskasing uplift, Ontario. The curved outcrop shows a vertical section at lower right, and a horizontal surface at top. The strong stretching lineation is parallel to the elongation direction of deformed upper-crustal diapiric batholiths. Plagioclase is very calcic; primary orthopyroxene has been mostly replaced by clinopyroxene and hornblende; mineralogy permits inference that original rock fractionated in a magma lake of impact origin.
Photograph by author.

Isolated seismic-reflection profiles have been made along irregular traverses across parts of Archean cratons in Canada, Australia, and South Africa. I showed and evaluated a Canadian example in Hamilton (2007a), and an Australian one in Hamilton (2011). The non-cylindrical three-dimensional complexity of upper-crust granite-and-greenstone terrains requires that any "upper crust" time interval not depicted as transparent must be cluttered with out-of-section reflectors, and the only continuous inclined reflectors in the profiles appear to me to be sideswipes from known long and thick vertical Proterozoic mafic dikes that trend at low angles to the traverses and at appropriate distances. However, the profiles in conventional reports are processed and interpreted with the assumption that almost all reflectors, including those from dikes(?), are in vertical planes beneath the traverses. The processing maximizes illusory continuities of reflectors, and migration in time is used to remove crossings of what may be unrelated out-of-section reflectors. Profiles are enormously over-interpreted by assuming all conceivable inclined reflectors to be in-section and to record structures imagined to be compatible with convergent and divergent plate tectonics, without comparison with profiles from known modern settings, and commonly with little regard for surface geologic constraints. Despite the severe northward stretching of the Yilgarn craton in Australia, for example, its minimally informative profiles are interpreted to record intricate east–west imbrication by desired convergent-plate thrust faulting, followed by extension along the same structures used as normal faults to back off with desired rifting the conjectured compressional vertical offsets, which are precluded by metamorphic petrobarometry.

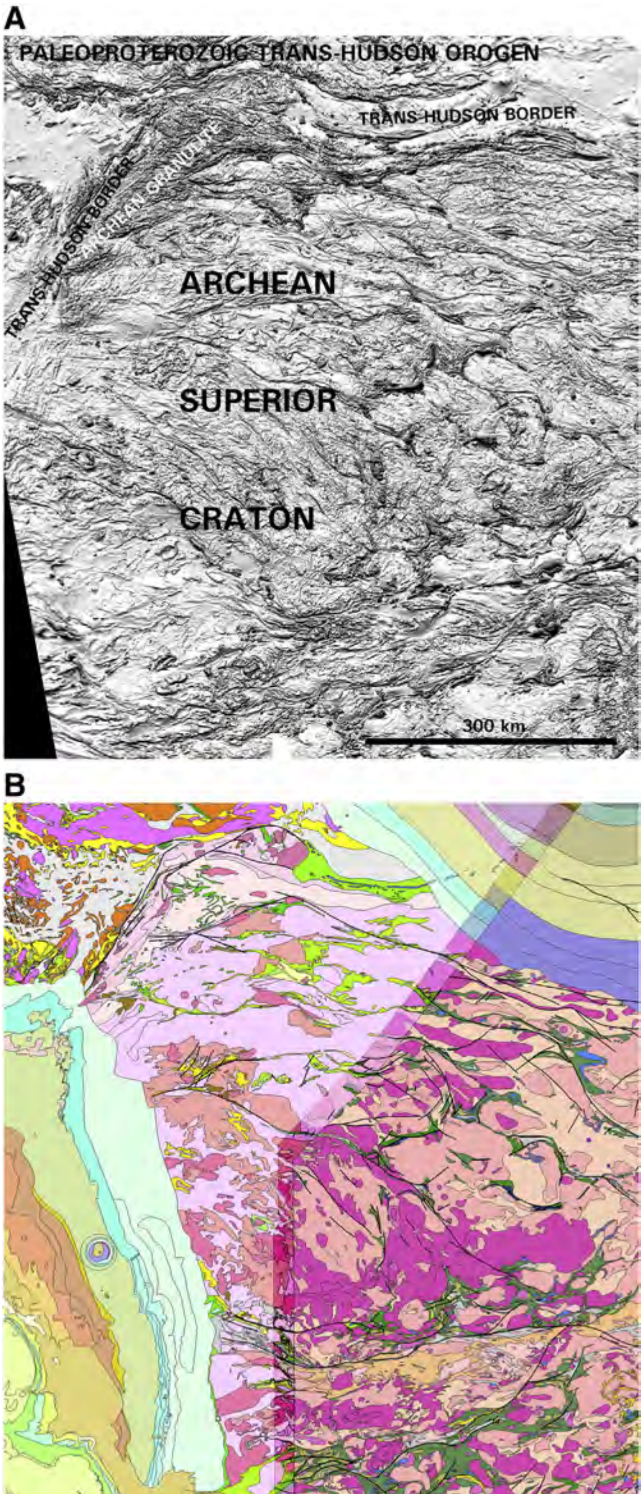


Fig. 10. Magnetic and geologic maps of northwestern Superior Craton, Canada, illustrating varying disruption of upper crust by vertical-tectonics domes and keels that formed simultaneously with flattening and extending of underlying mobile lower crust. Border between Manitoba (left) and Ontario is at right edge of color change in (B). (A) Shaded-relief map of crustal component of total aeromagnetic field anomalies. Archean craton is truncated by Paleoproterozoic rift and Trans-Hudson Orogen in northwest and north. (B) Geologic map. Subhorizontal thin Phanerozoic strata are in pastel shades in northeast and southwest; magnetic map shows Precambrian geology through this cover. Archean rocks in Ontario: pale pink, granitic rocks; red, gneiss; olive green, mostly metavolcanic rocks; gray, and pale yellow, mostly metasedimentary rocks. Archean rocks in Manitoba: pale pink, granitic rocks; pink, gneisses; green, mostly metavolcanic rocks. Dome-and-keel vertical-tectonics geology is conspicuous in east-central part of area, and in parts of southern third of area, but elsewhere is mostly disrupted. Maps show approximately the same area, and have corners, clockwise from upper left, at about 56.6°N/100.7°W, 56.8°N/88.6°W, 49.0°N/89.5°W, and 49.0°N/97.3°W.
Maps provided by Geological Survey of Canada.

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

Special mention of southwest Greenland is appropriate because one of its domes rimmed by greenstones, the Isua complex, has been the site of intensive geochemical work. This has provided much valuable information; a new example is the demonstration that Mesoarchean dikes have ^{142}Nd contents (products of short-lived radioactive ^{146}Sm) that preclude direct extraction from mantle rocks and instead fit derivation from a mafic source (protocrust?) that was separated from the mantle as early as 4.5 Ga (Rizo et al., 2012). However, the Isua literature also contains many unique-to-Greenland claims that are based on dubious local assumptions, on some of which I commented in Hamilton (2007a, 2007d). Regional reconnaissance mapping, mostly done decades ago and often by inexperienced students, showed typical Archean domes rimmed by infolded greenstones, with high ratios of vertical to horizontal tectonism. These domes, which include the Isua complex, are present where appropriate upper-crustal levels are preserved, although most of this region, which is in the shoulder uplift of the Early Cretaceous Baffin Bay rift, has been eroded into lower-crustal TTG gneisses. Several depositional contacts of greenstone sections on ancient TTG were well documented. The whole was interpreted, however, in isolation from detailed geologic mapping then progressing in other Archean cratons, primarily in terms of nappe tectonics. In the current era, which has been dominated by analysis of Isua specimens assigned to plate-tectonic settings, with little or no geologic input, this evolved into assumptions of stacks of rootless megathrusts produced by plate convergence. The additional assumption that most Isua greenstones are markedly older than is required by firm dating has spawned further dubious derivatives.

5.2. Relation of present crust to vanished mafic protocrust

Archean TTG crust is readily explained as produced by partial melting of a thick syn-accretional mafic protocrust. Most Archean TTG is quite different from Phanerozoic rocks given the same names, as noted above, and the chemistry of the TTG that dominates Archean crust, integrated with experimental and theoretical petrology, requires it to have been derived mostly by partial melting, at depths on the order of 50 km, of slightly hydrous mafic rock, with much garnet left in the residue (e.g., Hoffmann et al., 2011; Moyen and Martin, 2012; Zhang et al., 2013), or by recycling of earlier TTG crust that in turn had such a source. Phase petrology precludes direct derivation of either ancient or modern TTG from mantle rocks, or passage of TTG magma through mantle rocks. No adequate residual mafic source for the Archean rocks is now present either within the TTG crust or between it and the top of the dunitic mantle. No TTG melt could have been derived from, or have risen through, such dunite: the source has disappeared deeper into the mantle. Garnet-rich mafic granulites are minor components of exposed Archean deep crust and perhaps include bits of such protocrust residues (Fig. 12). Subcratonic mantle is dominated by magnesian olivine that is lower in density than would have been any garnet-rich protocrust residual after removal of TTG (Section 3), so any such residual protocrust was gravitationally unstable above hot dunite, and should have sunk to its neutral-density level. Generation of TTG continued intermittently until all protocrust had become densified and sunken residues.

The mafic rocks of greenstone belts—basaltic, and subordinate ultramafic and intermediate, lavas and shallow intrusives, none of them compositionally like their modern namesakes in either major elements or stratigraphic or structural associations—in my terms also owe their origin to protocrust. Some were more complete melts of protocrust than was TTG, and some may be products of interactions of remelted sunken protocrust with depleted mantle rocks.

The widely applied geochemical concepts of model ages, times of separation of melts from the mantle, "epsilons", and derivation of "juvenile" melts from the mantle, mostly based on systematics of mother/daughter Sm/Nd and Lu/Hf isotopes, are circular rationales extrapolated from the assumption of a slowly depleting upper mantle and of direct derivation of most igneous rocks from it. This

A

B

C

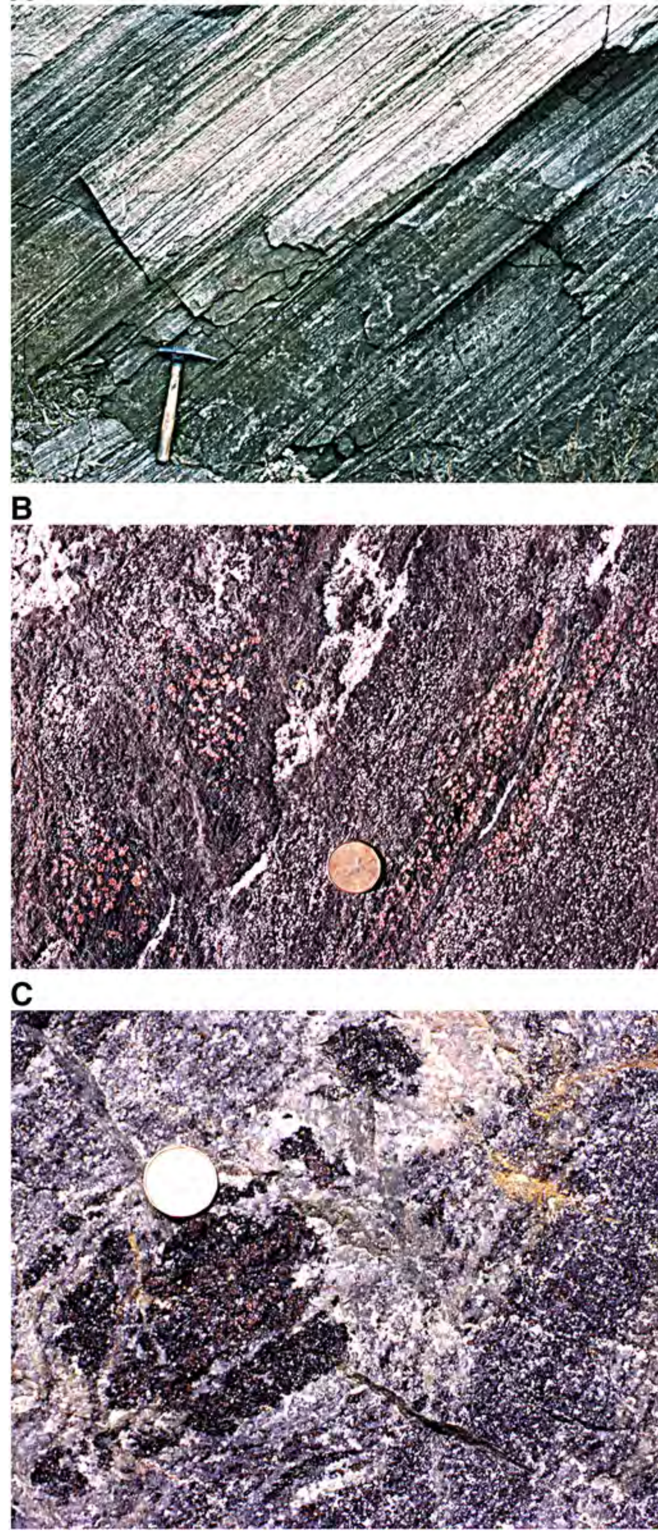


Fig. 12. Rocks of near-basal felsic Archean crust, in raised southeast edge of Kapuskasing uplift. (A) Straight gneiss, now hornblende tonalite and amphibolite with relict garnet, retrograded from granulite-facies mylonite. (B) Relicts of garnet-rich mafic garnet–clinopyroxene granulite in retrograde amphibolite ± clinopyroxene. (C) Garnet–clinopyroxene granulite (red and black) and garnet–clinopyroxene amphibolite retrograded from it (dark, on right), both being assimilated into tonalite with relict garnet. The garnet-rich granulites in (B) and (C) may be xenoliths of the residual protocrust from which TTG was derived by partial melting. Coin is 27 mm in diameter. Photographs by author.

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

assumption cannot explain, in phase-petrologic terms, generation of the extremely magnesian dunite that forms most sub-cratonic high mantle, and it is diametrically opposite to arguments here that this severely depleted mantle was produced by synaccretionary fractionation. An early-depleted dunitic upper mantle could not have contained the Sm–Nd and Lu–Hf quantities postulated by model-age and related assumptions. Contents of Lu and Hf in upper-mantle xenoliths are negligible in olivine, low to very low in orthopyroxene, and important in garnet and clinopyroxene (e.g., Ionov et al., 2005). In my terms, the garnet and clinopyroxene, which cannot have formed in equilibrium with the magnesian olivine with which they now occur, and their contained Sm, Nd, Lu, and Hf, represent re-enrichment of the upper mantle by sunken derivatives of ancient protocrust (Section 3). Insofar as model ages and "juvenile" designations of either mafic or felsic Archean rocks have any validity, they relate to time of extraction by partial melting of protocrust, not of mantle. For example, the Hf-isotope data from TTGs cited in support of origins from innumerable plumes from unfractionated lower mantle by Guitreau et al. (2012) are explicable in a plumeless Earth as indicating an origin in protocrust.

Isotopic evidence for just such derivation from synaccretionary protocrust, not directly from the mantle, is increasingly recognized by some geochemists. Thus, zircons in TTG and derivative quartzite, and associated amphibolite, in northern Quebec are dated as crystallized ~3.8 Ga, but display Lu/Hf and Sm/Nd systematics requiring origins in a mafic source that separated from the mantle ~4.4 or 4.5 Ga (Cates et al., 2013; Guitreau et al., 2013; see also O'Neil et al., 2012). Similar complex isotope systematics of southwest Greenland Paleoarchean tonalites are consistent with their derivation from a much older mafic protocrust (Amelin et al., 2011). Rizo et al. (2012) were cited in Section 5.1 for an analogous demonstration.

5.3. Crustal mobility

The common subhorizontal Moho, shallow erosion, and geology of Archean cratons all show that Archean crust was too hot and mobile to form internally rigid plates or to support mountains, that gravitational spreading maintained semiconstant thickness of cratonic crust, and that synchronous deformation of the widely exposed more brittle upper crust was produced by combinations of righting of density inversions due to crystallization of thick sections of mafic lavas above TTG, and of drag on subjacent TTG lower crust that was flattening and elongating. This prolonged behavior requires a continuously hotter substrate than that typical of any subsequent geologic time. The insulating character of crust shallower and cooler than the brittle–ductile transition (Section 2.1), and the then much higher radioactive heat productivity of TTG, explain this observed behavior. Despite the common assumption by specialists that Archean geology must be explained by plate tectonics, the structural geology and geochronology of both upper and lower Archean crust shows that internally rigid plates did not exist and hence that plate tectonics is precluded by definition. The lack of any indicators for plate interactions is discussed in Section 5.4.

What positive or negative loads drove the gravitational spreading of Archean crust? Uneven generation of TTG from protocrust and of densification and delamination of protocrust likely were important, as also was smoothing out the products of impact deformation and magmatism. Torques as the mass equator, changed by impact or internal processes including flowing crust, migrated toward the spin equator may have contributed. Spreading of continental TTG toward and over oceanic crust of course would suffice, but there is no preserved evidence for the presence of Archean lithospheric oceans.

Evidence for the spreading of Archean lower crust through crater-filling impact-melt constructs, both Hadean and Archean, may be recorded in many TTG gneiss terrains by contorted and dismembered layered igneous complexes, often large, wherefrom anorthosites are the most-studied rocks (e.g., Fig. 11). These contain very calcic plagioclase, typically ~An_{80}. Although widely assumed to have fractionated from endogenic melts, the complexes consist of fractionates that could have crystallized in magma lakes formed by impact melts of basaltic or TTG compositions. Layered calcic-plagioclase anorthosite, leucogabbro, gabbro and norite, pyroxenite, and dunite are associated—typical products of known fractionated magma lakes. The An content of plagioclase decreases markedly with increasing pressure of crystallization from water-poor mafic aluminous melts. Near-liquidus plagioclase in two noritic compositions studied experimentally by Longhi et al. (1993) was ~$An_{60–80}$ at 1 bar, but only ~$An_{40–65}$ at 10 kbar. Archean anorthosites are very calcic, likely crystallized at shallow depths, and are out of place in the deep-seated ductile gneisses where they commonly are now found. (The anorthosites common in much deep Proterozoic crust are less calcic, typically $An_{40–70}$.) The capping felsic fractionates (peralkaline granite, granophyre, and rhyolite?) and shock-fluidized breccias predicted by impact-lake explanations have neither been recognized nor sought in Archean assemblages, so if indeed once present, they may have been enough modified during subsequent deformation and metamorphism at upper amphibolite to granulite conditions to be now inconspicuous parts of gneiss complexes.

5.4. No plate tectonics or lithospheric oceans

There are no viable indicators of the operation of plate tectonics, or of the presence of lithospheric oceans, in Archean, Paleoproterozoic, or Mesoproterozoic terrains, although there have been spurious claims for ophiolites, blueschists, and subduction mélanges, myriad appeals made to the vaguest of analogies to support plate inferences, and baseless trace-element rationales widely claimed to require plates. Conversely, there is abundant evidence that Precambrian geodynamics were very different from Phanerozoic ones, and also that Archean and Proterozoic dynamics were mostly quite different from each other.

Clear indicators of magmatic arcs and of subduction of oceanic materials are abundant and extensive in Phanerozoic orogens, but they are unknown in any but the youngest Precambrian. It is informative (as with the disproofs of plumes provided by advocates thereof: Section 2.4.3) to see how this contrast is rationalized by advocates of plate tectonics throughout Precambrian time. Timothy Kusky, who has devoted his career to the search for evidence for Precambrian plate tectonics, provides an example. Kusky et al. (2013) presented extensive descriptions and maps of known subduction complexes in various Phanerozoic orogens, including broad tracts of mélanges and ophiolites, and acknowledged such to be lacking in the Precambrian, although they did repeat spurious claims from chemotectonics, vague associations, and misused terminologies for the presence of plate-tectonic rock types. They then stated that many Precambrian successions display "ocean plate stratigraphy", such as the presence of chert in a thick section of Archean mafic lavas (which are unlike MORBs or any other modern basalts) in the Pilbara craton, and, a non sequitur, that this designation requires operation of "sea floor spreading, subduction, and accretion". No mention was made of problems such as the proved presence of TTG depositionally beneath such "ocean plate stratigraphy"; e.g., in the Pilbara, see Hamilton (2007c, Figure 11C).

There of course are abundant indicators of modern-style plate tectonics in Phanerozoic orogenic terrains, exposed at similar erosion depths, and subduction of oceanic lithosphere beneath both continental and oceanic arc systems is widely confirmed. I have probably worked more broadly with such indicators than anyone else currently looking at early Precambrian terrains; for discussions and illustrations of the defining geology, petrology, and geophysics of convergent plate tectonics, see, for example, Hamilton (1969, 1970, 1978, 1979, 1988, 1995, 2007b, 2011). Even before those, I made (Hamilton, 1963) what I believe was the first use of major-element discriminants for distinguishing island arcs and ocean floor volcanic rocks accreted to continents, although I did not then comprehend the subduction mechanism of that accretion.

No ophiolites (sections of mafic lavas above cumulates above depleted mantle) have ever been found, nor any other geologic evidence that

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

requires existence of Archean lithospheric oceans or seafloor spreading, in terrains older than ~850 Ma. There are no indicators of subduction systems and vanished oceans (polymict mélanges, paired metamorphic belts, linear magmatic arcs, ophiolites, nor rocks petrologically resembling, in either major elements or associations, MORBs or intrusive or extrusive rocks of modern oceanic or continental arcs) although all of these terms, and others like "boninite" and "arc picrite" also intended to imply plate tectonics, have been misapplied to very different Archean and Proterozoic rocks and associations. For examples, see Hamilton (2011) for an evaluation of the misuse of "boninite" in Archean reports, and Hamilton (2007d) for a detailed analysis of misuse of "ophiolite" in Greenland.

The siren's call of "uniformitarianism" influences many geoscientists to wrongly assume that tectonomagmatic processes in the ancient and modern Earth must have been similar plate tectonics (and also, alas, plumes). Geochemists fill the gap left by the absence of any geologic evidence: all that is needed to assign modern settings to ancient rocks that are completely different in bulk compositions and associations is a few selected ratios of ratios of trace elements. Robert Kerrich and his students (e.g., Polat and Kerrich, 2004; Wyman and Kerrich, 2009) have long been leaders in re-asserting as fact the claim, for which they have produced no evidence, that a few such ratios can uniquely discriminate ancient oceanic and continental magmatic arcs, MORBs, rift basalts, and many other plate indicators, and also plumes (using disproved 1970s assumptions), plus many hybrids from settings unknown on modern Earth, all intricately intercalated in continuous stratigraphic sections and all of rocks whose major elements differ sharply from the claimed modern analogs. Polat (2012) belatedly acknowledged that there is now abundant isotopic evidence for early fractionation of massive protocrust, but asserted that investigation of causes must be limited to plate tectonics and plumes. Phase petrology, major-element compositions, rock associations, behavior of trace elements, and thermodynamics are all disregarded in these chemotectonic misrepresentations. High-field-strength elements are common components of the misused ratios, and I commented (Hamilton, 2011) on crustal-section data that disprove the assumptions behind these applications. Thousands of published reports by Precambrian specialists nevertheless have applied chemotectonics with the circular rationalization, parallel to that discussed earlier for plumology, that whatever is observed must be produced by the assumed processes, no matter how unlike the products are to what are claimed to be modern analogs.

The ratios used by Precambrian chemotectonicists are mostly selected from discriminants developed by Julian Pearce and his associates for modern igneous-rock assemblages, for which they "work" only about 60% of the time although they are applied even to individual samples in Precambrian successions. Pearce himself (2008) *wrote that not only are the discriminants inapplicable to the very different Archean mafic rocks to which they are misapplied, but that the differences between Archean and modern trace-element ratio trends show the purportedly oceanic rocks to be markedly contaminated by continental crust*—which accords with the field demonstration that the mafic melts rose through TTG crust. This has not curbed enthusiasm for the notion that a few ratios of ratios can solve all tectonic problems.

TTG dominates Archean crust, and its major age increments in any craton commonly have broad subprovincial distributions. (Archean-type TTG also occurs in lesser abundance in the early and middle Proterozoic.) It differs so markedly from modern rocks that share the same names, in trace element ratios as well as major elements, that chemotectonic assumptions cannot be forced on it. Minor calcic and magnesian tonalite and granodiorite do occur in modern mature oceanic island arcs, so their sharing the same broad rock names with the superabundant ancient TTG is widely asserted to require the latter to record oceanic arcs, despite the lack of the thus-predicted evidence for linear arcs, forearc basins, accretionary wedges, and sutures. Modern arcs rise above thick mafic basal crust, and their upper-crustal andesite, tonalite, and other evolved rocks are products of intracrustal processes, as is confirmed by exposed crustal sections through Phanerozoic arcs (continental Ivrea, and island-arc Kohistan and Talkeetna). The slab-source petrologic rationales commonly assumed by geochemists are false.

6. Archean cratonization and the Mohorovičić discontinuity

6.1. Archean summary

Archean magmatism, including the dominance and composition of TTG in preserved crust, is as predicted by explanations of derivation from a mafic protocrust, initially likely more than 100 km thick, and cannot be reconciled with direct mantle derivation. Conversely, such a protocrust is needed to explain the voluminous TTG. There is no viable evidence for Archean plate tectonics, and only speculation, predictions from which have failed all scientific tests, can be cited in support of plumes that carried heat and material from basal mantle to the surface. TTG came ultimately from a mafic source and left much garnet in the residue, which thus was much denser than the subjacent magnesian–dunite mantle. The mafic melts that rose through the TTG (after 3.6 Ga?) to crystallize as dikes and supracrustal volcanics were partial melts perhaps melted variously from in-place protocrust, from shallowly-sunken protocrust, and, for komatiites and other fertile ultramafic rocks, possibly from mixtures of remelted sunken protocrust and depleted-mantle rocks. Residual protocrust delaminated incrementally and sank through dunite to reach its neutral-density level.

Unlike the geologic record of subsequent eras, Archean lower-crust dynamics were dominated by long-continuing mobility and partial melting below a thin insulating upper crust, and by intermittent additions of new melt from subjacent protocrust. Throughout Archean time, the TTG-dominated lower crust was so mobile that it could not support mountains either flexurally or with Moho relief. Instead, it flowed laterally to maintain little-varying thickness and a subhorizontal Moho, and simultaneously rose as large mobile diapirs and new partial melts into upper crust as mafic volcanic accumulations sank to correct the density inversion due to surface crystallization of melts that had been light enough to rise through TTG. The generally shallow depth of erosion of Archean cratons, except where post-Archean deformation has intervened, is a product of this long-continued basal flatness, shows that this flatness was not a late development, and contrasts sharply with the commonly deep erosion of thickened-crust Proterozoic and early Paleozoic orogenic terrains. Archean crust was hotter because radioactivity was both more intense and more concentrated at shallow levels, and the insulating upper crust enabled retention of enough of this extra lower-crustal heat to account for the long-continuing disparate behaviors of upper and lower crust.

The sharp Moho now observed seismically between mostly-TTG Archean crust and subjacent magnesian dunite is the end product of intermittent delamination and sinking of dense residual remnants of initially intervening thick mafic protocrust. Archean cratons and their flat Mohos became stabilized when the underlying residual protocrusts had completely sunk into or through the dunitic high mantle, leaving no shallow melt source to further augment either the TTG or the overlying volcanic rocks. Stability also required that radioactivity had sufficiently decayed, or been removed by erosion of shallow rocks in which it had been concentrated, to enable cooler crust at depths such as 15 to 30 km. Cratonization was not a global end-Archean event, but occurred at various times in different regions, from ~2.9 Ga (as in parts of Pilbara craton, Australia, and Kaapvaal craton, South Africa) to ~2.0 Ga (as in other parts of those two, and of Fennoscandia), but with an apparent peak ~2.8–2.6 Ga in preserved cratons.

Archean tectonics and modern plate tectonics were both driven primarily from the top, and both reflect the changing radial distribution and intensity of radioactive heat sources, but were very different. There were no semi-rigid plates during Archean time, and plate tectonics was impossible; and the abundant geologic indicators that make

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

subduction sutures obvious in Phanerozoic orogenic belts are completely lacking in Archean assemblages. Plumological concepts have all been disproved, even though they survive as mythology.

6.2. Terrestrial planets

All terrestrial planets underwent synaccretionary fractionation and shallow concentration of radioactivity. Venus cooled rapidly to inactivity, whereas on Earth, downward recycling, a cooler surface, and perhaps a larger potassium content, enabled continuing activity in time-varying modes. I have not digressed into a discussion of little Mars, but see its purported young “volcanoes” as misinterpreted. Popular dynamothermal, plumological, and “stagnant lid” notions represent extrapolations of misconceptions regarding Earth.

Mercury lost most of its mantle in large primordial collisions that knocked the remnant planet into a unique highly eccentric orbit. Huge tidal stresses due to that eccentricity and proximity to the Sun maintain high internal temperatures.

7. The post-Archean Earth

Archean-style tectonics and magmatism continued in some regions until ~2.0 Ga. Elsewhere, evidence is fast accumulating, in important part from geochronologic studies of large numbers of zircons, that most or all Proterozoic orogens older than ~850 Ma formed from thick sedimentary and volcanic fills of basins on pre-existing Archean crust (summary in Hamilton, 2011). Additional recently published examples include highly evolved Archean basement beneath a Paleoproterozoic orogen in Tanganyika (Lawley et al., 2013), Archean beneath Neoproterozoic in China (Zheng et al., 2011), and Mesoarchean depositionally beneath Neoarchean greenstone belts in Australia, intruded by voluminous granites recycled in Neoarchean time from the older basement (Ivanic et al., 2012). Archean basement occurs as polycyclic gneisses exposed in erosional windows, and contributes zircon xenocrysts to younger granites recycled from it. Sedimentary packages in the deep interiors of broad Proterozoic orogens contain abundant detrital Archean zircons that must have come from internal, not external, sources.

Extension of what are now the margins of Archean cratons against Paleoproterozoic basins is recorded by erosion into lower crust of shoulder uplifts, on which, after subsidence, sedimentary and volcanic rocks overlapped from the basins. These passive margins characterize both sides of early Proterozoic basins where relationships are known, and no subducting margins have been demonstrated, nor have products of subduction been recognized within the complexly deformed and magmatized interiors of such basins. The amount of extension or rifting within basins is undocumented. Paleomagnetism of Precambrian rocks perhaps will yet define motions, but magnetism commonly is secondary or tertiary, very difficult to date, and cannot yet be integrated into reasonable polar-wander paths.

Popular dogma assumes that plate tectonics operated throughout all or most of Precambrian time (see representative claims by Korenaga, 2013) despite the lack of any physical evidence for it, and so trace-element pseudodiscriminants are misused in Proterozoic terrains, as in Archean ones, to infer diverse plate-tectonic, plumogenic, and composite settings of igneous rocks. As in Archean terrains, the Proterozoic rocks at issue, and their associations and occurrences, differ greatly from the modern ones thus claimed to be analogous, and there is no evidence to suggest that the selected ratios of ratios have the tectonic significance asserted for them. For example, richly potassic granitoids are supervoluminous in late Paleoproterozoic and Mesoproterozoic orogens and are popularly ascribed to island arcs, but such rocks do not exist in Phanerozoic island arcs, and are very rare in continental arcs.

Great crustal thickening and deep erosion, severe deformation, and outward spreading over the passive margins of flanking cratons typify Paleoproterozoic and Mesoproterozoic orogens. High-relief Mohos and vanished mountain systems were developed from basins and obviously involved substantial shortening, and hence convergence of flanking cratons, but this has yet to be shown to involve disappearance of oceanic lithosphere. Heating by radioactivity of basin fills and their felsic basements quantitatively accounts for most of the high-temperature metamorphism and the voluminous granites melted from basinal metasedimentary rocks and underlying ancient felsic crust, although addition of TTG from surviving protocrust, of mafic volcanic rocks, and of underplated thick mafic igneous complexes of yet-undefined genesis, also are common.

Phanerozoic plate-tectonic processes produced completely different rock assemblages. Their Mohos also are strikingly different. As exposed in the crust and uppermost mantle of the Ivrea (Italy), Kohistan (Pakistan), and Talkeetna (Alaska) upramped sections through magmatic arcs—I have traversed through the first two—the geophysical Mohos are within the arc sections of igneous rocks, and represent self-perpetuating density filters produced by fractionation of ultramafic mantle rocks and mafic crustal ones from melts rising from the mantle. They are not fossil boundaries. Thick mafic melts formed new basal crust, and provided the thermal engines for the secondary melts that rose closer to the surface. That the lower crust of active intra-oceanic island arcs is similarly mafic is shown by seismology (Calvert, 2011). These mafic rocks, like MORBs and oceanic-island rocks, may all be products of re-fertilization of depleted upper mantle that began in Archean or Hadean time.

I know of no viable geologic, structural, or petrologic evidence for existence of lithospheric oceans or for subduction within, or at the margins of, orogens older than ~850 Ma, nor for the full array of products of modern-style plate tectonics older than ~600 Ma. Perhaps between approximately those times, oceans evolved where primordial protocrust that had not given rise to voluminous capping TTG or other felsic materials was increasingly densified as eclogitic and other reactions became shallower in cooler environments, and delaminated and sank through low-density high-mantle rocks, thereby greatly enriching the upper mantle, and enabling plate tectonics.

Earth's unique habitability is a product of downward crustal recycling as well as of optimal distance from the Sun. It may not be a coincidence that the explosion of animal life forms, to quickly include all modern phyla, occurred about the time that modern-style plate tectonics provided widely diverse new habitats.

Acknowledgments

My long USGS research career emphasized active and inactive Phanerozoic convergent-plate tectonics in many parts of the world, variously continental, intra-oceanic, and accreted and collided. Mostly since then, I have seen much Archean geology, often guided by distinguished geologists, especially in the United States, Canada, Australia, and southern Africa. My understanding of geophysics and modern petrology has been enormously expanded over the last 15 years by extensive and continuing discussions with Don Anderson, Gillian Foulger, Anne Hofmeister, Romain Meyer, James Natland, Dean Presnall, and E.L. Winterer, all of whom also perceive, from their varying perspectives, paradigm change as decades overdue. The manuscript was much improved as a result of careful review by Hofmeister. I thank Irina Artemieva and Hans Thybo for the invitation to participate in this special volume.

References

Agashev, A.M., Ionov, D.A., Pokhilenko, N.P., Golovin, A.V., Cherepanova, Yu., Shrygin, I.S., 2013. Metasomatism in lithospheric mantle roots: constraints from whole-rock and mineral chemical composition of deformed peridotite xenoliths from kimberlite pipe Udachnaya. Lithos 160, 201–215.

Aki, K., Christoffersson, A., Husebye, E.S., 1977. Determination of the three-dimensional seismic structure of the lithosphere. J. Geophys. Res. 82, 277–290.

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

Ali, J.R., Fitton, J.G., Herzberg, C., 2010. Emeishan large igneous province (SW China) and the mantle-plume up-doming hypothesis. J. Geol. Soc. Lond. 167, 953–959.
Amelin, Y., Kamo, S.L., Lee, D.-C., 2011. Evolution of early crust in chondritic or non-chondritic Earth inferred from U–Pb and Lu–Hf data for chemically abraded zircon from the Itsa Gneiss Complex, West Greenland. Can. J. Earth Sci. 48, 141–160.
Anderson, D.L., 1989. Theory of the Earth.Blackwell Scientific Publications (366 pp.).
Anderson, D.L., 2007. New Theory of the Earth.Cambridge University Press (384 pp.).
Anderson, D.L., 2011. Hawaii, boundary layers and ambient mantle—geophysical constraints. J. Petrol. 52, 1547–1577.
Anderson, D.L., 2012. Questioning mantle plumes. Phys. Today 65 (10), 10–12.
Armstrong, R.L., 1991. The persistent myth of crustal growth. Aust. J. Earth Sci. 38, 613–630.
Artemieva, I.M., 2009. The continental lithosphere: reconciling thermal, seismic, and petrologic data. Lithos 109, 23–46.
Aulbach, S., Griffin, W.L., Pearson, N.J., O'Reilly, S.Y., Kivi, K., Doyle, B., 2004. Mantle formation and evolution, Slave Craton: constraints from HSE abundances and Re–Os systematics of sulfide inclusions in mantle xenocrysts. Chem. Geol. 208, 61–88.
Barlow, N.G., 1990. Estimating the terrestrial crater production rate during the late heavy bombardment period. Lunar Planet. Instit. Contrib. 746, 4–5.
Basilevsky, A.T., Head, J.W., 2007. Beta Regio, Venus—evidence for uplift, rifting, and volcanism due to a mantle plume. Icarus 192, 167–186.
Bédard, J.H., 2006. A catalytic delamination-driven model for coupled genesis of Archaean crust and sub-continental lithospheric mantle. Geochim. Cosmochim. Acta 70, 1188–1214.
Bédard, J.H., Harris, L.B., Thurston, P.C., 2013. The hunting of the snArc. Precambrian Res. 229, 20–48.
Begg, G.C., Griffin, W.L., Natapov, L.M., O'Reilly, S.Y., Grand, S.P., O'Neill, C.J., Hronsky, J.M.A., Poudjom Djomani, Y., Swain, C.J., Deen, T., Bowden, P., 2009. The lithospheric architecture of Africa: seismic tomography, mantle petrology, and tectonic evolution. Geosphere 5 (1), 23–50.
Bernstein, S., Kelemen, P.B., Hanghøj, K., 2007. Consistent olivine Mg# in cratonic mantle reflects Archean mantle melting to the exhaustion of orthopyroxene. Geology 35, 459–462.
Bowring, S.A., Williams, I.S., Compston, W., 1989. 3.96 Ga gneisses from the Slave province, Northwest Territories, Canada. Geology 17, 971–975.
Calvert, A.J., 2011. The seismic structure of island arc crust. In: Brown, D., Ryan, P.D. (Eds.), Arc–continent Collision. Frontiers in Earth Sciences. Springer, pp. 87–119.
Caro, G., 2011. Early silicate Earth differentiation. Annu. Rev. Earth Planet. Sci. 39, 31–58.
Caro, G., Kleine, T., 2011. Extinct radionuclides and the earliest differentiation of the Earth and Moon. In: Dosseto, A., Turner, S.F., Van Orman, J.A. (Eds.), Timescale of Magmatic Processes. Blackwell, pp. 9–51.
Cartwright, J., Huuse, M., Aplin, A., 2007. Seal bypass systems. AAPG Bull. 91, 1141–1166.
Cates, N.L., Ziegler, K., Schmitt, A.K., Mojzsis, S., 2013. Reduced, reused and recycled: detrital zircons define a maximum age for the Eoarchean (ca. 3750–3780 Ma) Nuvvuagittuq Supracrustal Belt, Québec (Canada). Earth Planet. Sci. Lett. 362, 283–293.
Chapman, C.R., Cohen, B.A., Grinspoon, D.H., 2007. What are the real constraints on the existence and magnitude of the late heavy bombardment? Icarus 189, 233–243.
Chopelas, A., 1996. Thermal expansivity of lower mantle phases MgO and $MgSiO_3$ perovskite at high pressure derived from vibrational spectroscopy. Phys. Earth Planet. Inter. 98, 3–15.
Christoffersson, A., Husebye, E.S., 2011. Seismic tomographic mapping of the Earth's interior—back to basics revisiting the ACH inversion. Earth Sci. Rev. 106, 293–306.
Clouard, V., Bonneville, A., 2005. Ages of seamounts, islands, and plateaus on the Pacific plate. In: Foulger, et al. (Ed.), pp. 71–90.
Collins, J.A., Wolfe, C.J., Laske, G., 2012. Shear wave splitting at the Hawaiian hot spot from the PLUME land and ocean bottom seismometer deployments. Geochem. Geophys. Geosyst. 13 (paper Q02007, 15 pp.).
Coltorti, M., Bonadiman, C., O'Reilly, S.Y., Griffin, W.L., Pearson, N.J., 2010. Buoyant ancient continental mantle embedded in oceanic lithosphere (Sal Island, Cape Verde Archipelago). Lithos 120, 223–233.
Dombard, A.J., Johnson, C.L., Richards, M.A., Solomon, S.C., 2007. A magmatic loading model for coronae on Venus. J. Geophys. Res. 112 (E4) (paper 6, 13 pp.).
Dziewonski, A.M., 2005. The robust aspects of global seismic tomography. In: Foulger, et al. (Ed.), pp. 147–154.
Elkins-Tanton, L.T., 2012. Magma oceans in the inner Solar System. Annu. Rev. Earth Planet. Sci. 40, 113–139.
Feynman, R.P., 1974. Cargo cult science. Eng. Sci. 37, 10–13 ([Caltech], June).
Foulger, G.R., 2010. Plates vs. Plumes: A Geological Controversy.Wiley-Blackwell (352 pp.).
Foulger, G.R., Jurdy, D.M. (Eds.), 2007. Plates, Plumes, and Planetary Processes. Geological Society of America Special Paper, 430 (997 pp.).
Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L. (Eds.), 2005. Plates, Plumes, and Paradigms. Geological Society of America Special Paper, 388 (881 pp.).
Foulger, G.R., Panza, G.F., Artemieva, I.M., Bastowa, F., Cammaranos, J.R., Evans, J.R., Hamilton, W.B., Julian, B.R., Lustrino, M., Thybo, H., Yanovskaya, T.B., 2013. Caveats on tomographic images. Terra Nova 25, 259–281.
Frost, D.J., 2008. The upper mantle and transition zone. Episodes 4, 171–176.
Gerya, T., 2013. Precambrian geodynamics: concepts and models. Gondwana Res. (in press, available online in final form as of August 2013).
Gibert, B., Seipold, U., Tommasi, A., Mainprice, D., 2003. Thermal diffusivity of upper mantle rocks: implications of temperature, pressure, and the deformation fabric. J. Geophys. Res. 108 (B8) (15 pp.).
Glikson, A.Y., 1999. Oceanic mega-impacts and crustal evolution. Geology 27, 387–390.
Grand, S., van der Hilst, R., Widiyantoro, S., 1997. Global seismic tomography—a snapshot of convection in the Earth. GSA Today 7 (4), 1–7.
Grange, M.L., Nemchin, A.A., Jourdan, F., 2010. Review of ages of lunar impact rocks—implication to the timing of Serenitatis and Imbrium impacts and the LB model. Lunar Planet. Sci. Conf. 41 (Paper 1275, 2 pp.).
Greau, Y., Huang, J.X., Griffin, W.L., Renach, C., Alard, O., O'Reilly, S.Y., 2011. Type I eclogites from Roberts Victor kimberlites: products of extensive mantle metasomatism. Geochim. Cosmochim. Acta 75, 6927–6954.
Grieve, R.A.F., 1980. Impact bombardment and its role in proto-continental growth on the early Earth. Precambrian Res. 10, 217–247.
Grieve, R.A.F., Pilkington, M., Parmentier, K., 1990. Large impact basins and the early Earth. Lunar Planet. Instit. Contrib. 746, 18–19.
Griffin, W.L., O'Reilly, S.Y., Afonso, J.C., Begg, G.C., 2009. The composition and evolution of lithospheric mantle: a re-evaluation and its tectonic implications. J. Petrol. 50, 1185–1204.
Griffin, W.L., Malkovetz, V., Belousova, E.A., O'Reilly, S.Y., Pearson, N.J., 2012. The world turns over. Mineral. Mag. 76, 1784.
Gu, Y.J., Dziewonski, A.M., Agee, C.B., 1998. Global de-correlation of the topography of transition zone discontinuities. Earth Planet. Sci. Lett. 157, 57–67.
Gu, Y.J., Dziewonski, A.M., Su, W.-J., Ekström, G., 2001. Models of the mantle shear velocity and discontinuities in the patterns of lateral heterogeneities. J. Geophys. Res. 106, 11,169–11,199.
Guitreau, M., Blchert-Toft, J., Martin, H., Mojzsis, S.J., Albarède, F., 2012. Hafnium isotope evidence from Archean granitic rocks for deep-mantle origin of continental crust. Earth Planet. Sci. Lett. 337, 211–223.
Guitreau, M., Blichert-Toft, J., Mojzsis, S.J., Roth, A.S.G., Bourdon, B., 2013. A legacy of Hadean silicate differentiation inferred from Hf isotopes in Eoarchean rocks of the Nuvvuagittuq supracrustal belt (Québec, Canada). Earth Planet. Sci. Lett. 362, 171–181.
Hamilton, W.B., 1963. Metamorphism in the Riggins region, western Idaho. U.S. Geological Survey Professional Paper, 436 (95 p. + map).
Hamilton, W.B., 1969. Mesozoic California and the underflow of Pacific mantle. Geol. Soc. Am. Bull. 80, 2409–2430.
Hamilton, W.B., 1970. The Uralides and the motion of the Russian and Siberian platforms. Geol. Soc. Am. Bull. 81, 2553–2576.
Hamilton, W.B., 1978. Mesozoic tectonics of the western United States. Pacific Section, Society of Economic Paleontologists and Mineralogists, Paleogeography Symposium, 2, pp. 33–70.
Hamilton, W.B., 1979. Tectonics of the Indonesian region. U.S. Geological Survey Professional Paper 1078, 345 pp. + 1:5,000,000 map.
Hamilton, W.B., 1988. Plate tectonics and island arcs. Geol. Soc. Am. Bull. 100, 1503–1527.
Hamilton, W.B., 1995. Subduction systems and magmatism. Geol. Soc. Lond. Spec. Publ. 81, 3–28.
Hamilton, W.B., 2002. The closed upper-mantle circulation of plate tectonics. Am. Geophys. Union Geodyn. Ser. 30, 359–410.
Hamilton, W.B., 2005. Plumeless Venus preserves an ancient impact-accretionary surface. In: Foulger, et al. (Ed.), pp. 781–814.
Hamilton, W.B., 2007a. Earth's first two billion years—the era of internally mobile crust. In: Hatcher, R.D., Carlson, M.P., McBride, J.H., Martínez Catalán, J.R. (Eds.), 4D Framework of Continental Crust. Geological Society of America Memoir, 200, pp. 233–296.
Hamilton, W.B., 2007b. Driving mechanism and 3-D circulation of plate tectonics. In: Sears, J.W., Harms, T.A., Carol, A., Evenchick, C.A. (Eds.), Whence the Mountains. Geological Society of America Special Paper, 433, pp. 1–25.
Hamilton, W.B., 2007c. An alternative Venus. In: Foulger, Jurdy (Eds.), pp. 879–914.
Hamilton, W.B., 2007d. Comment on "A vestige of Earth's oldest ophiolite". Science 318, 746.
Hamilton, W.B., 2009. Oceanic sediments on Venus. Geophysics 15 ([Colorado School of Mines] Spring).
Hamilton, W.B., 2011. Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated. Lithos 123, 1–20.
Harrison, T.M., 2009. The Hadean crust: evidence from >4 Ga zircons. Annu. Rev. Earth Planet. Sci. 37, 479–505.
Hasterok, D., 2013. A heat flow based cooling model for tectonic plates. Earth Planet. Sci. Lett. 361, 34–43.
Haus, R., Arnold, G., 2010. Radiative transfer in the atmosphere of Venus and application to surface emissivity retrieval from VIRTIS/VEX measurements. Planet. Space Sci. 58, 1578–1598.
Helffrich, G., 2000. Topography of the transition zone seismic discontinuities. Rev. Geophys. 38, 141–158.
Herrick, R.R., 2006. Updates regarding the resurfacing of Venusian impact craters. Lunar Planet. Sci. Conf. 37 (Paper 1588, 2 pp.).
Herrick, R.R., Dufek, J., McGovern, P.J., 2005. Evolution of large shield volcanoes on Venus. J. Geophys. Res. 110 (no. 1) (paper 2, 19 pp.).
Hickman, A.H., 1983. Geology of the Pilbara Block and its environs. Geol. Surv. West. Aust. Bull. 127 (268 pp.).
Hoffmann, J.E., Münker, C., Næraa, T., Rosing, M.T., Herwartz, D., Garbe-Schönberg, D., Svahnberg, H., 2011. Mechanisms of Archean crust formation inferred from high-precision HFSE systematics in TTG. Geochim. Cosmochim. Acta 75, 4157–4178.
Hofmeister, A.M., 2010. Scale aspects of heat transport in the diamond anvil cell, in spectroscopic modeling, and in Earth's mantle: implications for secular cooling. Phys. Earth Planet. Inter. 180, 138–147.
Hofmeister, A.M., Criss, R.E., 2005. Earth's heat flux revised and linked to chemistry. Tectonophysics 395, 159–177.
Hofmeister, A.M., Criss, R.E., 2013. How irreversible heat transport processes drive Earth's interdependent thermal, structural, and chemical evolution. Gondwana Res. 24, 490–500.
Hopkins, M., Harrison, T.M., Manning, C.R., 2010. Constraints on Hadean geodynamics from mineral inclusions in >4 Ga zircons. Earth Planet. Sci. Lett. 298, 367–376.

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

Hopkins, M., Harrison, T.M., Manning, C.R., 2012. Metamorphic replacement of mineral inclusions in detrital zircon from Jack Hills, Australia: implications for the Hadean Earth—Comment. Geology 40, e281.

Huang, J.X., Yoann, G., Griffin, W.L., O'Reilly, S.Y., Pearson, N.J., 2012. Multi-stage origin of Roberts Victor eclogites: progressive metasomatism and its isotopic effects. Lithos 142, 161–181.

Iizuka, T., Komiya, T., Ueno, Y., Katayama, I., Uchara, Y., Maruyama, S., Hirata, T., Johnson, S.P., Dunkley, D.J., 2007. Geology and zircon geochronology of the Acasta Gneiss Complex, northwestern Canada: new constraints on its tectonothermal history. Precambrian Res. 153, 179–208.

Ionov, D.A., Blichert-Toft, J., Weis, D., 2005. Hf isotopic compositions and HREE variations in off-craton garnet and spinel peridotite xenoliths from central Asia. Geochim. Cosmochim. Acta 69, 2399–2418.

Ivanic, T.J., Van Kranendonk, M.J., Kirkland, C.L., Wyche, S., Wingate, M.T.D., Belousova, E.A., 2012. Zircon Lu–Hf isotopes and granite geochemistry of the Murchison Domain of the Yilgarn Craton: evidence for reworking of Eoarchean crust during Meso-Neoarchean plume-driven magmatism. Lithos 148, 112–127.

James, P.B., Zuber, M.T., Phillips, R.J., 2010. Geoid to topography ratios on Venus and implications for crustal thickness. Lunar Planet. Sci. Conf. 41 (Paper 2663, 2 pp.).

James, D.E., Fouch, M.J., Carlson, R.W., Roth, J.B., 2011. Slab fragmentation, edge flow, and the origin of the Yellowstone hotspot track. Earth Planet. Sci. Lett. 311, 124–135.

Johnson, C.L., Richards, M.A., 2003. A conceptual model for the relationship between coronae and large-scale mantle dynamics on Venus. J. Geophys. Res. 108 (no E6) (18 pp.).

Jones, A.P., Pickering, K.T., 2003. Evidence for aqueous fluid-sediment transport and erosional processes on Venus. J. Geol. Soc. Lond. 160, 319–327.

Kaula, W.M., 1995. Venus reconsidered. Science 270, 1460–1464.

Kleine, T., Rudge, J.F., 2011. Chronometry of meteorites and the formation of the Earth and Moon. Episodes 7, 41–46.

Koppers, A.A.P., Staudigel, H., Morgan, J.P., Duncan, R.A., 2007. Nonlinear ^{40}Ar–^{39}Ar systematics along the Gilbert Ridge and Tokelau Seamount Trail and the timing of the Hawaii–Emperor bend. Geochem. Geophys. Geosyst. 8 (6) (32 pp.).

Korenaga, J., 2008. Urey ratio and the structure and evolution of Earth's mantle. Rev. Geophys. 46 (paper 2007RG000241, 32 pp.).

Korenaga, J., 2013. Initiation and evolution of plate tectonics on Earth: theories and observations. Annu. Rev. Earth Planet. Sci. 41, 117–151.

Kusky, T.M., Windley, B.F., Safonova, I., Wakabayashi, J., Polat, A., Santosh, M., 2013. Recognition of ocean plate stratigraphy in accretionary orogens through Earth history: a record of 3.8 billion years of sea floor spreading, subduction, and accretion. Gondwana Res. 24, 501–547.

Lawley, C.J.M., Selby, D., Condon, D.J., Horstwood, M., Millar, I., Crowley, Q., Imber, J., 2013. Lithogeochemistry, geochronology and geodynamic setting of the Lupa Terrane, Tanzania: implications for the extent of the Archean Tanzanian Craton. Precambrian Res. 231, 174–193.

Lazarov, M., Brey, G.P., Weyer, S., 2012. Evolution of the South African mantle—a case study of garnet peridotites from the Finsch diamond mine (Kaapvaal craton): part 1: inter-mineral trace element and isotopic equilibrium. Lithos 154, 193–209.

Lee, C.T.A., Luffi, P., Chin, E.J., 2011. Building and destroying continental mantle. Annu. Rev. Earth Planet. Sci. 39, 59–90.

Lillis, R.J., Frey, H.V., Manga, M., Mitchell, D.L., Lin, R.P., Acuña, M.H., Bougher, S.W., 2008. An improved crustal magnetic field map of Mars from electron reflectometry: highland volcano magmatic history and the end of the martian dynamo. Icarus 194, 575–595.

Lin, S., Beakhouse, G.P., 2013. Synchronous vertical and horizontal tectonism at late stages of Archean cratonization and genesis of Hemlo gold deposit, Superior craton, Ontario, Canada. Geology 41, 359–362.

Longhi, J., Fram, M.S., Vander Anwera, J., Montieth, J.N., 1993. Pressure effects, kinetics, and rheology of anorthositic and related magmas. Am. Mineral. 78, 1016–1030.

Macgregor, A.M., 1951. Some milestones in the Precambrian of southern Rhodesia. Proc. Geol. Soc. S. Afr. 54, 27–71.

Malkovets, V.G., Griffin, W.L., O'Reilly, S.Y., Wood, B.J., 2007. Diamond, subcalcic garnet, and mantle metasomatism: kimberlite sampling patterns define the link. Geology 35, 339–342.

Masursky, H., Eliason, E., Ford, P.G., McGill, G.E., Pettengill, G.H., Schaber, G.G., Schubert, G., 1980. Pioneer Venus radar results—geology from images and altimetry. J. Geophys. Res. 85, 8232–8260.

Merriman, J.D., Whittington, A.C., Hofmeister, A.M., Nabelev, P.I., 2013. Thermal transport properties of major Archean rock types to high temperature and implications for cratonic geotherms. Precambrian Res. 233, 358–372.

Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., Engdahl, E.R., Hung, S.-H., 2004. Finite frequency tomography reveals a variety of plumes in the mantle. Science 303, 338–343.

Morbidelli, A., Marchi, S., Bottke, W.F., Kring, D.A., 2012. A sawtooth-like timeline for the first billion years of lunar bombardment. Earth Planet. Sci. Lett. 355, 144–151.

Morgan, W.J., Morgan, J.P., 2005. Plate velocities in the hotspot reference frame. In: Foulger, Jurdy (Eds.), pp. 65–78 (+ electronic supplement).

Moyen, J.-F., Martin, H., 2012. Forty years of TTG research. Lithos 148, 312–336.

Murakai, M., Ohishi, Y., Hirao, N., Hirose, K., 2012. A perovskitic lower mantle inferred from high-pressure, high-temperature sound-velocity data. Nature 485, 90–94.

Neumann, E.-R., Simon, N.S.C., 2006. Ultra-refractory mantle xenoliths from ocean islands: how do they compare to peridotites retrieved from oceanic sub-arc mantle? Lithos 107, 1–16.

Niu, F., Levander, A., Ham, S., Obayashi, M., 2005. Mapping the subducting Pacific slab beneath southwest Japan with Hi-net receiver functions. Earth Planet. Sci. Lett. 239, 9–17.

O'Neil, J.O., Carlson, R.W., Paquette, J.-L., Francis, D., 2012. Formation age and metamorphic history of the Nuvyuagittuq Greenstone Belt. Precambrian Res. 220, 23–44.

O'Neill, H.S.C., Palme, H., 2008. Collisional erosion and the non-chondritic composition of the terrestrial planets. Philos. Trans. R. Soc. Lond. A 166, 4205–4238.

O'Reilly, S.Y., Zhang, M., Griffin, W.L., Begg, C., Hronsky, J., 2009. Ultradeep continental roots and their oceanic remnants: a solution to the mantle reservoir problem? Lithos 211S, 1043–1054.

Pearce, J.A., 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classication and the search for Archean oceanic crust. Lithos 100, 14–48.

Pidgeon, R.T., Nemchin, A.A., Meyer, C., 2010. The contribution of the sensitive high-resolution microprobe (SHRIMP) to lunar geochronology. Precambrian Res. 183, 44–99.

Pilidou, S., Priestley, K., Gudmundsson, Ó., Debayle, E., 2004. Upper mantle *S*-wave speed heterogeneity and anisotropy beneath the North Atlantic from regional surface wave tomography: the Iceland and Azores plumes. Geophys. J. Int. 159, 1057–1076.

Polat, A., 2012. Growth of Archean crust in oceanic island arcs. Geology 40, 383–384.

Polat, A., Kerrich, R., 2004. Precambrian arc associations: boninites, adakites, magnesian andesites, and Nb-enriched basalts. Developments in Precambrian geology, 13. Elsevier, pp. 367–397.

Presnall, D.C., Gudfinnsson, G.H., 2011. Oceanic volcanism from the low-velocity zone—without mantle plumes. J. Petrol. 52, 1533–1546.

Rampone, E., Hofmann, A.W., 2012. A global overview of isotopic heterogeneities in the oceanic mantle. Lithos 148, 247–261.

Rasmussen, R., Fletcher, I.R., Muhling, G.R., Gregory, C.J., Wilde, S.A., 2011. Metamorphic replacement of mineral inclusions in detrital zircons from Jack Hills, Australia: implications for the Hadean Earth. Geology 39, 1143–1146.

Rasmussen, R., Fletcher, I.R., Muhling, G.R., Gregory, C.J., Wilde, S.A., 2012. Metamorphic replacement of mineral inclusions in detrital zircons from Jack Hills, Australia: implications for the Hadean Earth—reply. Geology 40, e282.

Rizo, H., Boyer, M., Blichert-Toft, J., O'Neill, J., Rosing, M.T., Paquette, J.-L., 2012. The elusive Hadean enriched reservoir revealed by ^{142}Nd deficits in Isua Archaean rocks. Nature 491, 96–100.

Shirey, S.B., Harris, J.W., Richardson, S.H., Fouch, M., James, D.E., Cartigny, P., Deines, P., Viljoen, F., 2003. Regional patterns in the paragenesis and age of inclusions in diamond, diamond composition, and the lithospheric seismic structure of southern Africa. Lithos 71, 243–258.

Smrekar, S.E., Sotin, C., 2012. Constraints on mantle plumes on Venus: implications for volatile history. Icarus 217, 510–523.

Solomon, S.C., Head, J.W., 1982. Mechanisms for lithospheric heat transport on Venus: implications for tectonic style and volcanism. J. Geophys. Res. 87, 9236–9246.

Steinberger, H., Werner, S.C., Torsvik, T.M., 2010. Deep versus shallow origin of gravity anomalies, topography and volcanism on Earth, Venus, and Mars. Icarus 207, 564–577.

Tackley, P.J., 2012. Dynamics and evolution of the deep mantle resulting from thermal, chemical, phase and melting effects. Earth Sci. Rev. 110, 1–25.

Tarduno, J., Bunge, H.-P., Sleep, N., Hansen, U., 2009. The bent Hawaiian–Emperor hotspot track—inheriting the mantle wind. Science 324, 50–53.

Tosi, N., Yuen, D.A., 2011. Bent-shaped plumes and horizontal channel flow beneath the 660-km discontinuity. Earth Planet. Sci. Lett. 312, 348–358.

Urey, H.C., 1951. The origin and development of the earth and other terrestrial planets. Geochim. Cosmochim. Acta 1, 209–277.

Van Kranendonk, M.J., Ivanic, T.J., Wingate, M.T.D., Kirkland, C.L., Wyche, S., 2013. Long-lived, autochthonous development of the Archean Murchison Domain, and implications for Yilgarn Craton tectonics. Precambrian Res. 229, 49–92.

Vervoort, J.D., 2012. Evolution of the depleted mantle—revisited. American Geophysical Union Fall Meeting, Abstract V43E-06.

Vervoort, J.D., Kemp, A.L.S., Patchett, P.J., 2012. Evolution of the depleted mantle and growth of the continental crust: improving on the imperfect detrital zircon record. Geophys. Res. Abstr. 14 (Abstract EGU2012-12498-1).

Wagner, L., Forsyth, D.W., Fouch, M.J., James, D.E., 2010. Detailed three-dimensional shear wave velocity structure of the northwestern United States from Rayleigh wave tomography. Earth Planet. Sci. Lett. 299, 273–284.

Warren, J.M., Shimizu, N., Sakaguchi, C., Dick, H.J.B., Nakamora, 2009. An assessment of upper mantle heterogeneity based on abyssal peridotite isotope compositions. J. Geophys. Res. 114 (paper B122023, 36 pp.).

Wasch, L.J., van der Zwan, F.M., Nebel, O., Morel, M.L.A., Hellebrand, E.G.W., Pearson, D.G., Davies, G.R., 2009. An alternative model for silica enrichment in the Kaapvaal subcontinental lithospheric mantle. Geochim. Cosmochim. Acta 73, 6894–6917.

Wasserburg, G.J., DePaolo, D.J., 1979. Models of earth structure and strontium isotope abundances. Proc. Natl. Acad. Sci. 76, 3594–3598.

Weis, D., Garcia, M.O., Rhodes, J.M., Jellinek, M., Scoates, J.S., 2011. Role of the deep mantle in generating the compositional asymmetry of the Hawaiian mantle plume. Nat. Geosci. 4, 831–838.

White, W.W., 2010. Oceanic island basalts and mantle plumes—the geochemical perspective. Annu. Rev. Earth Planet. Sci. 38, 133–160.

Whittington, A.G., Hofmeister, A.M., Nabelek, P.I., 2009. Temperature-dependent thermal diffusivity of the Earth's crust and implications for magmatism. Nature 458, 319–321.

Wieczorek, M.A., 2009. The gravity and topography of the terrestrial planets. Planets and Moons, 10. Elsevier (ch. 5, 35 pp.).

Wolfe, C.J., Solomon, S.C., Laske, G., Collins, J.A., Detrick, R.S., Orcutt, J.A., Bercovici, D., Hauri, E.H., 2009. Mantle shear-wave velocity structure beneath the Hawaiian hot spot. Science 326, 1388–1390 (+ electronic supplement).

Wood, B., 2011. The formation and differentiation of Earth. Phys. Today 64 (12), 40–45.

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009

Wyman, D.A., Kerrich, R., 2009. Plume and arc magmatism in the Abitibi subprovince: implications for the origin of Archean lithospheric mantle. Precambrian Res. 168, 4–22.

Yu, G., Jacobsen, S.B., 2011. Fast accretion of the Earth with a late Moon-forming giant impact. Proc. Natl. Acad. Sci. 108, 17,604–17,609.

Yuan, H., Romanovicz, B., 2010. Lithospheric layering in the North American Craton. Nature 466, 1063–1068.

Zhang, C., Holtz, F., Koepke, J., Wolff, P.E., Ma, C., Bédard, J.H., 2013. Constraints from experimental melting of amphibolite on the depth formation of garnet-rich restites, and implications for models of early Archean crustal growth. Precambrian Res. 231, 206–217.

Zheng, J.P., Griffin, W.L., Li, L.S., O'Reilly, S.Y., Pearson, N.J., 2011. Highly evolved Archean basement beneath the western Cathaysia Block, south China. Geochim. Cosmochim. Acta 75, 242–255.

Please cite this article as: Hamilton, W.B., Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.08.009