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# *Terrestrial planets fractionated synchronously with accretion, but Earth progressed through subsequent internally dynamic stages whereas Venus and Mars have been inert for more than 4 billion years*

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## ABSTRACT

**Popular models of slow unidirectional evolution of each planet are based on dogmatized 1970s–1980s speculations that Earth has a perpetually hot core that drives narrow vertical plumes of unfractionated mantle which produce volcanoes, propel lithosphere plates, and are compensated by subduction. Long-lasting hot cores, plumes, and minimal fractionation were dogmatized also for Venus and Mars, by analogy, but with a different stagnant-lid conjecture, rather by disrupted-lid plate tectonics, for each. Physics, empirical data, and planetary imagery disprove all three mutually incompatible models. Radiogenic heat, ~5× greater than now, forced synaccretionary magma-ocean fractionation of each planet before 4.5 Ga. This produced thick mafic protocrusts, concentrated radioactivity at shallow depths, and permanently depleted lower mantles. On Earth, the protocrust lay directly above refractory dunite, in turn above denser fractionates. The shallow concentrations of radioactivity allowed deep interiors to cool quickly. Venus and Mars have never since had hot cores or asthenospheres, and their "volcanoes" and other features popularly attributed to plumes are products of bolide impacts on internally inactive planets.**

**Only Earth had enough radioactivity to remain warmer and to generate partial melts from protocrust to make Archean, and possibly Hadean, felsic crust. Dense garnet-rich residues of protocrust delaminated, sank through the low-density dunite, and began upper-mantle re-enrichment. Archean cratons stabilized where sinking of residua left derivative felsic crust directly upon sterile buoyant dunite. Where some protocrust remained, Proterozoic crustal activity ensued. This was mostly in the form of basin filling atop Archean felsic crust, commonly followed by radioactive heating, partial melting of basement plus fill, and structural inversion. Top-down enrichment of the upper mantle by evolving processes reached the critical level needed for plate tectonics only ca. 0.6 Ga. Plate motions are driven by subduction, which rights the**

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**density inversion due to top-down cooling of asthenosphere to lithosphere. Circulation is closed within the upper mantle.**

**Primary fractionation was hot and dry. The inner planets may have received most of their water in a barrage of icy bolides, centered ca. 4.1 or 4.0 Ga, best dated on Mars and Venus but in accord with terrestrial and, possibly, lunar data. Earth's new water may have enabled formation of Archean tonalite-trondhjemite-granodiorite from protocrust. Increasing downward cycling of volatiles into Earth's upper mantle ever since has been essential for continuing tectonism and magmatism.**

## INTRODUCTION

Dominant interpretations of the evolution, internal dynamics, and crustal histories of Earth, Venus, and Mars have for 30 years been based on flawed speculations. This paper presents evidence supporting this broad charge from across many disciplines within geoscience, planetology, and physics, and derives alternative explanations.

Most solid-Earth and solid-planet scientists now active entered the profession after the early 1980s. The reality of plate tectonics, as an approximate geometric description of *relative* motions of parts of Earth's outer shell, had by then been proved. Also by then, bad guesses regarding Earth's internal workings by a few geologists and geochemists had been incorporated into assumed mechanisms, dogmatized, and extrapolated to Venus and Mars. Details vary widely with specialty and planet, but most popular dynamic explanations for each of the three planets visualize conjectural whole-mantle convection throughout their histories, driven primarily by core-heated plumes, accompanied by slow net differentiation of crust that is still far from complete. There have always been dissenters, but the continuing dominance of these concepts in textbooks and research papers shows that most investigators keep their interpretations concordant with the initial speculations. I argue here that these basic popular assumptions, and their divergent derivatives, can be separately falsified for each planet.

This report summarizes evidence that Earth, Venus, and Mars underwent synaccretionary melting, and fractionation of thick mafic protocrusts that contained most of each planet's U, Th, K, and light-ion lithophile elements (LILE). Venus and Mars quickly chilled to internal inactivity because their heat-producing elements were concentrated at shallow depths. Only Earth, far larger than Mars and with twice the potassium content of Venus, generated enough protocrustal heat to fractonate felsic crust, begin downward recycling of densified residual protocrust, progress through different stages of Archean and Proterozoic tectonism and magmatism, and initiate plate tectonics in very late Proterozoic time.

This model is opposite to popular explanations, which violate thermodynamic principles, ignore radioactive heat, and misread planetary imagery. All three planets are commonly regarded as having perpetually hot cores that maintain whole-mantle convection, but divergent conjectures have been added for each planet. Earth is usually assigned a bottom-up convective drive that has maintained plate tectonics throughout most of geologic time. Venus is assigned a much more vigorously circulating mantle, but beneath a thin unbroken lithosphere. The lithosphere is assumed to have been transformed a half-billion years ago by plume-generated upward-directed tectonism, with little surface magmatism, in highlands, and by downward motion, accompanied by voluminous magmatism, above sinking cold, dense antiplumes in lowlands. Venusian topography formed then is commonly postulated to have been precisely maintained dynamically ever since by rising plumes and sinking antiplumes that have unchanging configurations and velocities and produced no new surface effects. Mars commonly also is assigned a permanent stagnant lid, but the plumes speculated to produce its "volcanoes" have neither vertical effects as on Venus, nor horizontal ones as on Earth. Numerous published papers have forced geologic and geophysical interpretations to fit these conflicting conjectures for each planet. Mercury must have had an exceptional history. Its core is outsize, its orbit is highly eccentric, and it is greatly stressed tidally by the nearby Sun. It is not considered here.

Radioactivity, even now the major source of Earth's heat, was ~5× greater in the young planets, and would have vaporized each accreting planet had melting not occurred synchronously with accretion. U, Th, and K partition selectively into melts, and it is not possible that any of the three planets are unfractionated, or have had steady-state dynamics throughout their histories, although both of those are widely assumed.

The popularly assumed hot-core drives are not supported by viable evidence from any of the three planets. Purported terrestrial support from seismic tomography and fluid-dynamic modeling is illusory. Conventional concepts of ongoing endogenic activity in Venus and Mars are incompatible with surface imagery. The Venusian surface was not produced by young plumes, but instead is saturated with ancient impact craters and basins, and impact-melt constructs. Ancient impact structures are universally, and correctly, recognized on Mars, where, however, the quite different plume speculations are based on the false assumption that the huge Martian "volcanoes" resemble incrementally constructed Hawaiian volcanoes, which further are wrongly assumed to have formed by a plume. Imagery indicates each Martian "volcano" to have formed from a single sluggishly spreading batch of melt explicable by a large impact. Earth remained active because only it had enough radioactivity to generate felsic crust by endogenic partial melting of protocrust. Delamination and sinking of densified residual protocrust, perhaps including voluminous water and $CO_2$ only after ca. 4.0 Ga, ultimately enabled plate tectonics.

This paper builds on prior syntheses. I (Hamilton, 2007a, 2011) described a model of terrestrial plate tectonics driven from the top by subduction. Circulation is confined above the great seismic discontinuity at a depth of ~660 km, upon which subducting slabs are laid down. I (Hamilton, 2007b, 2011, 2013) argued that plate tectonics was lacking during most of Precambrian time, when non-plate-tectonic mechanisms evolved. Archean felsic crust was derived by partial melting of synaccretionary mafic protocrust, and Proterozoic orogens developed atop Archean felsic crust that was not yet stabilized by complete delamination and sinking of residual protocrust. Gradual re-enrichment of upper mantle in LILE, volatiles, and heat producers *from the top* enabled plate tectonics, which began in the late Proterozoic. I presented abundant radar imagery from Venus that falsifies the conventional assumption of a young planetary surface deformed by plumes, and instead requires preservation of an impact-saturated Hadean surface (Hamilton, 2005, 2007c, 2011, and 2013). All of these papers presented evidence against plume-driven whole-mantle circulation.

## EARTH

### Obsolete Popular Models

Mostly marine geophysical and geologic data were used in the late 1960s and 1970s to prove the relative motions of lithosphere fragments that define plate tectonics (review by Hamilton, 2002). The new data did not define either absolute motions or mechanisms, but most then-new mobilists accepted speculation that plate motions were bottom-driven products of whole-mantle convection (op. cit.). This was soon merged with geologic and geochemical conjectures about "plumes," "primitive lower mantle," and "depleted upper mantle," and the mixture was dogmatized. These speculations are still widely accepted despite abundant multidisciplinary evidence against all of them. Integration of marine geophysics and onshore geology along subducting plate boundaries, including that by me in Indonesia and surrounding regions (Hamilton, 1979), requires that plate tectonics be driven from the top by subducting slabs. These slabs sink, more steeply than they dip, from hinges migrating oceanward.

Popular models for slow, progressive, and unidirectional evolution of Earth, Venus, and Mars by processes unique to each were derived by attaching different circular rationales for each planet, mostly in isolation from the others, to the assumption that they shared core-driven mantle convection throughout their histories. The following summaries of these chains of conjectures, and of objections to them, are in part abridged from Hamilton (2011, 2013). Among those who have long raised similar, and other, objections to popular speculations regarding Earth are Anderson (2013), Foulger (2010), Hofmeister (2010, 2014), and Hofmeister and Criss (2005, 2012, 2013, 2015).

The popular models for the three planets share the starting assumption that their dynamics are controlled by plumes driven by hot cores. This speculation is unsupported by evidence and is thermodynamically unsound. The conjecture often begins with Urey's (1951) postulate: metallic iron that was dispersed in the accreted Earth accumulated heat from its surroundings, melted, and carried the heat down to the growing core, gaining heat from gravitational potential energy en route, thereby superheating the core and leaving an otherwise unfractionated mantle. (Refutation: this chains mathematical, mechanical, and thermodynamic errors, including disregard of the inviolate second law of thermodynamics [Hofmeister and Criss, 2015]. Core fractionation must have been synchronous with accretion, and mostly occurred when gravity and distances were much smaller than in popular calculations. Heat, and heat-generating radionuclides, necessarily remained in the silicates, wherein distance to the surface was decreased, and hence heat was more quickly lost to space. Hot iron cannot sink through higher-density cold iron.) In alternative popular models, Earth's mantle fractionated but was re-homogenized by solid-state convection, which has continued ever since. (Problems: both variants of starting speculations ignore the overwhelming effect of radiogenic heat.) Earth's core is postulated to have been kept eternally hotter, by perhaps 500 °C, than the adjacent mantle by a combination of retained primordial heat plus latent heat of crystallization. (Retention of ancient heat is impossible given plausible thermal conductivities. Latent heat is misconstrued, for it can be released no faster than the mantle cools and carries it away; it retards cooling, but can neither produce nor maintain superheat.) This core heat is assumed to be concentrated in spots along the core-mantle boundary (another second-law violation), from which hot plumes rise toward the surface. Conventional concepts describe an imaginary Earth wherein plumes are narrow, are of solids that behave as ideal liquids, lack integrated properties, have low "viscosity" and high thermal expansivity, lose no heat to their surroundings and do not react with them, undergo no melting, crystallization, or phase changes, and rise through the great thermal barrier of the negative-Clapeyron-slope 660 km discontinuity. (Real-Earth properties require that any rising lower-mantle masses be broad, sluggish, reactive, losing heat, and unlikely to cross the 660 km discontinuity.)

These popular speculations, and the many derivative conjectures, are widely misrepresented as fact. In Earth, rising plumes are widely claimed to produce volcanoes and magmatic provinces, heat and refertilize asthenosphere, and drive lithosphere plates. (The very different speculations of plume behaviors of Venus and Mars are discussed in subsequent parts of this report.) On all three planets, negative-buoyancy plumes are modeled to take cooled material back down to the core-mantle boundaries, where it is reheated and recycled. Lower mantles are speculated to maintain mostly primitive compositions by mixing, while upper mantles are slowly depleted by net growth of crust.

Hofmeister and Criss (2013) documented how measurements of oceanic heat flows and of thermal conductivities of rocks are disregarded in the popular modeling used to illustrate plume speculations. Earth's global heat flow is arbitrarily increased ~50% above measured values, from an observed 30 TW to a hypothetical ~45 TW, to support plume models (op. cit.). The spurious high value is obtained by substitution of a hypothetical curve for measurements of age-varying oceanic heat flows. The curve is proved invalid by its extension to infinite heat flow at zero age. Modelers skirt this impossibility by truncating integration under the curve where a desired global total of ~45 TW is reached (e.g., Hasterok, 2013). The fictitious 45 TW is then miscited as the basis for assuming that current heat transfer from core to mantle is ~15 TW, as desired to drive imaginary plumes (e.g., Driscoll and Bercovici, 2014).

The plume concept is based on speculation by Morgan (1971) that the Emperor-Hawaiian chain of southeastward-younging volcanoes and seamounts formed sequentially in the Pacific plate as it passed over a narrow vertical plume of hot material that had been rising steadily from deep mantle for 70 million years. Any igneous features elsewhere that could be selected to fit progressions, on the Pacific and other lithosphere plates, approximately compatible in Euler geometry with a fixed Emperor-Hawaiian plume, recorded analogous age progressions above other fixed vertical plumes. Both assumptions were promptly dogmatized. They are still being widely cited as facts in textbooks and voluminous research papers, but have since been disproved. Morgan himself (as first author of Morgan and Morgan, 2007) acknowledged that his many suggested compatible "hotspot tracks" in the Pacific and North American plates do not exist. To explain all the misfits, he conjectured that plumes rise vertically into the upper mantle, where they tunnel thousands of kilometers laterally and squirt up volcanoes in any chronologic and spatial sequence. Tarduno et al. (2009) demonstrated that even the Emperor half of the purported type example severely misfits the concept, and rationalized that its plume was blown about by "mantle wind." Many other plume tracks failed testing of predictions, and plume proponents have rationalized that plumes variously rise at any angle, and merge, diverge, and corkscrew up through the mantle. Skeptics are more direct. The Canary Islands and seamounts, once a purported plume track, range in age from 142 to 0 Ma, and fit no conceivable sequence in any direction (van den Bogaard, 2013). There can be no "hotspot reference frame" for plate tectonics, and popular geodynamic speculations derived from that concept are invalid.

Elaborate chemical and physical rationales were erected on the original vertical-plumes speculations, and also have been largely disproved. Purported chemical and isotopic signatures of deep-mantle, even core-mantle boundary, origins were disproved by plume-advocate White (2010), but are still widely misapplied as paleotectonic discriminants. There are no chemical or isotopic features common to purported plume lavas other than a general dissimilarity to spreading-ridge basalts, which of course is required by the disparate thermal settings of spreading centers and plate interiors. Add-on conjectures regarding large igneous provinces, balloon heads, and thin tails of hypothetical plumes have also been disproved by plume proponents as well as skeptics.

Plumes are widely claimed to be needed to add deep-mantle heat to the upper mantle. This overlooks thermal conductivities, abundantly defined by laboratory measurements. The lithosphere is an insulating lid, and asthenosphere is ~200 °C hotter than is assumed in plume speculation (Hofmeister and Criss, 2013). Seismic tomography cannot image mantle convection, but does show subducting slabs lying down on the seismic discontinuity ~660 km deep (Foulger et al., 2013; references in Hamilton, 2011). Purported images of lower-mantle slabs and plumes are artifacts of inappropriate processing unconstrained by essential crossfire rays. Misleading depictions of deep slabs are generated by algorithms that assign to lower mantle time advances gained by subparallel rays from earthquakes high in subducting slabs as they exit obliquely downward through the slabs. The unique image, often-cited and often-reproduced, of the "Farallon slab" purportedly subducting through the lower mantle (Grand et al., 1997, their fig. 1) is based on time-advanced raypaths from Andean-slab quakes to North American receivers. The relevant S waves, for example, gain >6 seconds en route (fig. 1 of Hamilton, 2011; reproduced as fig. 7 of Foulger et al., 2013). Plume depictions are generated by arbitrarily assigning to desired depths relative, not absolute, slowness of subparallel rays rising steeply to isolated islands. See Foulger et al. (2013) for detailed discussion and many examples.

Plume conjectures have failed all tests, but few researchers have sought other explanations. Advocates now claim plume properties, products, and behavior to be whatever is observed or imagined wherever plumes are postulated. Plume study has evolved from testable speculation to myth (Anderson, 2013; Dickinson, 2003).

### Synaccretionary Magmatic Fractionation

Thermal conductivities of mantle rocks preclude retention of ancient heat, and require that global heat loss approximately equals current heat generation (Hofmeister, 2010, 2014). Earth's measured heat loss of ~30 TW is about that now generated by current radioactivity if enstatite chondrite is indeed a major component (e.g., Hofmeister and Criss, 2005, 2013; and see below), whereas a carbonaceous-chondritic Earth would now generate only ~20 TW from its long-lived radioisotopes.

The deeper a planet's radioactivity, the hotter its mantle and the slower it cools. The shallower the radioactivity, the cooler the mantle and the faster it cools. If Earth's "primitive" lower mantle of popular models existed even now, the planet would melt—and heating just by long-lived radioactive U, Th, and K was ~5× greater in the young Earth (Hofmeister and Criss, 2013). Those three heat producing elements partition selectively into melts, so their upward concentration by synaccretionary melting and magmatic fractionation is required, probably into a thick mafic protocrust atop a zone-refining magma ocean that migrated upward with accretion. Synaccretionary magmatic fractionation is indicated by similar arguments for Mars and Venus, even though Mars is much smaller, and therefore cooled faster, and although Venus has only half as much absolute $^{40}$Ar in its atmosphere as does Earth (Kaula, 1999) and so likely has only half as much solid-planet potassium. The enormous early terrestrial radioactive heat is commonly overlooked. Thus, Griffin et al. (2014) did not consider it while assuming the early mantle to have been homogenized and primitive. Elkins-Tanton (2012) invoked brief heating by short-lived $^{26}$Al as contributing to very early melting in terrestrial planets, but did not consider long-lived heat-generating isotopes. Impact heating is often invoked to produce widespread melting, but its effect would have been shallow and quickly dissipated to space. It did produce magma lakes, however.

Earth's bulk composition cannot be as popularly assumed. The carbonaceous chondrite favored by many geochemists does not contain nearly enough iron. "Pyrolite," favored by some geophysicists, is merely an arbitrary mixture of basalt and peridotite. Mixtures of meteorites, including enstatite chondrite as a major component, appear to be required instead, and would have yielded a refractory lower mantle (e.g., Hofmeister and Criss, 2013).

## Evolution of Crust and Upper Mantle

The upper mantle has become more enriched with time, not progressively depleted as in popular models. Very early separation of a thick mafic protocrust from a magmatically depleted mantle is indicated for Earth by the greatly increased knowledge of geochemistry and of upper mantle petrology, geophysics, and evolution gained during the past 20 years. This in turn allows explanation of the changing dynamic and petrologic evolution of crust and mantle through time, which is inexplicable with popular models. Thick ancient mafic crusts are indicated also for the Moon, Venus, and Mars by apparent lack of mantle rocks within even their deepest impact excavations, and by other features.

The Mohorovičić discontinuity (Moho) beneath Archean cratons is starkly different from that beneath younger crust, for it commonly is a sharp subhorizontal contact that varies little in depth around the world. It separates felsic and intermediate crust (mostly tonalite-trondhjemite-granodiorite, TTG) from low-density high-velocity mantle. Receiver-function characterizations of the Moho of the Kaapvaal and Zimbabwe cratons of southern Africa are shown by Figure 1, from D.E. James et al. (2003; also see Youssof et al., 2013). Any transition across the abrupt and nearly constant velocity-step Archean Moho cannot commonly be thicker than ~500 m. Seismic study of other cratons yields mostly compatible results. Subcratonic lithospheric mantle is now known from studies of xenoliths and from seismic tomography to be mostly extremely refractory high-Mg dunite (Bernstein et al., 2013).

Archean TTG is mostly more silicic and sodic, is less calcic and magnesian, and has more steeply fractionated rare earth elements than post-Archean rocks given the same broad rock names. Experimental petrology has long been known to require derivation of Archean TTG by moderately hydrous partial melting of mafic rock under pressure-temperature (P-T) conditions that left much garnet in the residue, or by recycling from felsic rock thus derived. (Ziaja et al., 2014; add new data.) A little such dense residue is often found in deep-crustal TTG exposed by erosion in post-Archean uplifts, but no underplate of the required voluminous residuum now lies between Archean TTG and dunite (Fig. 1; for references documenting much of the following summary, see Hamilton [2013]). The dunite that now abruptly underlies TTG crust is far too refractory to be a residue left by removal of TTG. Incremental delamination of intervening mafic protocrustal residue, densified by TTG removal to assemblages dominated by garnet and clinopyroxene, and sinking of that residue through underlying lower-density dunite provide the apparent explanation. Some of the residue was trapped in the dunite and is brought up as xenoliths in kimberlite, but most sank through the dunite into deeper upper mantle. Neither the present basal-crustal

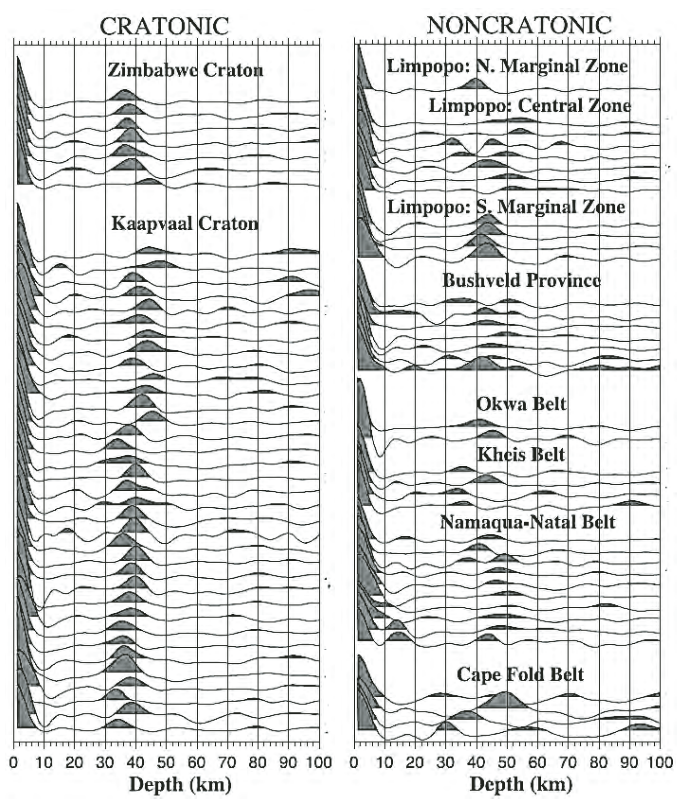


Figure 1. Receiver-function stacks at broadband seismic stations in southern Africa, organized by tectonic provinces. S waves converted from P waves at the Moho dominate most signals. The unique Archean Moho (cratons, and Limpopo margins) is uniform, subhorizontal, and sharp, and separates tonalite-trondhjemite-granodiorite crust from high-Mg dunite. The strikingly different diffuse and variable Mohos of post-Archean provinces reflect great changes in tectonics and geodynamics. From D.E. James et al. (2003, their figure 2), reproduced by permission.

nor possible xenolithic residua have compositions appropriate for the subducted-slab origins of conventional Precambrian speculations. The long-term mobility of crust and subjacent dunite, indicated by both the flat Moho and crustal geology, is also incompatible with postulates of Archean plate tectonics. Reheating of the sunken residue released its remaining fusible components, which were the major source of re-enrichment of the dunite via formation of orthopyroxene and more ferroan olivine, plus combinations with clinopyroxene and garnet (where pressure was high) or spinel (where pressure was low). The transformations were accomplished by metasomatism and obliteration of primary mineralogy. In these terms, mafic protocrust was a synaccretionary fractionate above uniform dunite, and the protocrust sourced both TTG and most of the subordinate mafic volcanic rocks of Archean crust.

My conclusion from such information is that stabilization of cratons resulted from complete sinking of dense residual protocrust, which left TTG buoyed up by light sterile dunite that could contribute no material to the crust. Archean crust commonly has been much less eroded than has most Proterozoic or Paleozoic orogenic crust, and cratons were stabilized at times varying from 2.9 to 2.3 Ga. Archean crust floated on the buoyant dunite and maintained semiconstant thickness, and lower crust and dunite were too hot and mobile to support mountains. Such lower-crustal mobility, continuous for hundreds of millions of years or even a billion years, is required also by the geology and geochronology of Archean cratons (Hamilton, 2007b, 2013), and accords with the combination of high crustal radioactivity and the insulating lid of low-thermal-conductivity upper crust.

The mantle rocks seen as xenoliths in kimberlites and in some basalts and lamprophyres, and the ultramafic rocks of ophiolites, are almost all from the lithosphere. Samples from beneath Archean cratons display temporal and geographic trends opposite to those predicted by popular models. Where not metasomatized by the magmas that carried them to the surface, they are extremely refractory magnesian dunite throughout at least the top 150 km of lithospheric mantle. The average compositions of sample suites vary only from $Fo_{92.0}$ to $Fo_{93.0}$ (Bernstein et al., 2013; Fo, forsterite content, equals Mg number). Most of the total range of samples is contained between $Fo_{91.5}$ and $Fo_{94.0}$. This high-temperature dunite could not have formed by magmatic crystallization in equilibrium with even the minor orthopyroxene that now often occurs in xenoliths from it (Bernstein et al., 2013), let alone with the clinopyroxenitic and garnetiferous rocks also present. Those more fertile rocks variously record subsequent metasomatism, sunken dense rocks, and products of new melts from below the dunite. Griffin and coworkers provided much of the petrologic evidence for this refertilization (e.g., Griffin et al. 2014, and Beyer et al., 2006). Such trends are mapped in three dimensions (3-D) by detailed seismic tomography (Artemieva, 2009) that quantitatively discriminates mantle thermal perturbations (S-wave velocity, *Vs*, decreases more than does P-wave velocity, *Vp*, with increasing temperature) from compositional ones (*Vs* and *Vp* decrease together as mean atomic density increases with, particularly, increasing iron), and relates these to xenoliths, crustal ages, and other factors. The tomography confirms the petrologic inference that the xenolith sample is strongly biased by metasomatism by the melts that carried the xenoliths to the surface. Uniform high-Mg dunite strongly dominates the upper mantle beneath Archean cratons away from late-rising melts, and metasomatism increases both deep in the lithosphere and near the margins of cratons against younger orogens. The uniformity and extreme depletion of the ancient dunite accords with fractionation in the synaccretionary magma ocean deduced earlier, and with separation of a since-vanished mafic protocrust above it. The uniformly refractory dunite is not explicable by the popular speculation that incremental separations of small batches of mafic melt have gradually depleted the mantle throughout geologic time.

The Moho beneath Proterozoic and Phanerozoic terrains, by contrast, varies much more in depth, often is gradational and indistinct, and generally separates mafic lower crust from variable mantle (e.g., post-Archean provinces of Fig. 1). Proterozoic crust commonly is deeply eroded yet often still quite thick, and has a Moho that is highly irregular and commonly is indistinct (e.g., Fig. 1). Proterozoic crust and uppermost mantle supported high mountains. Exposed Phanerozoic arc-magmatic Mohos (e.g., of oceanic-arc Kohistan in Pakistan, and of continental-arc Ivrea in Italy, both of which I have examined) show them to be constructional parts of the arcs and self-perpetuating density filters. Uppermost rocks of the geophysical mantle beneath young arc crust commonly are magmatically layered ultramafic arc rocks. Most Phanerozoic ophiolites also show constructional Mohos, not accumulations of oceanic crust directly atop fossil or reworked mantle, which occurs deeper in the sections. Hamilton (2011, 2013) cited many petrologic and geochemical papers demonstrating that lithospheric mantle beneath younger felsic crust is progressively more enriched and more pervasively modified, and suboceanic mantle beneath the crustal-associated ultramafic rocks more so. Si, Fe, Al, Ca, and Cr, and other components of basalt, including suites of trace elements, all of which are incompatible with primary crystallization with $Fo_{93}$ olivine, have been added metasomatically to the margins and bases of the lithospheric mantle beneath Archean cratons, with formation of varied fertile and depleted rocks in disequilibrium assemblages. The progressive depletion of upper mantle through time advocated by most geochemists has not occurred.

Rare xenoliths and xenocrysts, variably inverted and reconstituted to lower-pressure minerals, have been inferred to record origins in deeper parts of the upper mantle, above the 660 km discontinuity, and possibly even lower mantle. Knowledge of these is too sparse and ambiguous for integration into a 4-D synthesis. Further, the lower mantle may be markedly more refractory than the upper mantle.

Impact specialists have long recognized that the early Earth must have been heavily bombarded. I argue below, as in Hamilton (2005, 2007c), that large Hadean impact-melt constructs are widespread on Venus, and that they are present, but less extensive, on Mars. Such constructs on Earth must have contributed erratic shallow fractionation and irregularities, subsequented recycled mechanically and petrologically, rather than remaining above effectively rigid mantle as on Venus and Mars.

The youngest large impact on the Moon is dated as ca. 3.8 Ga (see following section on the Moon). Many younger Archean beds of impact spherules are documented in Australia and South Africa. The spherules often contain mafic material (Glikson, 1999), which I presume came mostly from protocrust, whereas Glikson (1999) presumed oceanic sources. Locations and local products of those impacts are not known. Proved major Precambrian impact-melt structures include Sudbury, Ontario, Canada, 1.8 Ga, and Vredefort, South Africa, 2.05 Ga. I regard apparently shock-injected breccias in the floors of the great overlapping fractionated magma lakes of Bushveld, South Africa (which are the same age as the adjacent Vredefort impact-melt sheet), and of Stillwater, Montana (2.7 Ga) (Hamilton, 2007b), as also indicative of impact-melt origins. Exposures of Archean lower-crustal gneisses include in many regions large dismembered sheets of highly calcic anorthosites (low-pressure fractionates, almost uniquely Archean), often with other mafic and ultramafic rocks indicative of formation in layered complexes. These might have formed in impact-melt lakes of Hadean(?) and Archean age. I expect thick high-temperature alkalic granite and granophyre to have formed atop such lakes, but such have neither been sought nor recognized with the anorthosites, so if present they may now mostly be unremarkable granitic gneisses.

Archean crust is typified by long-mobile TTG lower crust beneath an upper crust of diapiric batholiths and of supracrustal rocks that had subregional extents before disruption by batholiths and by stretching and other distortion above moving lower crust (Hamilton, 2013, and references therein). Volcanic rock types and associations are unlike any in the modern world. Uniformitarianism, “the present is the key to the past,” is properly applied in much geologic interpretation. However, it is misused by most Precambrian specialists, who claim it to require a young Earth controlled by the same plate-tectonic and plume processes that they postulate for the modern planet (e.g., Furnes et al., 2015). Earth’s radiogenic heating was still 2.5× greater at 3 Ga than at present, and it is not possible that internal distribution of radioactivity and heat, and hence dynamic processes, could have been similar to those now operating, nor does anything observed in the geology suggest that they were. The only basement rocks ever seen depositionally beneath Archean mafic and ultramafic lavas are older TTG (Hamilton, 2007b, and references therein). No ophiolites, subduction mélanges, oceanic or continental magmatic arcs, oceanic crust, or other evidence for plate tectonics, or for oceanic lithosphere, older than ca. 1 Ga have been documented. Modern-style plate tectonics is indicated only after ca. 0.6 Ga (Hamilton, 2007b, 2011, 2013).

Plate tectonics nevertheless is popularly assumed to have operated throughout most of Precambrian time. Most Precambrian papers of the past 20 years contain speculative assignments to plate-tectonic and plume settings of rocks and associations that bear no similarity to those in the purported modern analogues (e.g., Furnes et al., 2015). No geologic or petrologic data suggest operation of plate tectonics, and so selected ratios of ratios (commonly neither absolute amounts nor simple ratios) of a few trace elements are widely cited as requiring many Precambrian mafic lavas to have formed in oceanic spreading ridges, oceanic island arcs, or “oceanic islands” (misused as synonymous with “plumes”), and hence to indicate the operation of plate tectonics plus plumes through most of geologic time. Many of the ratios are selected from discriminants developed by Julian Pearce and his associates for modern igneous assemblages, but the actual Precambrian plots vary markedly from those, and bulk compositions and associations of the Precambrian rocks differ strikingly from their purported modern analogues. Pearce (2008) himself emphasized that not only are the discriminants inapplicable to the very different Archean rocks, but that the data clearly show purportedly oceanic Archean rocks to be markedly contaminated by continental crust. This is as required by the field evidence that the mafic melts rose through older TTG crust.

Ratios of high field strength elements to rare earth elements are widely misused as such discriminants. The regional continental flood-lava sheets of late Archean ferroandesites (rocks with almost no modern equivalents) of Western Australia plot mostly in the oceanic island arc field of one ternary plot, Ti/Zr/Y, of this type (Thorne and Trendall, 2001). It is obvious to all that the vast stratigraphic continuity of these sheets precludes an island-arc origin, but this disproof of the utility of the discriminant for Archean rocks of non-modern compositions is widely overlooked. Ratios of ratios of trace elements continue to be misused as definitive tectonic discriminants. Thus, Furnes et al. (2015) misused the ratios to assign a dozen precise plate-tectonic and plume settings, plus imaginative mixtures thereof, to mafic rocks in about a hundred volcanic suites throughout the world’s Precambrian, and claimed this to indicate uniformitarian tectonics and geodynamics throughout geologic time.

No boundary of a Proterozoic orogen by indicators of subduction, either beneath the adjacent cratons or beneath the Proterozoic materials, has been demonstrated. Lower and middle Proterozoic orogens are popularly assumed to record closing of oceans by subduction, and to be dominated by collided island arcs, even though no arc-type rocks, and no sutures, high-P low-T metamorphic rocks, subduction mélanges, or ophiolites are known. The orogens do fit the contrary scenario of filling, radiogenic heating, and inversion of basins developed on top of older felsic crust that had not yet been stabilized by loss of all protocrustal material. See Hamilton (2007b, 2011, 2013) for some examples.

Exposed contacts between Proterozoic orogens and Archean cratons are marked by Proterozoic strata lapping onto the cratons, commonly thrust cratonward during metamorphism, plutonism, and inversion of the basin fills. Where both sides of Proterozoic orogens are exposed, as in Trans-Hudson and Labrador “Trough” in the Canadian Shield, both are of this type. Both north and south margins of the early Proterozoic Limpopo orogen of southern

Africa show typical Archean Mohos (Fig. 1). The deeply eroded interior of that orogen exposes abundant recycled Archean basement as well as plutonized Proterozoic basin fill. Archean basement has now been proved in the deeply eroded interiors of many Proterozoic orogens previously assumed to be oceanic, and sediments from Archean sources are voluminous in the interiors of many Proterozoic orogens (e.g., Bickford and Hill, 2007). Proterozoic granitic rocks are dominantly highly potassic, which with other features, including Archean cores in zircons, requires in most cases mobilization from craton-sourced sediments and from Archean basement beneath the basins. Radiometric heating of deeply buried basement and sediments quantitatively accounts for metamorphism and plutonism. Many Proterozoic orogens contain very high-temperature mid-crustal rocks, explicable with radioactive heating beneath low-conductivity upper crust. The much-subordinate TTG of Archean type in Proterozoic orogens presumably records derivation from synaccretionary protocrust still beneath the Archean basement.

As only Archean cratons are characterized by abrupt Mohos between TTG and extremely depleted buoyant mantle rocks, I surmise that Proterozoic basins developed where cratons had not been stabilized by complete delamination of densified protocrust. Proterozoic orogens display erratic vague and transitional Mohos (e.g., Fig. 1) and have voluminous lower-crustal mafic rocks.

Modern-style plate tectonics (see subsequent section) began only ~600 m.y. ago, after a poorly understood transition period, and was enabled by top-down enrichment of initially depleted upper mantle by, mostly, densified residual protocrust. Modern oceanic mantle is highly variable, not homogenized by mixing as is assumed in most geochemical work (see Hamilton [2011, 2013] for references). Top-down enrichment of extremely depleted ancient protomantle is compatible with many studies of dredge and xenolith mantle samples from ridges, islands, and arcs, and also from outcrop samples of late Phanerozoic collision complexes. Moderately re-enriched ancient shallow depleted mantle extends hundreds of kilometers out under oceanic crust on both sides of the South Atlantic and occurs as stranded scraps in central parts of the ocean.

The preceding synthesis posits much distributed horizontal transport during the mobile-crust Archean era, but does not attempt to define motions within or between either Archean cratons or Proterozoic orogens. Such motions may ultimately be defined with paleomagnetic data, but problems of inconsistencies, inadequate sampling, ages of rocks, age, stability, and history of magnetization in mostly altered rocks, paleohorizontals, flattening of inclinations by compaction, and rotations and lateral motions between nuclei are all formidable obstacles. The broadest review (Piper, 2014) of global Precambrian paleomagnetic data relied on statistical clustering to smooth out the effects of such shortcomings in a huge database. He deduced that a little-varying Precambrian supercontinent underwent only modest external and internal-differential motions from late Archean until ~0.6 Ga, when plate tectonics began and the supercontinent rapidly fragmented, except for a brief period of rapid motions ca. 2.2 Ga. This is roughly compatible with my analysis. By contrast, Buchan (2013) deduced that there are only16 reliable paleomagnetic poles available from the Superior craton of Canada, but that these require continuous rapid, chaotic, and large motions of that fraction of the Canadian Shield. Schmidt (2014) selected more poles from the Australian Precambrian and, in part by resolving ambiguities in favor of fitting polar-wander curves, came up with two optional Buchan-like patterns of rapid and erratic motions.

## The "Depleting Mantle" and "Juvenile Magmas" Fallacies

The widely accepted notion that Earth has only slowly and incompletely fractionated effectively began as speculation by Urey (1951), and approached its present form as a derivative model of divergence through time between radioactive and daughter isotopes because of the different chemical behaviors of the isotope behaviors in actual crustal rocks and in a *hypothetical* slowly fractionating mantle (e.g., DePaolo and Wasserburg, 1976). They assumed lower mantle to be still "primitive" and unfractionated, and upper mantle to have been slowly depleted, from a homogeneous chondritic composition, by the still-incomplete removal of crust-forming juvenile magmas. Measured variations in Rb-Sr and Sm-Nd mother-daughter isotopes in crustal igneous rocks were rationalized in these terms, and other isotope pairs were added later. Arithmetic expressions of the speculations, including $T_{DM}$, model ages, epsilons, and evolving chondritic uniform reservoir (CHUR) and depleted MORB mantle (DMM), were devised to characterize hypothetical mantle depletions and sources and histories of derivative melts.

One isotope pair, currently much used in these exercises, is particularly important for early Earth history. Our primary direct information on Earth's Hadean crust comes from 4.4 to 4.0 Ga zircons, as clastic grains in ancient sediments and xenocrysts in some Archean TTG. Kemp et al. (2010) expanded and evaluated work with Hf isotopes in some of these zircons. $^{176}Lu$ decays to $^{176}Hf$ with a half-life of 37 billion years. Lu, the heaviest rare earth element, tends to stay in solid phases, particularly garnet, and does not crystallize in zircon. Tetravalent Hf, a transition metal, tends to enter melts, and to crystallize in Zr positions in zircon. The ratio of radiogenic $^{176}Hf$ to primordial $^{177}Hf$ in unaltered zircon thus should remain that of the melt from which the zircon crystallized. Measured Hf in crustal rocks is conventionally compared with a hypothetical mantle with chondritic Lu and Hf initial composition, ~20 or 30 ppb of Lu and ~150 ppb of Hf (Bouvier et al., 2008b) that evolved ("DMM") by progressive removal, linear throughout geologic time, of ocean-ridge basalt by plate tectonics.

Known mantle petrology disproves the starting assumption of slowly depleting chondritic mantle. As discussed above, the actual high upper mantle of the early Earth was extremely refractory high-Mg dunite, which could not have yielded any of the products attributed to it in popular models. It lost almost all of its initial Lu and Hf in high-temperature processing, and typically has non-detectible Hf and only ~1 ppb of Lu (e.g., Beyer et al., 2006). The arithmetic derivatives used by geochemists can relate to separations of crustal melts from ancient protocrust, but not from subjacent mantle. In my terms, Earth's Lu was concentrated in garnetiferous lower protocrust, and to an unknown extent also in denser mantle beneath the high sterile dunite, whereas global Hf went primarily into protocrust.

Reliable analyses of Hf in Hadean zircons indicate derivation of their parental melts from a very low Lu source, presumably basaltic, that had fractionated from bulk Earth ~4.5 Ga (Kemp et al., 2010; their figure 4B). I concur with those authors that this fractionate was mafic protocrust, and that its Hadean derivatives were fractionated from impact melts, not endogenic magmas. Archean zircons, from ca. 3.8–2.5 Ga, by contrast show highly variable Hf that is erratically much less radiogenic than hypothetical depleting mantle (which thus is incompatible with the standard model), but mostly more radiogenic than the basaltic source of the Hadean zircons (Kemp and Hawkesworth, 2014; their figure 8). Kemp and Hawkesworth attributed the change to the onset of plumes, plate tectonics, and chondritic-mantle sources, all of which I reject. I suggest that the Hadean impact melts came instead primarily from the non-garnetiferous upper part of the protocrust, and that the Archean change to TTG reflects hydrous partial melting that included the lower protocrust, wherein residual Lu-retaining garnet increased with time, as a response to the late Hadean delivery of voluminous asteroidal water to Earth. Voluminous recycling of felsic crust, and melts from upper mantle that was re-enriched from the top, early by delaminated residual mafic crust and later by subduction, can also be read into the data arrays for Proterozoic and Phanerozoic rocks (e.g., Kemp and Hawkesworth, 2014; their figure 12). Analogous evaluations regard mantle histories of other isotope pairs.

## Plate Tectonics

Continued recycling of protocrustal derivatives ultimately allowed Earth to enter its present dynamic mode of plate tectonics. Addition of abundant water by icy bolides ca. 4.0 Ga is suggested subsequently to have been essential also. The oldest known complete suites of indicators of subduction and seafloor spreading are ca. 600 Ma, although transitional parts of the array may have formed from ca. 1 Ga onward. I have presented elsewhere (Hamilton, 2007a, 2011, 2013) some of the evidence for a late beginning of plate tectonics and some of the plate-interaction and other evidence for the kinematic model summarized here. The ages of subduction-indicating blueschists (Tsujimori and Ernst, 2014) provide corroboration. Low-pressure epidote-glaucophane blueschists are younger than 620 Ma except for an outlier at 760 Ma. High-pressure lawsonite blueschists are younger than 500 Ma except for a 560 Ma outlier. It is unlikely to be a coincidence that evolution of multicellular animals, slow and taxonomically limited from ca. 600–540 Ma and then ballooning to include almost all extant phyla by ca. 515 Ma, was coincident with the plate-tectonic expansion of Earth's marine habitats and nutrient-enriching processes.

Plate tectonics is characterized by the skittering about of plates of lithosphere above weak asthenosphere that is close to its solidus temperature, so a global asthenosphere also may have first formed ca. 600 Ma. Only then had enough protocrustal materials and volatiles been recycled downward through the upper mantle that the increasingly fusible composition allowed even the decreasing radiogenic heating to form asthenosphere. Powerful evidence against the presence of an asthenosphere in Venus includes the non–Earth-like strong correlation of long- and middle-wavelength Venusian topography and geoid, discussed in the section on Venus, although an asthenosphere is popularly assumed merely because Earth has one.

Comprehension of plate tectonics has long been hampered by speculation that a "hotspot reference frame," based on Morgan's (1971) disproved vertical-plumes conjecture, defines "absolute" plate motions. The lack of any kinematic sense to plate motions as viewed in that hypothetical frame has contributed to the conjecture by modelers that plate propulsion is produced by deep-mantle processes and that trenches and spreading ridges are mostly fixed (e.g., Huang and Davies, 2007). Even brief examination of a map of seafloor ages shows that although any one boundary segment might be regarded arbitrarily as fixed, almost all other boundaries must move relative to it, most boundaries are changing lengths and shapes while moving, and all triple junctions are migrating. The Atlantic Ocean, which has almost no bounding subduction because its plates include the flanking continents, is slowly widening, whereas the Pacific Ocean, which is bounded by outward subduction almost continuously from New Zealand clockwise to the Antarctic Peninsula, is spreading several times faster than the Atlantic and yet is narrowing at approximately the same areal rate as the Atlantic is enlarging. It follows that subduction hinges roll back into incoming plates of oceanic lithosphere. No subducting slabs inflect abruptly over fixed hinges at trenches and slide down fixed slots, although they are thus commonly depicted by modelers. Actual hinges retreat, and slabs sink more steeply than they dip. Seismicity and tomography define transient positions of steeply sinking slabs, and cannot be fixed trajectories as popularly assumed. Sinking of slabs in front of overriding plates is shown also by the common structure of the fronts of overriding plates. Subducting lithosphere typically dips only ~5° beneath fronts of overriding plates, and well back under them inflects in broad curves to inclinations commonly between 30° and 80°. Most thin fronts of both oceanic island-arc and Andean continental-margin plates bear forearc basins of little-deformed strata, which show those thin leading edges to have been uncrumpled during the durations of basin sedimentation, commonly at least tens of millions of years. The broad, thin accretionary wedges, formed where voluminous sediments are present in the trench or on an incoming oceanic plate, record vast internal imbrication and shearing, but are in front of, and beneath, overriding plates. Good high-amplitude seismic tomography shows that slabs older than ca. 50 Ma when they begin to subduct are plated down on the great seismic discontinuity at ~660 km depth, which may be a compositional boundary as well as a thermodynamic one. This requires another rolling hinge at the lower limit of slab sinking. The downplated slabs are overpassed by overriding plates. Younger slabs can be traced down only to 200 or 300 km, where apparently they reach neutral buoyancy and also are overpassed, with yet-undefined geometry, by overriding plates. As noted above, purported tomographic depictions of lower-mantle slabs are artifacts of faulty processing.

These relationships require a top-down control of subduction. Oceanic lithosphere is mostly asthenosphere that has been chilled from the top to produce a density inversion. It thickens, increasing the density imbalance, as a function of increasing age to ca. 60 Ma. The mass and strength of the lithosphere hold it together, prohibit fragmentation into numerous sinking pieces, and drive the plate toward its subduction exits from the surface. The drive is aided by the common trenchward slopes of both the top (seafloor) and bottom (asthenosphere contact) of the lithosphere, and subduction corrects the density inversion. That this mass push is part of the driving force is shown by features such as the fast-evolving Gulf of California–San Andreas fault transform system between diverging triple junctions. Subduction, and the arc magmatism associated with it, stop abruptly where the western Pacific plate comes in lengthening transform contact with the North American plate. Spreading and subduction do not continue beneath North America because the mass drive no longer operates.

These and other features are integrated into a model of plate-tectonic circulation, driven by top-down chilling, lithosphere-mass push, and some slab pull, that is closed within the upper mantle above the 660 km discontinuity (Fig. 2; Hamilton, 2007a). Subduction, with migrating hinges at both tops and bottoms of sinking slabs, transfers oceanic lithosphere from a shrinking ocean, e.g., the Pacific, to an enlarging one, e.g., the Atlantic, or to an enlarging oceanic back-arc basin behind an advancing island arc, e.g., the Philippine Sea and Marianas arc. Overriding plates advance over the steeply sinking inclined slabs, and the mass deficit behind them is filled by overpassed sunken lithosphere. Spreading behind the overriding plate, such as Atlantic spreading behind South America, can be no faster than subducted lithosphere is transferred to compensate the spreading. In the other direction, the sinking slab pushes the entire upper mantle beneath the inbound plate back under that plate. This forces rapid spreading of the ocean, e.g., the Pacific, whose lithosphere is being subducted. Very slow spreading is accomplished primarily by extensional faulting of exposed pre-existing lithospheric mantle.

Subduction controls plate motions, including spreading, so Antarctica, surrounded by retreating oceanic spreading ridges, likely is approximately fixed with regard to the bulk mantle. The relative motions of global plates make kinematic sense in an Antarctica-fixed framework (map and discussion in Hamilton [2007a]), for within this frame major-plate velocities and rotations mostly accord with rolling-back subduction boundaries. Spreading ridges migrate continuously to tap fresh asthenosphere. The process is enabled by Earth's heat, but requires no involvement of material from the lower mantle.

This model of top-down organization, circulation closure above the 660 km discontinuity, subduction control of spreading velocities, and subduction transfer of balancing mass between shrinking and expanding upper-mantle regions readily accounts for the multitude of plate effects that are inexplicable with the popular assumption of whole-mantle convection. Triple-junction evolution, including the San Andreas example noted above, is one such effect. Long-distance migration of small subducting arcs into or through confined spaces (Banda, Caribbean, Scotia, Rif, and Carpathian arcs are examples) is another effect. So is the bathtub configuration of lithosphere plated down on the 660 km discontinuity as the New Hebrides and Tonga arcs diverge. Collisions of arcs with each other or with subducting or stable continental margins require top-down and mass-transfer control, as do the usual prompt polarity reversals of subduction to the outsides of collided masses. That subduction occurs beneath only one side of an internally stable plate at a time defies analysis with popular models.

The mantle transition zone, between the penetration-enhancing seismic discontinuity at a depth of ~410 km and the great penetration-inhibiting discontinuity at ~660 km, has been the repository for much subducted oceanic lithosphere for ~600 m.y. Recycling from this reservoir occurs wherever seafloor spreading opens thermal windows. The present Mid-Atlantic Ridge may now be fed by lithosphere plated down on the "660" during Paleozoic closure of the proto-Atlantic ocean (Foulger et al., 2005).

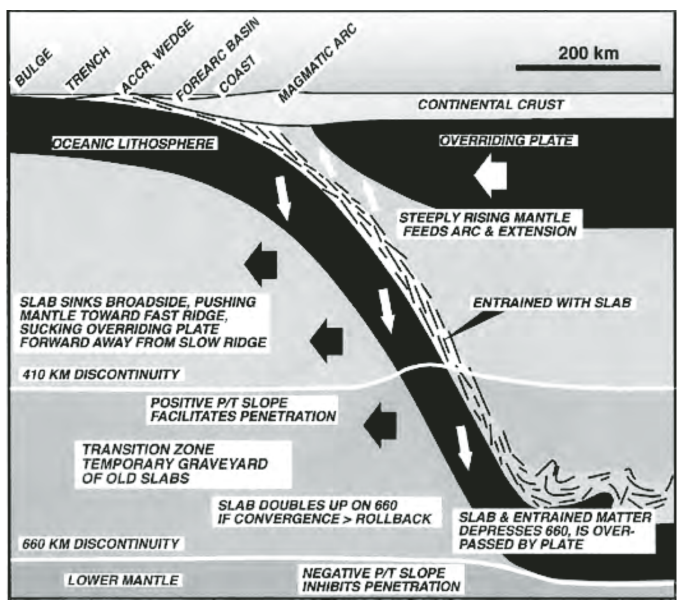


Figure 2. Plate-tectonic circulation is driven from the top and is closed within the upper mantle. Top-down cooling of oceanic asthenosphere produces lithosphere and a density inversion, which is righted by subduction at a broad hinge that rolls back in front of the overriding plate. The steeply sinking slab pushes all sub-lithospheric mantle back under the incoming plate, producing rapid spreading, and pulls the overriding plate and mid- to upper mantle toward the slab. The slab is plated down on the 660 km discontinuity, which transfers shrinking-ocean lithosphere to beneath the overriding plate and balances the spreading that enables its advance. From Hamilton (2007a, his figure 17). Accr.—accretionary; P/T—pressure-temperature.

### Terrestrial Crustal Dichotomy?

In a later section, I suggest that an origin of the Moon by fission from Earth is more plausible than the widely accepted giant-impact explanation. Either origin might have produced hemispheric dichotomy on Earth, like that still retained by early-chilled Mars, with a bimodal distribution of protocrust. This would have profoundly affected subsequent crustal development by both impact and internal-dynamic processes. Archean crust on Earth was argued previously to underlie Proterozoic orogens, and both are being increasingly recognized also beneath substantial parts of Phanerozoic systems (e.g., Turkey and Iran; Nutman et al., 2014). Archean crust may now be present, mostly in multiply recycled form, over 25% or so of Earth's surface. Perhaps this areal limitation partly reflects an ancient dichotomy. Piper's (2014) paleomagnetically defined Precambrian supercontinent accords with this.

### Core Heat

What keeps Earth's outer core above its solidus temperature, if indeed ancient heat cannot be retained, and radioactivity is now concentrated high in the crust and upper mantle? The light-element content and proportion of liquid in the outer core are poorly constrained, and core-mantle boundary temperature is accordingly known only to be within a range perhaps as broad as 3000–5000 K. Even the low end of that range may present a problem. Effects that may be implicated include frictional heating by lunar and solar tides, and frictional heating accompanying gyroscopic transfers of angular momentum back and forth between core and mantle, or fractions thereof, in response to migrations through Earth's spin axis as mass distributions are changed by plate tectonics and other processes. Perhaps magnetic-polarity reversals, wandering of the magnetic-dipole axis, and the present slight net westward drift of the non-dipole component of the core field are related to gyroscopic transfers.

### Arrival of Water

Obsolete assumptions by geochemists of a slowly warming and fractionating Earth are the basis for popular speculation that Earth's hydrosphere and atmosphere evolved from volatiles expelled from Earth's interior. Early accretionary water instead may have been lost during the synaccretionary high-temperature processing indicated by the extremely refractory upper-mantle dunite. Present water, both internal and external, may record primarily late-accretionary additions. Extensive delivery of water to Mars and Venus, centered ca. 4.1 or 4.0 Ga, is deduced in following sections. Permissive support for about the same timing for Earth comes from the age, ca. 3.9 Ga, of the oldest proved hydrous materials. Tonalites, which require substantial water in their melts, go back at least to 3.9 Ga. Seawater, as recorded by water-laid sediments and pillow basalts, was certainly present by 3.6 Ga, and ages as old as 3.9 Ga have been advocated but poorly documented (Hamilton, 2007b). As noted above, Hadean zircons, older than ca. 4 Ga, formed in felsic or intermediate igneous rocks and have compositions apparently indicative of low-water impact-melt fractionates rather than of endogenic hydrous melts.

## EARTH'S MOON

The Moon, like Earth, is popularly assumed to have had a long history of slow fractionation. Early differentiation of a thick mafic protocrust can be inferred instead. Hf isotopes of lunar Hadean zircons define origins of melts from low-Lu "basaltic" protocrust formed ca. 4.5 Ga (Kemp and Hawkesworth, 2014; their figure 6B), and other lunar features fit impact generation of post-fractionation melts. The surface-saturating late-accretion bombardment of the Moon by large bolides (Fig. 3) occurred between ca. 4.5 and ca. 3.8 Ga, probably with declining intensity. This provides the main basis for dating large impact structures on the terrestrial planets, which must have been similarly bombarded after they also reached essentially full sizes. The saturation-bombardment record has been almost entirely obliterated by recycling on Earth, but most of the record younger than ca. 4.5 Ga likely is still in view on Moon, Venus, and Mars.

### Prior Plumes Controversy

The Moon's craters and basins, as seen in telescopic images from Earth, were long and widely regarded as products of endogenic magmatism—by plumes, in current jargon. Bob Dietz and Ralph Baldwin argued, correctly, that they were impact structures, but it was not until optical images were received in the mid-1960s from some of the one-way Ranger rockets, showing obvious impact cratering down to meter scale, that majority opinion changed. Dietz also argued long ago that the maria are filled by impact melts. He was broadly correct in my view, although current popular opinion favors endogenic melts.

### Origin by Fission from Earth?

A fission origin of the Moon from Earth when Earth had reached essentially full size, had a metallic core, and still had a magma ocean, thus no later than ca. 4.50 Ga, appears to account for three sets of major constraints on the origin of the Moon better than does the popular giant-impact explanation. (1) The mean orbit of the Earth-Moon pair is almost circular and almost precisely in the ecliptic plane. (2) Earth and Moon have essentially identical isotopic ratios of oxygen, silicon, magnesium, titanium, potassium, tungsten, and chromium. Some of these ratios are different from those of most samples of material from other parts of the Solar System, and the ratios in different elements result from different processes and histories. (3) The Moon has a low bulk density, and at most a small metallic core, which precludes an Earth-like proportion of iron.

The Moon is widely assumed to have been produced by a giant impact on Earth—collision of a Mars-sized body with

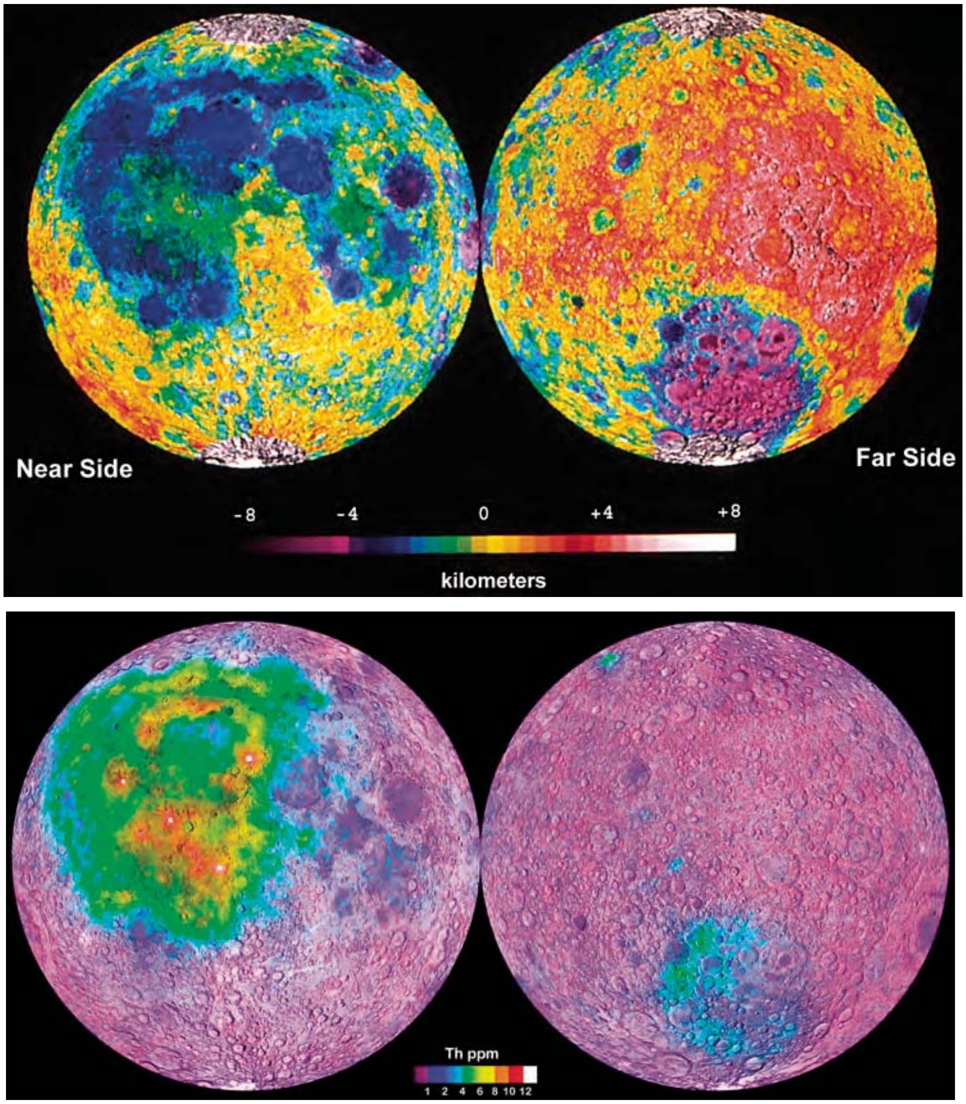


Figure 3. Top: Topography of front and back hemispheres of the Moon, illustrating saturation of the surface by impact structures between ca. 4.5 and 3.8 Ga. Bottom: Thorium content of surface materials. Diameter of the Moon is 3500 km. Clementine and Lunar Prospector maps provided by National Aeronautics and Space Administration.

Earth late in the main accretion phase, after separation of Earth's core. This suggestion appears to be incompatible with constraints 1 and 2 above, however, and can account for only constraint 3. Elkins-Tanton (2013, p. 696) wrote: "We are either modeling the wrong process [giant impact], or we have the process wrong." Canup (2013), Elliott (2013), and Stewart (2013) also flagged major problems with a giant impact.

Fission of the Moon from Earth also has problems, but warrants rigorous evaluation because it appears to be compatible with the three listed constraints and with the terrestrial magma-ocean argument presented earlier. Fission was advocated long ago by Darwin (1902), and subsequently by Wise (1963, 1969) and Durisen and Gingold (1986). The hypothesis, in current form, requires that Earth was spinning rapidly, its day less than 4 h long, when it reached its maximum size after separation of the core but while much of the mantle was molten. The final rapid rotation can be explained by preservation of angular momentum as the moment of inertia decreased via fractionation and self-compression of the growing Earth. Early rotation, and much else, cannot be explained with the popular models that begin with a 2-D proto–Solar System disk wherein the Sun forms before the planets. See Hofmeister and Criss (2012) for a 3-D approach to the problem, with simultaneous formation of the Sun and planets. This much changes angular-momentum considerations.

Another option, co-accretion of Earth and Moon, with initial formations at about the same distance from the Sun followed by capture appears to be incompatible with constraints 1 and 3.

## Evolution of the Moon

The popular model for lunar geology, developed 40 years ago mostly on the basis of tiny rock fragments in Apollo samples of polymict shock breccias, postulates prolonged crystallization of a magma ocean and of endogenic magmas, and a near lack of impact-generated melts other than shock-melted glass. This has many questionable aspects. See O'Hara (2000) for an extensive critique of its petrology, and Stöffler et al. (2006) for some of the age determinations that are difficult to explain with it. Post-Apollo orbiting vehicles have since added much information about composition, topography, and gravity. Figure 3 shows the surface concentration of orbitally mapped thorium, one indicator of magmatic fractionation, and Figure 4A illustrates a fractionated complex.

The surface-saturating bombardment of the Moon by large bolides is bracketed between ca. 4.5 and ca. 3.8 Ga. Studies of radiogenic products of short-lived radioisotopes indicate condensation of Solar System materials to have begun by ca. 4.567 Ga (references in Hamilton [2013]). The Moon had essentially its present size, and all or most of its fractionated crust, by ca. 4.46 Ga (the age of the oldest crustal rocks yet dated with a $^{147}Sm/^{143}Nd$ isochron) or ca. 4.42 Ga (the oldest zircon well dated by U/Pb; Nemchin et al., 2009). An earlier date of ca. 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). Imbrium, the youngest large impact basin on the nearside of the Moon, is dated by U-Pb analyses of impact-melt zircons as 3.92 Ga (Liu et al., 2012). A "late heavy bombardment" at about that time is often assumed but poorly documented. Large multi-ring Orientale impact basin, mostly on the farside hemisphere, appears to be somewhat younger on the basis of crater-count dating, perhaps 3.8 Ga. Large impacts must have continued at least this late on the terrestrial planets.

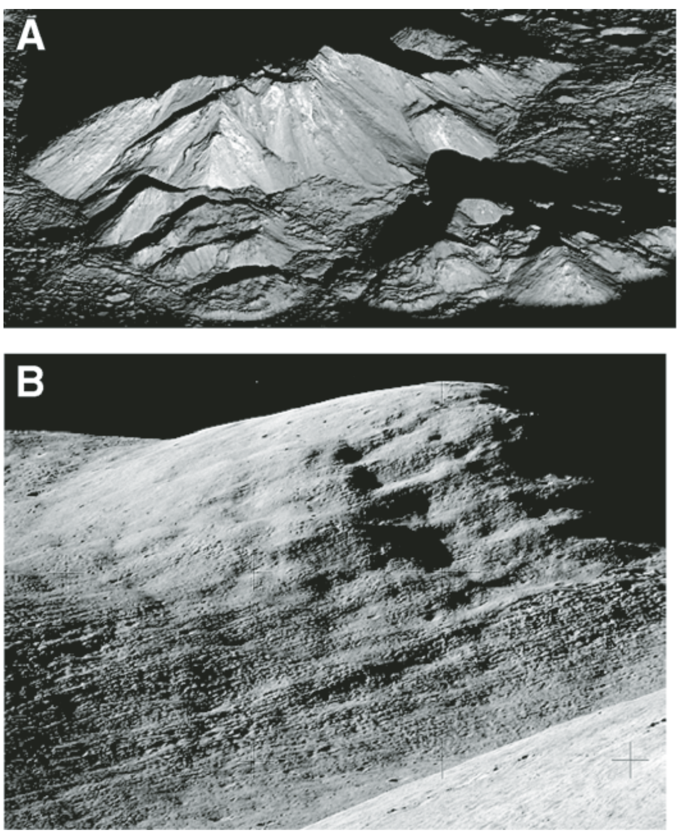


Figure 4. Layered rocks in lunar uplifts. A: Conical central uplift, ~2 km high, in 110 Ma Tycho crater. Spectroscopy indicates uplift to be of igneous fractionates. Lunar Reconnaissance Orbiter photograph from Arizona State University (USA). B: Silver Spur, a raised block in the southeastern rim of Mare Imbrium, relief ~600 m. Silver Spur is unsampled, and might be either sediments or layered fractionates that are older than 3.9 Ga. Apollo 15 70-mm photograph AS15–11250, from Lunar and Planetary Institute, Houston, Texas, USA.

There are no known exposures of mantle ultramafic rocks on the Moon (Greenhagen et al., 2010). The largest and deepest impact excavation, the South Pole–Aitken depression, ~2000 km in diameter, in the south part of the farside, displays a substantial Th anomaly (Fig. 3) that is presumably a product of differentiation of a thick sheet of impact melt. This accords with a large thickness of crust still beneath the basin floor, and casts doubt on the conventional chained assumptions of lunar evolution and gravity-topography-density relationships, from which only very thin crust is deduced for this crater (e.g., Wieczorek et al., 2013). South Pole–Aitken is saturated with lesser craters and must be quite old. Northwest of the center of the nearside is an even larger quasicircular topographically low region of high anomalies of magmaphile elements, including Th (Fig. 3), the KREEP-Procellarum region (KREEP is an acronym for some of the magmaphile components: potassium [K] + rare-earth elements [REE] + phosphorous [P].). As others have emphasized, this region may mark a huge fractionated still-older impact melt sheet or construct, recycled by subsequent impacts and, again, requiring a thick pre-impact protocrust.

The often-neglected constraint of gravity data on evolving mantle rheology is discussed primarily in the following section on Venus. Comparison of the lunar geoid (Wieczorek, 2007, his figure 7) and topography in those terms permits inferences that the KREEP-Procellarum impact products are fully compensated isostatically and are ancient, the highlands and South Pole–Aitken basin are partly compensated, and the young maria impact complexes are supported by near-rigid lunar mantle. The Moon may have been chilled to inactivity long before ca. 4.0 Ga.

Impact melts are limited largely to glass within impact breccias in most lunar interpretations. Even mare basalts are commonly assigned to endogenic melting, with or without contributing impact effects. I suspect that instead, complete impact melts were common. Age determinations of basalt fragments in Apollo and Luna breccia samples scatter down to as late as 3.2 Ga (Stöffler et al., 2006), when lunar impacts were still generating abundant shock breccias with impact-melt glass (Fernandes et al., 2013; their figure 8), and the impacts were producing heat for post-breccia melting (Fernandes and Artemieva, 2012). If the tiny Moon indeed remained hot through much of geologic time, then thermal conductivities require tidal heating, not retained heat. The proposal by Hofmeister and Criss (2013) that Earth's lower mantle is titaniferous is compatible with the extremely high titanium contents of some lunar basalts.

What formed the large highland regions of the Moon? Garrick-Bethell et al. (2014) removed calculated effects of large impact basins from topographic and gravity data sets and subjected the residual fields to spherical-harmonic analysis. They deduced degrees 2–4 to record primarily early tidal heating and asymmetric crustal fractionation of a then-molten Moon, thereby generating thicker highland crust. They further deduced that a frozen tidal bulge developed as the distance between Earth and Moon increased. A possible alternative to this may be that the anorthositic rocks, widespread in small exposures (Donaldson Hanna et al., 2014) and conventionally attributed to magma-ocean fractionation, formed instead as fractionates in early impact-melt constructs. Lunar anorthosites vary so widely in trace elements that a simple origin as a magma-ocean fractionate is implausible (Russell et al., 2014). The Moon's zircon dates, obtained variously from isolated grains in shock breccias and from crystals in fragments of granophyre (crystallized rapidly from high-T low-water granitic melt) and norite, scatter with decreasing abundance from ca. 4.4 to ca. 3.8 Ga (Pidgeon et al., 2010). These also may date fractionated impact melts. The early-fractionated basaltic source for lunar melts was noted above. I argue below that very large magmatic constructs were formed by impacts throughout the large-bolide bombardments of Venus and Mars.

### Arrival of Water?

Some lunar imagery (e.g., Fig. 4) shows layered rocks that might be either thick sedimentary strata or layered fractionates of impact-melt magma lakes, neither of which is considered to be present on the Moon in most popular models. The illustrations here are of the central uplift (Fig. 4A) in the floor of Tycho, a young impact crater, and of a raised block (Fig. 4B) in the southeastern rim of Mare Imbrium. The Tycho layering follows the conical central uplift, and so was subhorizontal before the impact. Layered rocks exposed in the left shoulder of the uplift are ~1.5 km thick. Spectroscopy from orbiter Clementine defines the Tycho uplift as of layered mafic and calcic igneous rocks (Tompkins and Pieters, 1999), which I would assign to a fractionated impact lake rather than to an endogenic intrusion.

The 600-m-thick section of layered rocks in the Imbrium-rim Silver Spur uplift (Fig. 4B) predates the 3.92 Ga Imbrium impact, and is the most convincing stratigraphic section of three Imbrium-rim mountainsides of apparently layered rocks photographed, but not sampled, by Apollo 15 astronauts. The geologists who studied the pictures (Swann et al., 1972) regarded the apparent thin layering in each of the three mountains to be illusions due to selective illumination of random fractures by a brilliant low sun because crossing sets of lineations were seen in the photographs of each site. Such illusionary crossings indeed appear within Figure 4B. However, the thick rubble-covered parallel slope-and-cliff layers that dominate high Silver Spur cannot be illusory, and their parallelism with apparent thin-layer striping throughout much of that photograph provides evidence for the stratigraphic reality of those thin layers also. Further, narrow canyons in lunar maria (e.g., Hadley Rille at the Apollo 15 site) that are commonly, but tentatively, ascribed to collapse of deep lava tubes (e.g., Howard and Head, 1972) have plan shapes and topography suggestive of rapid aqueous cutting, perhaps by flash floods from icy bolides that melted on impact.

The inference that the Imbrium impact exposed products of previous water flooding in the raised basin rim predicts that water-laid sediments should be present within the Imbrium ejecta blanket. Such materials can be inferred. Wilshire and Jackson (1972) illustrated and described the lithic clasts in Imbrium ejecta sampled at the Apollo 14 site. Most are very small, shocked, and thermally metamorphosed, and their primary fabrics have mostly been obliterated. Most lithic clasts are of rocks that were finely comminuted before, or by, the Imbrium impact. Many obviously are shattered igneous rocks, but many others could have been poorly sorted fine-grained sediments provided those were washed in from impact-comminuted mafic rocks. (The lander-sampled plains sediments of Venus are analogous in having approximately basaltic major elements.) Many lunar rocks and glasses are now known to contain small amounts of water (<300 ppm; e.g., Hui et al., 2013). Although lunar and terrestrial water is commonly assumed to be mostly primordial, it is suggested in this report that most of the water was added by a barrage of icy missiles from the then-outer part of the main asteroid belt. Perhaps a landscape analogous to the sedimented one of much of Mars is hidden beneath the space-weathered rubbly and impact-recycled surface of the Moon.

## POPULAR MODELS FOR EARTH, VENUS, AND MARS

The 1970s assumption that Earth's dynamics are dominated by fixed vertical plumes was applied to Venus and Mars, and dogmatized for them also. Core-driven plumes are now widely asserted to control the internal dynamics of Venus and Mars, but with utterly different non–Earth-like effects on each. Venus and Mars obviously lack plate tectonics, and both are popularly assigned stagnant-lid lithospheres that, however, respond to fixed vertical plumes in quite different ways. Venusian lithosphere is commonly speculated to have undergone intricate vertical deformation from beneath by plumes, without disruption, a half-billion years ago, and the resulting topography is conjectured to have been precisely maintained dynamically ever since by plumes of constant buoyancy and configuration. Plumes are popularly speculated to have fed long-continuing large-volcano magmatism on Mars, much of it concentrated in one region, while producing little horizontal or vertical deformation. The contrasts between postulates for the three planets underscore the implausibility of all of them, but geologic and geophysical interpretations of Venusian and Martian imagery are forced to accord with those speculations.

Counter interpretations of Venusian and Martian imagery, including impact effects, are made in following sections. The geology and geophysics of both planets shows them to have chilled at the protocrust stage and to have been inert targets for bolides for more than 4 b.y. They had thick mafic crusts before late-accretion saturation bombardment of their surfaces. They display no viable evidence for plumes, and they did not progress through subsequent dynamic and magmatic stages as did Earth.

## VENUS

Figure 5 shows Venusian topography with superimposed radar-backscatter brightness. Venus is almost as large and massive as Earth but shows strikingly different development. I argue that the visible surface of Venus is saturated with impact structures and impact-melt constructs from the 4.5–3.8 Ga era, that the conventional speculation that the thousands of observed circular structures were produced by young plumes and diapirs is specious, and that Venus has been relatively immobile internally since chilling soon after synaccretionary fractionation of thick crust. Venusian specialists, by contrast, consider Venus to have even more active core-driven plume circulation than they assume for Earth, confined beneath a fixed lid that is thinner than Earth's lithosphere but is undeformed horizontally, and to have plumes that have been precisely fixed in positions, thermal properties, buoyancy, and dynamics for perhaps half a billion years.

Earlier in this paper, I emphasized evidence that a thick basaltic protocrust formed on Earth by synaccretionary fractionation, and that a residual part of the protocrust has since been recycled downward to re-enrich the upper mantle and to enable subsequent tectonism and magmatism. The analysis in this section shows that no such late tectonism and magmatism, and hence no such recycling, affected Venus. The explanation for the cooling of Venus may lie in its lower radioactivity and slightly smaller size. The Venusian atmosphere contains only half as much $^{40}$Ar (a daughter isotope of radioactive $^{40}$K, half-life of 1.5 billion years) as does that of Earth. Solid Venus likely contains proportionately less heat-generating K (Kaula, 1999). A cooler lower mantle would be far more resistant to buoyancy displacements than even terrestrial lower mantle, which has circulation-inhibiting high viscosity and low thermal expansivity. A solid metallic core provides the obvious explanation for Venus' lack of a magnetic field, and eliminates the heat source popularly speculated to drive Venusian plumes. The surface temperature of Venus is almost the Curie temperature, so any crustal remanance once present has been obliterated.

### Ancient Impacts, Not Young Plumes, Dominate the Surface of Venus

Low-resolution 1970s and early 1980s radar imagery of Venus showed many rimmed circular structures, up to 2000 km in diameter, that had the apparent morphology and size/frequency distribution of impact structures. They were regarded as such by many contemporary interpreters, and recognized as requiring the surface of Venus, like that of Mars and Earth's Moon, to be ancient (e.g., Masursky et al., 1980). The present paper emphasizes the same conclusion. This direction of investigation

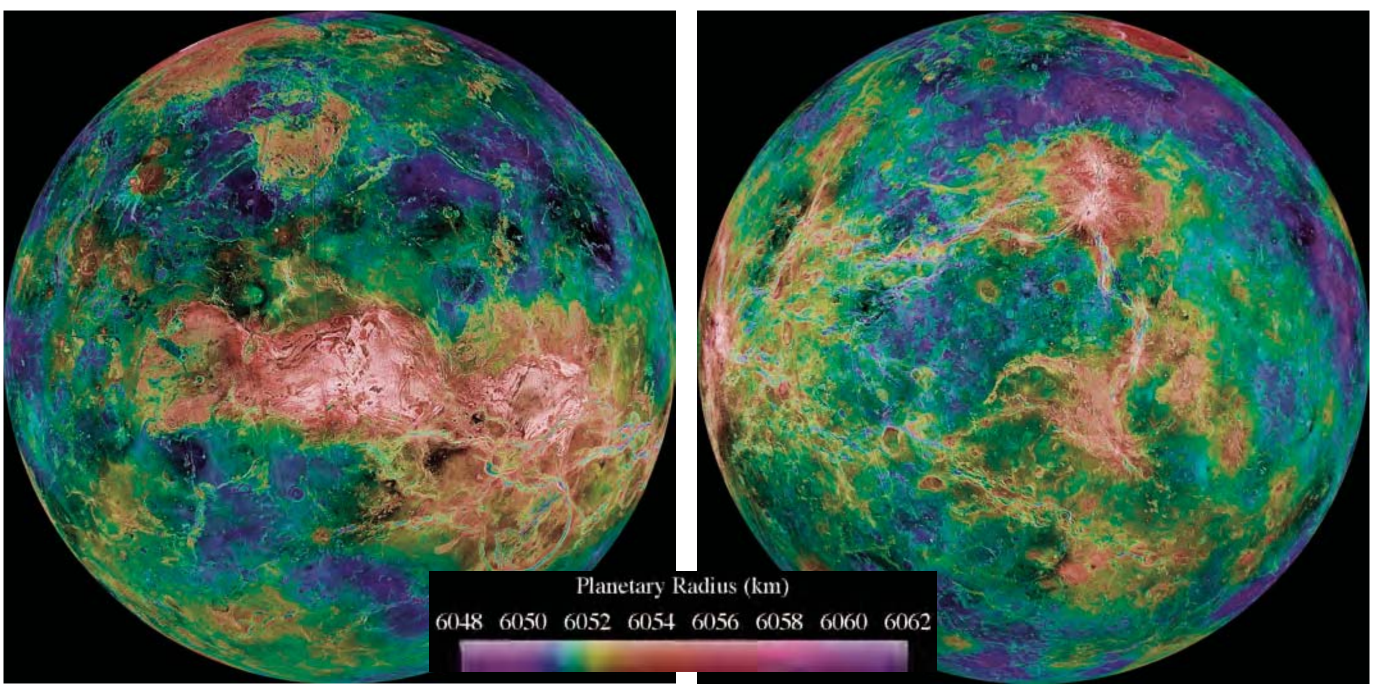


Figure 5. Topography of the eastern (left) and western (right) hemispheres of Venus. Altitude (as planetary radius; average is 6052 km) shown by color; radar backscatter brightness is shown by shading. Maps by U.S. Geological Survey.

was effectively blocked by prompt and widespread acceptance of speculation by Solomon and Head (1982) and Solomon et al. (1982). The evolution, internal dynamics, thermal structure, and physical properties they assumed for Venus, by analogy with those they assumed for similar-sized Earth, and without analysis of the Venusian structures at issue, precluded preservation of ancient surface features on Venus. They deduced that only young features could now be seen on the eternally mobile Venus of their conjectures. Impacts disappeared from published discussions in favor of endogenic processes before high-resolution radar imagery was obtained by orbiter Magellan in 1990–1994.

Many thousands of large circular structures, up to ~2000 km in rim diameter, were obvious in the imagery obtained in Magellan's first nearly full cycle of Venusian coverage, in 1990–92. Analysis of possible impact origins of these was not made by Venusian specialists because the 1982 conjectures cited above had become dogma. Concurrent with generation of that early Magellan imagery, Schaber et al. (1992) postulated that only ~800 small craters (subsequent additions raised the planetary total to ~1000), with rim diameters from ~10–280 km, scattered sparsely and randomly about the planetary surface and obviously relatively young, were essentially unmodified and obviously are of impact origin. All other circular structures, far more numerous and mostly larger, were simultaneously assumed, by default rather than by analysis, to be products of mantle plumes, which further were assumed to have resurfaced Venus in a catastrophic event late in its history (Head et al., 1992; Squyres et al., 1992; Stofan et al., 1992). These 1992 extrapolations from the 1982 speculations were in turn quickly dogmatized, and have since been elaborated in many subsequent speculative papers in the conventional literature. Herrick and Rumpf (2011) showed that most of the purportedly unmodified structures in fact are severely modified, but they too accepted the assumption that only this small selection of circular structures recorded impacts. The basis for discriminating purported young exogenic circular structures from old endogenic ones has not been objectively evaluated in mainline reports. Venusian imagery displays thousands of obvious large impact structures. There is no basis for the popular separation of products of impacts and conjectural plumes, as I illustrate in the next section (Hamilton, 2005, 2007c; Vita-Finzi et al., 2005).

Magellan slant-radar imagery is compiled into grayscale maps of backscatter brightness. The images superficially resemble optical photographs but contain quite different information, and casual observers often are misled. Backscatter brightness, unlike optical albedo, increases with surface roughness on approximately centimeter-to-meter scale for Magellan's radar wavelength of 12.6 cm; with increasing perpendicularity of slope to the look direction; and with surface electrical conductivity. Features buried beneath meters-thick surficial deposits can be imaged. The cross–flight line horizontal dimension of backscatter maps is proportional to slant range, not to optical angle, and is draped on generalized topographic models, which results in topographic illusions where actual local relief is high. Paired images with different inclinations of same-side slant-radar view can be examined with optical stereoscopy when their brightness patterns are similar, but these present other confusing topographic illusions. Paired images looking east and west are available for part of the planet, but structures can appear quite different when illuminated from opposite sides, and backscatter brightness in such pairs is commonly too different to allow optical stereoscopy. Magellan low-resolution nadir-radar altimetry shows many critically important features (e.g., Figs. 7 and 9) invisible in backscatter, but is disregarded in most conventional work.

Hamilton (2005, 2007c, 2011, 2013) presented Magellan radar backscatter-brightness images, and nadir-radar topographic images, of hundreds of the relevant circular structures at all scales. A few representative images are in this paper. These images show saturation bolide bombardment of both highlands and large parts of lowlands. Small to huge individual or superimposed impact structures are widespread. Cookie-cutter superpositions of many rimmed structures on others defy endogenic analysis. The popular distinction between the sparse small, young craters accepted as formed by impacts and the far more abundant, and mostly larger, craters and basins conventionally assigned to plumes and diapirs is arbitrary and inconsistent within a broad continuum. There are rimmed basins, resembling lunar maria but up to 2000 km in diameter, and also large, deep quasicircular depressions to 2500 km in diameter.

Aramaiti "Corona" (Fig. 6) is only one of many hundreds of rimmed circular structures that preserve apparent impact morphology and yet are assumed to have been formed by plumes. It is unusual in having been repeatedly singled out in conventional literature for conflicting detailed interpretation as formed by a plume. Aramaiti has a central peak, steep crater wall with slump blocks, and gently sloping lobate debris apron, the outer part of

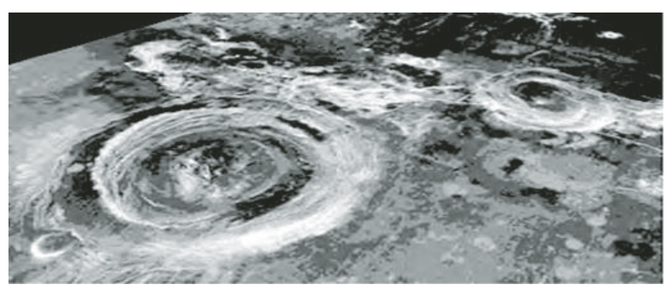

Figure 6. Aramaiti "Corona" (left) has impact morphology: circular rim, inner diameter ~275 km, slump scarps on inner wall, concentric central uplift, gentle outer slopes beyond which lobate ejecta blanket is visible on left; location 26°S, 82°E. Topography is softened by erosion, and ejecta blanket is partly buried by sediments. Interpretation: Aramaiti was produced by an impact on the floor of a shallow sea, and modified by submarine erosion and deposition. Radar-backscatter brightness draped on low-resolution topographic model with vertical exaggeration 3× to give pseudoperspective view, by Trent Hare, U.S. Geological Survey. Aramaiti has been repeatedly interpreted in conventional literature as a product of lithosphere deformation by a plume.

which is covered by younger material. Contours of all components have been smoothed by later processes. Among the mutually contradictory plume explanations of Aramaiti, none of which either evaluate the obvious alternative of an impact origin or are based on terrestrial analogues in any setting, are those by Grindrod and Hoogenboom (2006), Lang and López (2015), Squyres et al. (1992), and Stofan and Smrekar (2005). These postulate deformation of thin lithosphere above a plume by delamination, inward-directed overthrusting, collapse, and diverse other structural processes, none of which address, or account for, the classic impact morphology. Aramaiti appears to be a young structure formed by an impact in a shallow sea (see next section), into sediments that had buried the impact-saturated basement (compare with Fig. 7, of a different area).

Something like 80% of all of the Venusian circular structures that are arbitrarily excluded from the impact category, including most of those in the lowlands where hypothetical plumes cannot easily explain their abundance, and are simply omitted from conventional maps and discussions. Only about a thousand circular structures, and clusters thereof, selected mostly from the highlands, are given specific plume explanations. Speculations by different groups are often incompatible, as for just-noted Aramaiti, and one's rising plume can be another's sinking antiplume. The

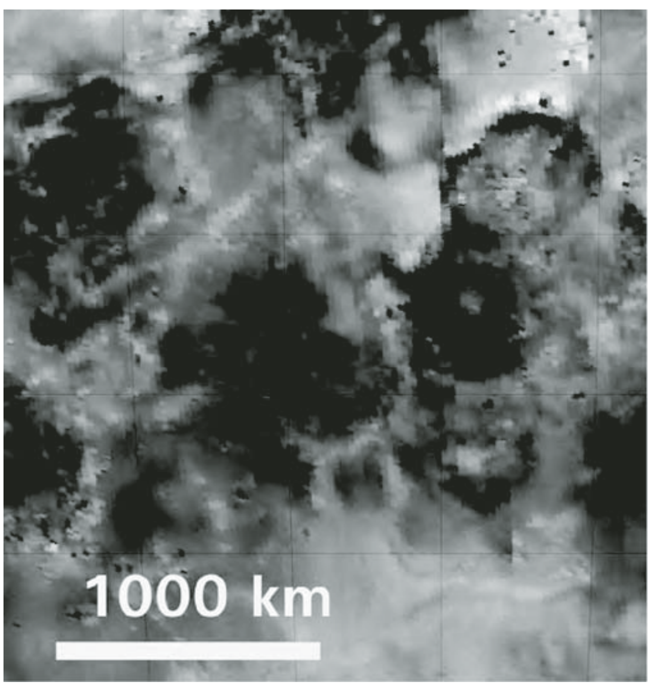


Figure 7. Nadir-radar topographic image of the mostly plains region from ~5° to 25°S, 30° to 50°E, light is high, dark is low, nonlinear scale, total relief ~3 km. The overlapping and variably modified rimmed circular depressions are interpreted as impact craters that saturated the basement surface and were covered by marine sediments that have been variably compacted into them. These features are mostly invisible in radar-backscatter brightness, and are overlooked in conventional work. Map by U.S. Geological Survey.

consistent circularity and impact morphology of the structures of all sizes are obfuscated in interpretations. A common approach (Jurdy and Stoddard, 2007, their figure 4) is to sketch irregular blobs outside rimmed circular structures, or around clusters of overlapping circular structures, and then to interpret the blobs as products of plumes and diapirs without considering the circles. Another approach uses a "perspective image," wherein confusingly rounded large-pixel nadir-radar columnar topography is exaggerated vertically by 20 or 30 ×. This has been done, for example, to Aramaiti (Squyres et al., 1992, their figure 16b). The resulting enormously high and lumpy images bear no resemblance to actual structures, and are cited to support speculations unique to Venus. Models of plume-raised landforms, involving intrusive magmatism, surface overthrusting or underthrusting or other deformation, and collapse into hidden plumes and diapirs, all mostly without surface volcanism, are proposed to explain circular craters and basins of all rim diameters up to 2000 km. Intricate classifications of postulated plume products, none of which either have terrestrial analogues or account for the circularity, are proposed. The most common are "coronae" of many subtypes.

Many highland bedrock areas are saturated with overlapping circular impact structures. In the plains, by contrast, sedimentation has buried most of the old structures, although in many regions they are still conspicuous in topography via sediment compaction (Fig. 7). Many lesser clusters of old structures also are obvious on the plains in backscatter images alone. Even where only relatively young and conspicuous structures are exposed, only a minority of small examples of those are classed as recording impacts. Figure 8 shows a wide range in preservation and modification of what I regard as impact structures formed during and after sedimentation and erosion in a transient ocean.

Estimation of the maximum age of the craters arbitrarily classed as of impact origin, and thereby the age of the popularly postulated plume-generated global surface constructed shortly before those sparse structures began to form, incorporates huge ambiguities. Uncertainties involve bolide flux and sizes, and also bolide types and their variable destruction in the superdense atmosphere. The maximum age that can thus be calculated for the craters accepted as recording impacts varies with the poorly constrained assumptions from ca. 0.3 to 3.8 Ga, the latter limit coming from lunar analogy. A young limit provides the fewest problems for plume speculations, and about ca. 0.5 Ga is commonly chosen. This is claimed to be the age of surfacing of the planet by a great surge of plumes that raised and contorted the highlands, with little volcanism, and of sinking antiplumes that pulled down the lowlands while somehow flooding them with basalt flows. Such explanations are mostly extrapolated from the 1992 speculative papers listed above.

## Aqueous Erosion and an Ancient Ocean

The elemental and isotopic composition of the Venusian atmosphere indicates that an ancient deep ocean was likely present (Kulikov et al., 2006). Superabundant visible geologic features

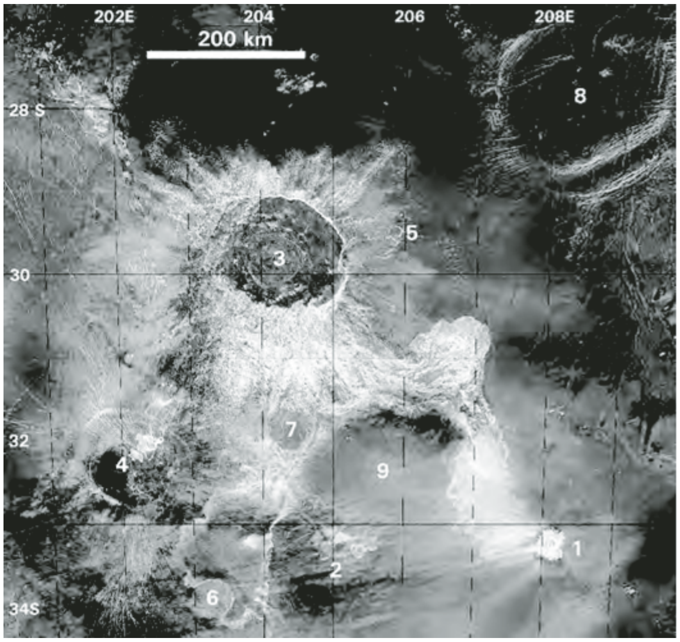


Figure 8. Radar-backscatter image of variably preserved impact craters, numbered in order of increasing age. 1—Tiny Cohn crater; 2—cluster of four tiny craters (above number); 3—Isabella crater, second-largest "pristine" crater on Venus, rim-crest diameter 175 km, filled by smooth sediment, outer parts of its lobate debris apron and its long runout to the southeast are smeared and subdued and presumably were submarine; 4—Deep crater, with rim 60 km in diameter, and ejecta apron, partly covered by Isabella ejecta; 5—Tiny Alimat crater (left of number) is buried except for its rim; 6, 7—craters with rims ~50 km in diameter; 8—mostly buried crater, rim diameter ~200 km; 9—rim of depression compacted above 200 km crater deflected Isabella ejecta. Several other more-modified craters can be seen in altimetry and larger-scale backscatter. Conventional reports accept 1, 3, and 5 as "pristine" impact structures, classify 4 and 8 as plume formed, and overlook the others. Map by U.S. Geological Survey.

support the same conclusion. However, conventional Venusian interpretations of Magellan imagery incorporate the assumption that because the surface temperature under the dense Venusian $CO_2$ greenhouse atmosphere now averages ~460 °C, and because all visible landscape features are assumed to be geologically young, the visible landscape cannot have been modified by liquid-water processes. It is on this basis that only minimally modified small craters are accepted as of impact origin, even though most craters so designated in fact are substantially modified. Herrick and Rumpf (2011) showed that only a small fraction of these designated craters preserve their initial radar-bright breccia fills, and that fills and ejecta blankets of most such craters have been variably covered by smooth radar-dark material. They assume this material to be un-Earthlike smooth basalt flows, even within craters too small to have generated much impact melt, whereas I regard them, like the vast radar-dark plains, as sediments. Variable modification of craters is shown on many of my published images, mostly in Hamilton (2005, 2007c), but including some in the present paper. Many of these images also display erosion of components. Faint ejecta lobes about many circular structures likely include radar visibility through thin cover. That the distinction between craters conventionally accepted as of impact origin and those relegated by default to plumes and diapirs is wholly arbitrary is obvious (Hamilton, 2005).

Both eroded bedrock canyons and distributary channels across the lowlands demonstrate past subaerial and submarine erosion and sedimentation (Jones and Pickering, 2003), but the conspicuous evidence for fluvial features and oceanic sedimentation has yet to be acknowledged in any mainline Venusian report. Radar altimetry, not considered in most conventional work, invaluably supplements backscatter imagery. The altimetry of Figure 7 shows a plains area to consist of variably buried overlapping impact craters, which are almost invisible on backscatter imagery of the same area (figure 13 in Hamilton, 2007c). Figure 9 shows erosional canyons, inconspicuous in the backscatter image but obvious in the paired altimetric map, that dissect a quasicircular plateau of the type I discuss later as a huge construct of impact melt, plus a younger moderate-sized impact crater whose circularity is more obvious in altimetry than in backscatter. Jones and Pickering (2003) illustrated morphologic details of other such canyons.

Figure 11 shows lowland distributary channels in its upper-left part. Venusian lowland channels have semiconstant rectangular cross sections, like those of terrestrial submarine distributaries of turbidites, which likely these are (Jones and Pickering, 2003). One channel is continuous for almost 7000 km with such a cross section. Venusian plume advocates explain it, and the lesser geometrically similar channels, as unique-to-Venus processes, including continuous collapse of lava tubes in regional lava sheets (Lang and Hansen, 2006), or melting by superheated lava rivers flowing across basalt plains (e.g., Oshigami and Namiki, 2005). Smooth-surfaced thin lobate deposits, spatially related to such channels and visible in backscatter-brightness imagery, were interpreted by Ghail and Wilson (2014) as pyroclastic flows, whereas I interpret them as subaqueous turbidites.

I interpret the radar-dark Venusian plains as formed by fine-grained sediments, derived primarily from impact-comminuted debris and deposited in a transient ocean, that variably cover an ancient impact-saturated surface, and that are themselves disrupted by many other impact structures. The plains are dark in backscatter brightness because their surface is smooth. They cannot be rough like most basalt, the conventionally assumed surface material. Optical-scanner pictures from four Soviet landers (reproduced as figure 21 in Hamilton, 2005) show the plains to consist of horizontally platy smooth material, as expected of undeformed strata statically metamorphosed by the hot atmosphere. The images were so interpreted in contemporary Russian work (e.g., Basilevsky et al., 1985). No pictures suggest ropy, blocky, or clinkery lavas that resemble terrestrial basalts. There are no plausible eruption sites for hypothetical flood basalts. There are vast fields of small randomly strewn low cones with smooth, gentle slopes, which resemble terrestrial mud volcanoes (but not steep and rough basalt cones, as per conventional assumption), and presumably record dewatering of underlying

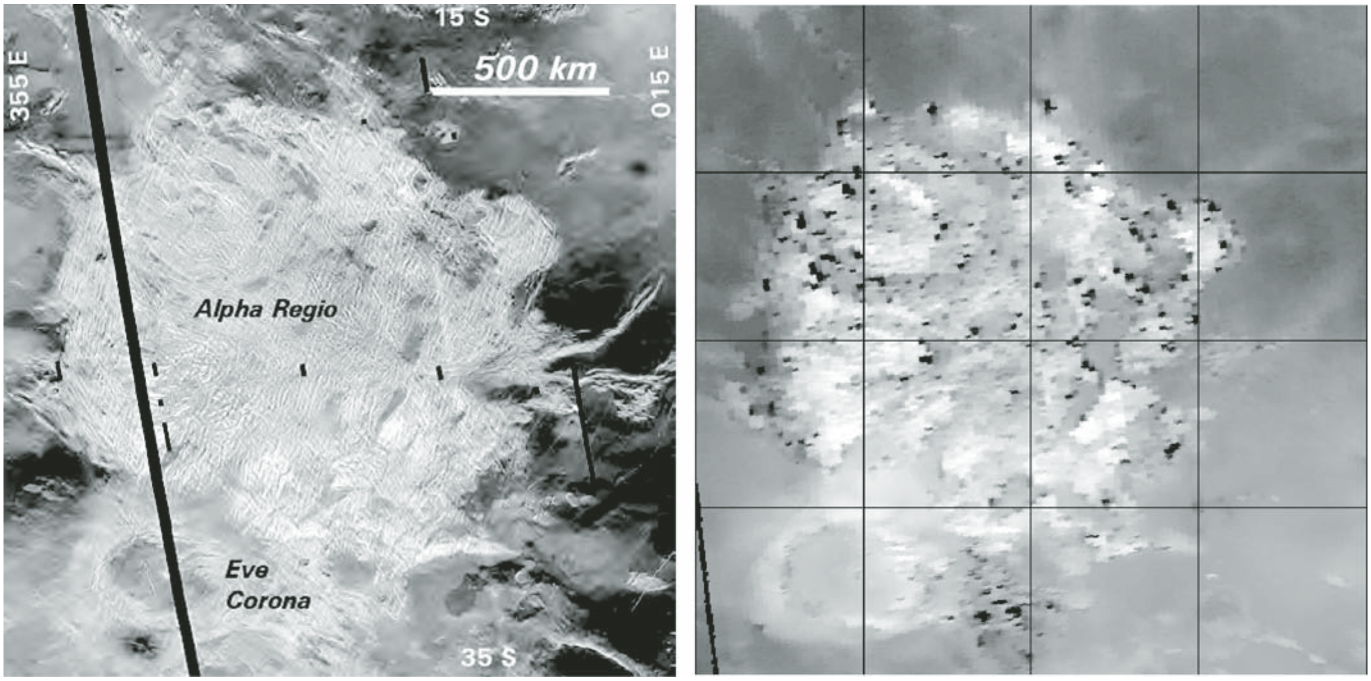


Figure 9. Paired images of eroded quasicircular Alpha Regio "tessera plateau." Left, east-look radar backscatter; right, nadir-radar altimetry, light is high, dark is low, nonlinear scale. Alpha Regio impact-melt pancake rises 3 km above plains, and is deeply dissected by broad valleys obvious in altimetry, but seen in backscatter only as small patches of smooth (radar-dark) sediments. The low summit region may be inherited from a large caldera. Note the circularity of impact-crater "Eve Corona" in altimetry, and its lobate ejecta blanket in reflectivity. Outer parts of both structures are covered by plains sediments, and the subdued character of Eve suggests a submarine origin. It is unclear whether the crater is older or younger than the plateau. Conventional view: plateau and "corona" are products of young plumes, and no aqueous erosion or deposition is recorded on Venus. Maps by U.S. Geological Survey.

sediments. The conventional view of the plains as formed of flood basalts cannot be reconciled with the simultaneous speculation (see the following section on geodesy) that the plains are pulled down by sinking cold plumes.

Venusian plains display large tracts of reticulated polygonal fracturing, or low-relief faulting, partly coextensive with fields of apparent mud volcanoes. The nested polygons-within-polygons are kilometers in diameter. Their obvious terrestrial analogue is geometrically and dimensionally similar, and similarly variable, polygonal faulting, which is now known from detailed three-dimensional seismic surveys to be widespread in marine basins of fine-grained sedimentary strata and to be produced by subsurface dewatering by compaction, which also generates associated mud volcanoes (Cartwright, 2007). The terrestrial structures are small-throw normal faults. Venusian and terrestrial examples are shown in Figure 10. Conversely, the similarity of the Venusian patterns to the terrestrial ones reinforce the interpretation that Venusian plains are floored by marine sediments. Venusian polygonal structures are seen on the surface, and, like the associated mud volcanoes, presumably record top-down dewatering as the sediments dried out following evaporation of seawater.

Many more Venusian examples of polygon-in-polygon deformation were illustrated by Smrekar et al. (2002), who assumed that the deformation must record some unique-to-Venus high-temperature process. They recognized that the polygons are far too large to be products of cooling of the basalt lavas they assumed to surface the plains. They speculated that the polygons formed by cooling of very thin crust regionally heated by huge shallow but unexposed magmatic intrusions, or else were produced by great changes in top-down climatic heating and cooling.

Seawater that decreased in depth with time seems widely indicated. Many relevant features are illustrated in Hamilton (2005, 2007c), and a few are shown in figures in this report. Regional seafloor deposition above crater-saturated terrain, followed by compaction into the structures accompanying desiccation, is widely represented (Figs. 7 and 8). Softening of impact morphologies by standing water varies from modest (Fig. 6) to severe, and indicates submarine formation. Thin sedimentary cover of some outer ejecta aprons suggests shallow-water impacts (Figs. 8 and 9). I have recognized no clear evidence for long-stable shorelines, but serial recessive shorelines can be inferred on some high-standing crater rims isolated in the plains. Highly fluidized ejecta with very long runouts (Fig. 8) may record variously impacts into shallow water, impacts into water-rich sediments, and impacts by water-rich bolides. Radar-dark crater floors presumably indicate erosion from inner walls.

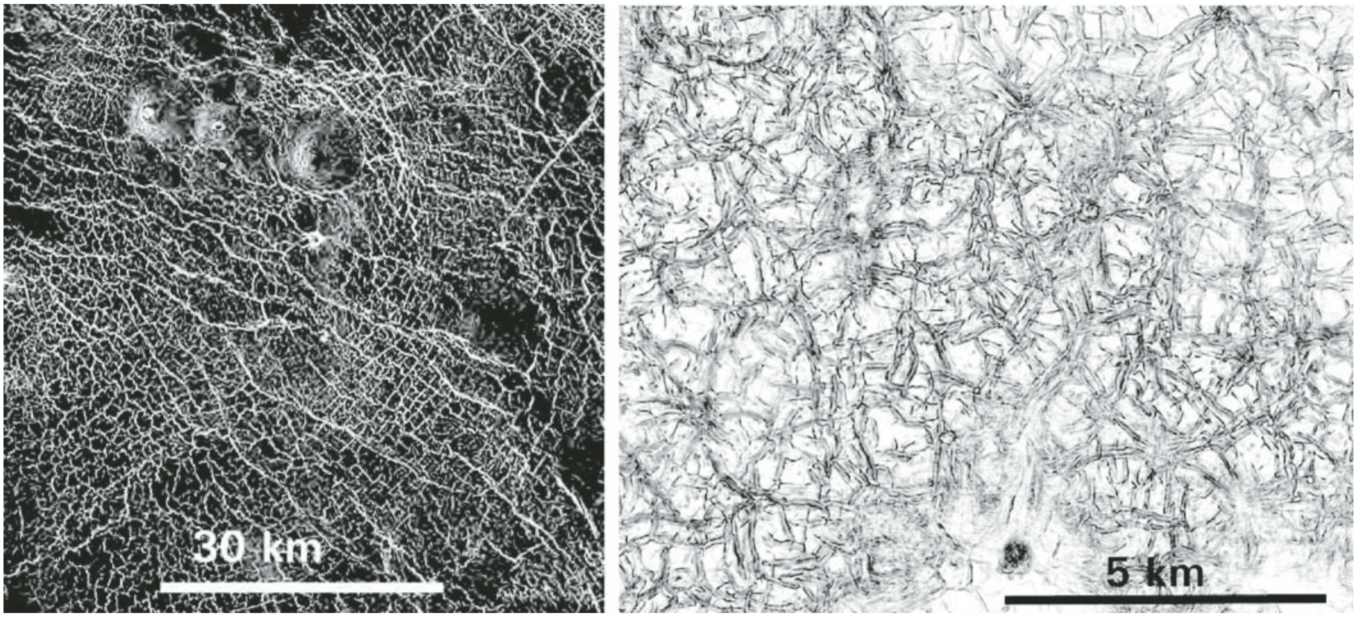


Figure 10. Polygonal faulting on Venus and Earth. Left: Polygonal faulting of radar-dark oceanic sediments of Venusian plains, ~29°N, 43°E. Smooth low circular hills in the north are mud volcanoes. Circular-arc fractures through the east half of the image likely overlie the buried rim of a large impact basin. (Conventional interpretation: A plain of thin basalt flows shows thermal-contraction joints, the low hills are basalt cones, and no sediments or impact basins are present on Venus.) Map by U.S. Geological Survey. Right: Polygonal faulting in the subsurface of Eocene sediments in the Møre Basin, North Sea, offshore Norway. Margins of nested polygons of various sizes are small faults produced by dewatering of fine-grained marine sediments; small circular structure at the bottom center is a mud pipe that fed a mud volcano preserved on a buried surface higher in the section. Horizontal slice through a three-dimensional seismic-reflection model, from Cartwright (2007), reproduced by permission.

## Arrival of Water

Venusian and Martian seas appeared late in the era of saturation bombardment by large bolides. The time of hydration was deduced previously to have been before ca. 3.9 Ga on Earth, and before 3.92 Ga on the Moon if it was similarly deluged, so simultaneous delivery centered on ca. 4.1 or 4.0 Ga may have affected all of them. The source of the water is suggested in the final section of this paper to have been a barrage of icy asteroids. On Venus, the resulting ocean gradually disappeared during a substantial period after cessation of large-bolide bombardment ca. 3.8 Ga.

## Geodesy and Venusian Mantle Rigidity

Geodetic evidence supplements the geologic interpretations that refute young-surface speculation and instead require long-lasting stability of topography and structure. Venusian geoid and topography show strong direct correlation at all wavelengths between ~1500 and 12,000 km (Steinberger et al., 2010; see also maps by Wieczorek [2007], or the contrasting maps of Venus and Earth by Catherine Johnson (Johnson and Richards, 2003) and David Sandwell (as available in 2005 on his ucsd.edu website) reproduced in Hamilton [2007c, 2013 (with a corrected Venusian topographic scale)]). The geoid reduction is a critically informative display of global gravity. It is the spherical-harmonic depiction of the altitude difference between a calculated global equipotential surface, sea level for example, and the planetary ellipsoid, minus the rotational gravity term. This derivation requires that at short wavelengths the geoid, like closely related free-air gravity, correlates directly with topography on a scale shorter than that of isostatic compensation. On a larger scale, Earth's continents, oceans, and mountain systems are almost invisible in the geoid because they are balanced isostatically in the hot, weak upper half of the upper mantle, and the dominant geoid signal gives information on deeper density variations. (The Bouguer gravity reduction, by contrast, in effect assumes that shallow isostasy does not function, and so its signal is overwhelmed by the long- and mid-wavelength correlation of regional topography that is compensated by shallow isostatic balance.)

The obvious explanation for the striking correlation between Venusian topography and geoid is that the topography is supported by strong upper mantle, and that the hot and highly mobile mantle, very thin lithosphere, and asthenosphere of Venusian plume speculation do not exist. Geodesist Kaula (1995) recognized the correlation to thus indicate an upper mantle far stronger and stiffer than Earth's, likely because of a very low content of volatiles and of cooler internal temperatures due to fractionation of most heat-producing elements into ancient mafic crust. Venusian plume advocates assert that, on the contrary, the correlation of geoid and topography indicates extreme mantle mobility, whereby dynamic uplift and downpull of thin lithosphere by positive and negative plumes, vastly more vigorous than the plumes they imagine for Earth, overwhelm static isostasy. Barnett and McKenzie (2000), Basilevsky and Head (2007), Dombard et al. (2007), Herrick et al. (2005), P.B. James et al. (2010), Smrekar and Sotin (2012), and Steinberger et al. (2010) are among the many who assume the Venusian geoid to be a proxy for dynamic vertical control of topography by extremely active rising and sinking plumes. As the *same* geoid-correlative topography is popularly attributed to formation by plumes a half-billion years ago, the sizes, configurations, thermal structures, buoyancies, and motions of those positive and negative plumes are postulated to have remained constant since then without producing further surface changes. A corollary of this conjecture is that circular structures produced by plumes and diapirs should be abundant in highlands and sparse in lowlands. This is widely asserted to be the case (e.g., by Dombard et al., 2007, and Jurdy and Stoddard, 2007). The omission of most lowland circular structures from maps and mention is thereby claimed to be evidence for their non-existence. The speculation also overlooks the conflict with the simultaneous conjecture that global plume-fed volcanism was almost entirely limited to vast basaltic floods formed above huge cold downwellings. I see both lowlands and highlands as saturated by ancient impact structures, variably obscured by sediments in the lowlands (e.g., Fig. 7) and by large impact-melt constructs in the highlands (discussed in the next section).

The popular assumption that extreme mantle mobility overrides the geodetic constraint on rheology liberates modelers to assume whatever properties and motions of hot mantle and crust they deem appropriate to illustrate endogenic explanations of observed features of any size. Kaula (1995, p. 1463) termed this "wish fulfillment." Thus, Smrekar and Sotin (2012) stated that Venusian plumes require a mantle much weaker, hotter, and wetter than Earth's—which does not increase the plausibility of their simultaneous proposal that fixed plumes and thermal columns have maintained unchanging dynamic topography through half a billion years. Substitution of chained assumptions of compositions, temperatures, rheologies, densities, and average thicknesses for the geoidal constraint allows calculation of thin crust as desired to support evolutionary speculations, shallow isostatic compensation, and hyperdynamic hot mantle. Herrick et al. (2005, p. 11) properly noted that their modeling of great mantle mobility was based on "debatable and largely unconstrained" assumptions, and Steinberger et al. (2010, p. 575) admitted that "Obviously, our results depend on a number of assumptions." Even the few modelers who thus acknowledge that they are merely illustrating speculations do not consider alternatives.

## Large Impact-Melt Constructs

So what did produce the middle- and large-scale topography that geodesy shows to be supported by strong mantle? Much of the answer lies in impact-generated magmatic constructs.

Figure 11 illustrates many Venusian features in a region about the size of North America. Low uplands of old rocks display abundant impact structures 100–600 km in rim diameter. The fewer lowland impact structures obvious in this backscatter imagery include doublets and cookie-cutter overlaps. The unearthly broad, but very low, "volcano" mostly within an impact basin, and the huge viscous-pancake "tessera plateau" of lava slumped from breaks in the rim of an impact basin 1500 km in diameter, formed from impact melts generated near the end of main bolide accretion. These features are only sparsely pocked by subsequent small impact structures, so lunar analogy would date them as ca. 3.8 Ga. However, everything in the area of Figure 11 is conventionally assumed to be endogenic and only perhaps a half-billion years old, except that sparse tiny craters, barely visible at this scale, are accepted as recording recent impacts.

Some Venusian "volcanoes" are seen to be enclosed by, or to overflow, circular rims of impact basins, within which I presume they formed by impact melting. Most such "volcanoes" within circular rims are concentric to those rims, and the eccentric one in Figure 11 records a low-angle bolide in my view. Venusian "volcanoes" are randomly scattered about the planet, and range in diameter from ~400 to 1000 km. They have far larger areas than terrestrial volcanoes, but non–Earth-like gentle slopes, typically ~1°. Conventional papers illustrate them with enormous vertical exaggerations to suggest analogy with terrestrial volcanoes (Fig. 12). They have single summits, commonly broad, often with very large shallow collapse calderas that require extremely extensive melt at shallow depth. All Venusian "volcanos" appear to have formed in single mobilization events. None show the prolonged growth of terrestrial volcanoes and igneous provinces. None show multiple summits, nested volcanoes, rift zones, or unambiguous flank eruptions. Venusian "volcanoes" formed throughout the era of large impacts, for they vary from greatly disrupted by large and small impact structures to sparsely pocked by small craters.

The quasicircular "tessera plateaus" (Figs. 9, 11, and 13) are larger, ~1200–3000 km in diameter and a few kilometers high, and also are popularly attributed to plumes. They too show a broad range in disruption by large and small impact structures (large impact craters cut the "tessera" remnant in the northeastern part of Fig. 7), so they also formed throughout the bombardment era. Direct evidence for impact is provided by the broken-rimmed and partly emptied melt-containing basin of Figure 11, outflow from which produced a plateau with diagnostic "tessera" flow structures. "Tesserae" have convex-upward profiles, very broad summit plateaus, and continuous structures that indicate spreading as single batches of mobile material. They display no incremental growth. Minimally eroded "tesserae" have surface patterns of folded compositional layers and shear fabrics, with axes subparallel to slope contours, that become tighter downslope toward the margins (Figs. 11 and 13). The enormous viscous-magma pancakes spread sluggishly outward in continuous single events. Hansen (2006) reiterated my impact-melt evidence and interpretation (Hamilton, 2005, p. 803–805 and her figures 18 and 19). (Hansen's previous papers explained

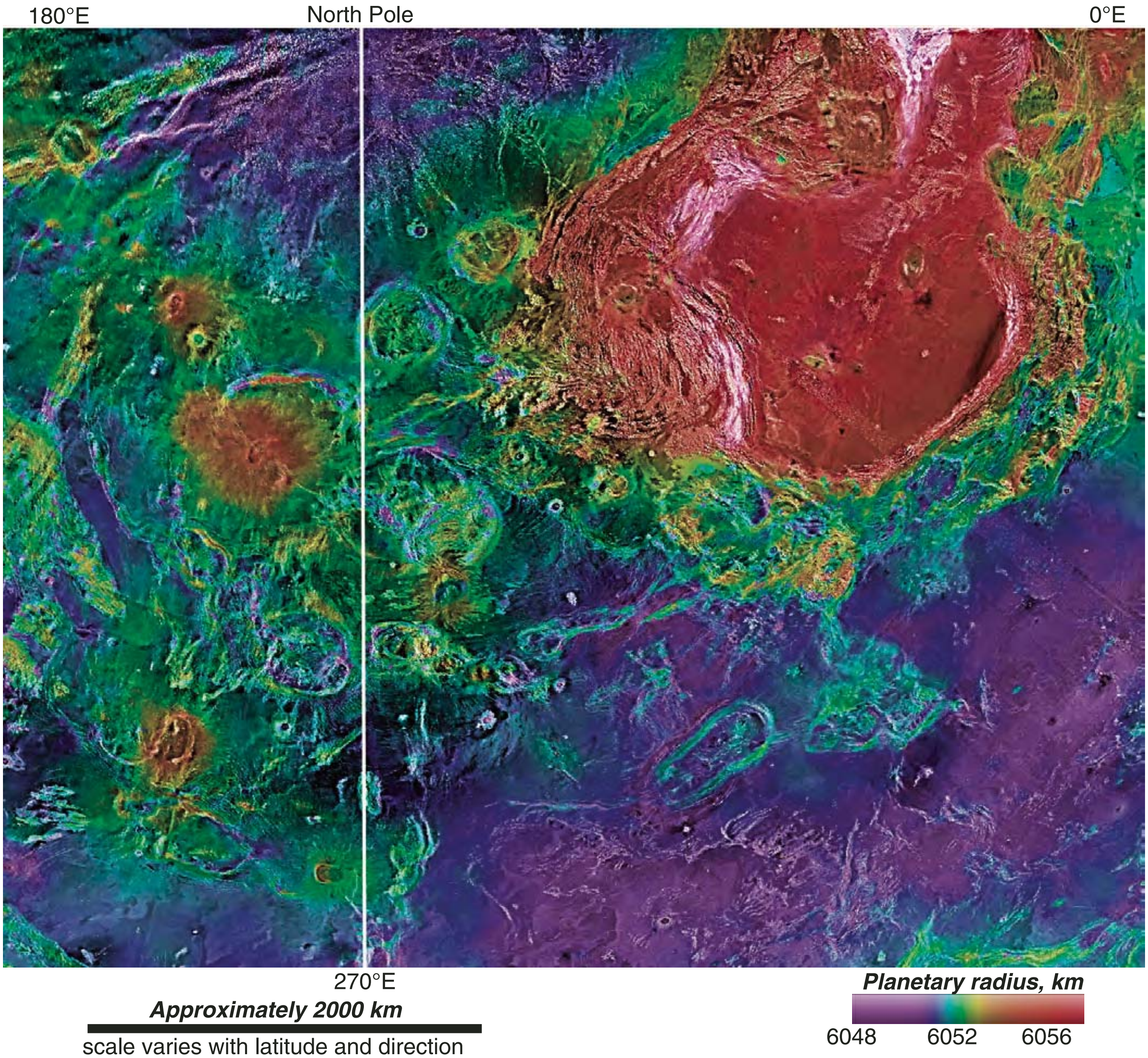


Figure 11. Part of the northern hemisphere of Venus, altitude shown by color, radar backscatter brightness by shading. The many circular structures, rim diameters 100–600 km, in the uplands are old impact structures; a few more show through lowland sediments. Huge flat-floored impact basin "Lakshmi Planum," upper right, contained its melt sheet in the southeast, but melt slumped out to the west, northwest, and north, and formed a "tessera" megaflow plateau. A broad "volcano," only ~2 km high (largest brown area west of the 270°E meridian), is of melt that flowed over much of the rim of the impact basin in which it formed; this crater is superimposed on an older crater to the west. (Everything in view is conventionally assumed to be of endogenic plume-related constructs, or products of circular subduction inward toward a descending plume, except for sparse small "pristine" impact craters, whose ejecta show at this scale as bright rings <3 mm in outside diameter.) Polar stereographic projection; corners of map, clockwise from upper left, are at 71°N, 180°E; 55°N, 0°E; 28°N, 313°E; and 42°N, 243°E. Map from U.S. Geological Survey.

Figure 12. Perspective illustrations of Maat Mons, Venus, with radar-backscatter brightness draped on a topographic model. Top: Image as published by Roth and Wall (1995, their figure 3.1) to illustrate "the tallest shield volcano on Venus," vertical exaggeration 23×. Bottom: Same image, without vertical exaggeration. The single-peak construct is broad but very low, shares no features with terrestrial volcanoes, and is regarded here as an impact-melt construct. The Mons is 400 km in diameter, and is centered at 0.5°N, 194.6°E.

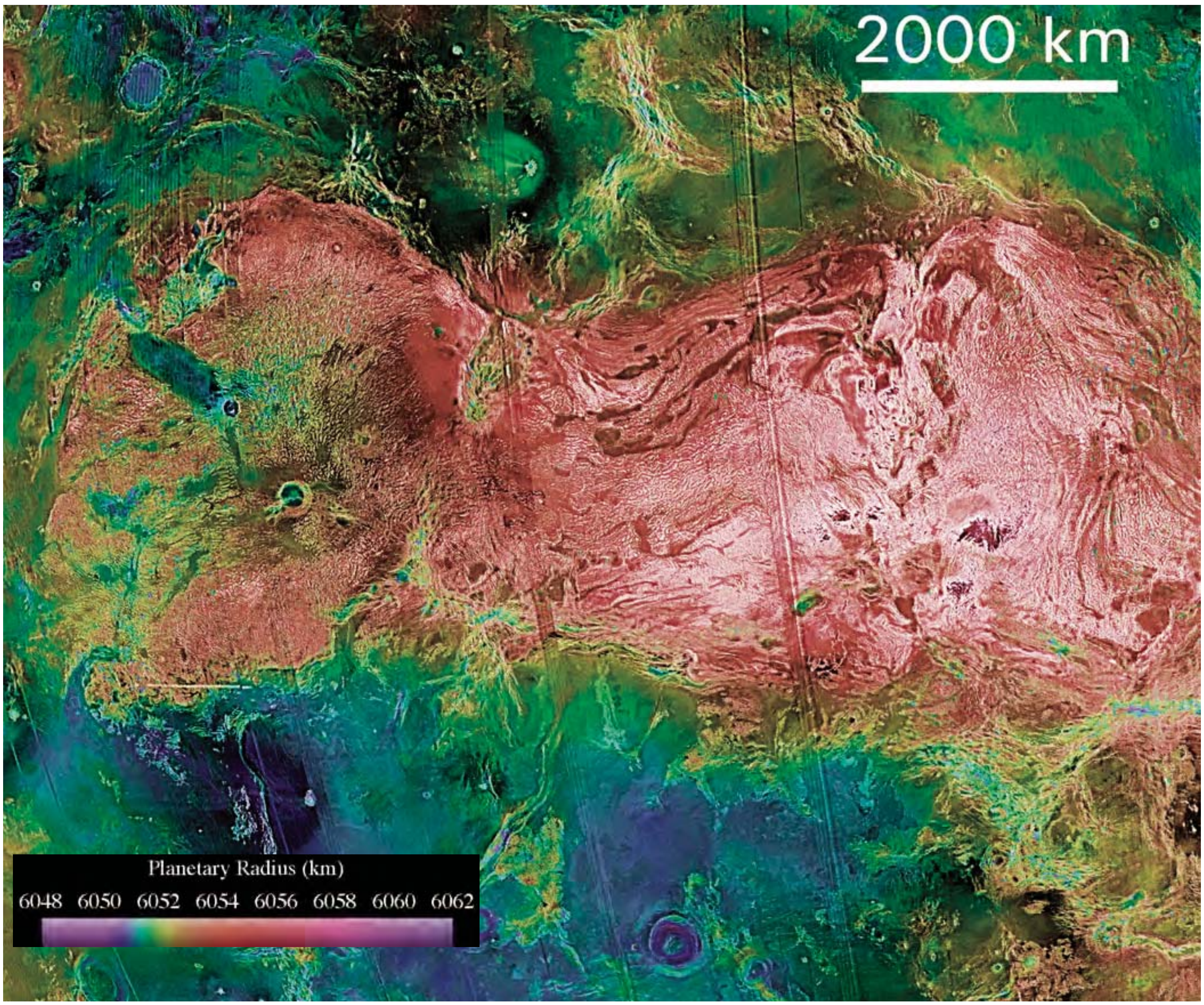


Figure 13. Ovda Regio highland, Venus, a composite of three "tessera plateaus" (mostly reddish altitude colors), constructs from three large impact melts like the Lakshmi one of Figure 11. Altitude shown by colors, radar-backscatter brightness by shading. Flow structures and outward-tightening flow fabrics show the two eastern giant pancakes to have been simultaneously mobile, spreading radially, stretching tangentially, and interfering along their boundary. Thus, they formed from simultaneous impacts. The western plateau is dissected by quasi-radial stream valleys and pocked by small pre-"pristine" impact craters, yet it also appears to have interfered with the simultaneously mobile central megaflow, so relative ages are in doubt. This enlarges the central equatorial part of the eastern-hemisphere map of Figure 5. Simple cylindrical projection, bounded approximately by latitudes 16°N and 27°S, and longitudes 45°E and 108°E. Map provided by U.S. Geological Survey.

"tesserae" first by diverse endogenic processes, and later [Hansen et al., 2000] by deformation of thin crust from beneath, plus magmatic augmentation, by huge plumes.) Thermal emissivity of some areas of the Venusian nightside, including Alpha Regio (cf. Fig. 9), has been measured by the Venus Express satellite through the near-infrared 1.02 µm window in atmospheric absorption. Such emissivity increases with content of ferrous iron in rocks, and may indicate "tesserae" to be surfaced by felsic rocks (Haus and Arnold, 2010), which is consistent with fractionation. Emissivity from that "tessera" is lower than from other types of terrain, which makes likely a composition low in ferrous iron, which would include felsic and anorthositic rocks (Gilmore et al., 2015). This accords with my inference that "tessera" are fractionated impact-melted magma lakes.

### Venus Discussion

The preceding information supports the conclusion that Venus, like Earth, fractionated as it accreted, and had a thick mafic protocrust above depleted mantle before 4.50 Ga. Unlike Earth, Venus chilled internally at this stage or soon after, and was subsequently a passive target for large bolides that continued at least until ca. 3.8 Ga. Meager data suggest that Earth shared this Hadean evolution. Earth's very different post–impact-saturation history was postulated above to be due to higher protocrustal radioactivity when water became available. A 50% lower content of Venusian $^{40}$K indicates total Venusian heat production from U, Th, and K to have been ~25% lower than Earth's at 4 Ga. This enabled generation of secondary TTG felsic crust from Earth's similar thick protocrust, and thereby inaugurated downward recycling of some radioactivity and fusible components that remained in densified residual protocrust. This in turn enabled continuing terrestrial upper-mantle activity, and ultimately an asthenosphere and plate tectonics. Nothing in visible Venusian geology suggests any such progression.

The many visible large magmatic constructs formed from the surface-saturating bombardment of Venus after it had attained essentially full size. The younger of these persist as large correlative topographic and geoid highs, and therefore formed after the mantle was cool and dry and any possible early asthenosphere had disappeared by cooling. The Venusian mass equator is controlled by this topography and is now close to the equator of very slow retrograde spin. The bombardment constructs must have caused the mass equator to shift erratically through time to keep it near the spin equator. The slight extension recorded by Venusian "rift" zones, and much of the regional fracturing of the surface, may be due to the stresses developed as Venus thus migrated through its axis. The rift zones typically follow broad ridges with very gentle slopes. These ridges commonly are drawn with enormous vertical exaggerations (e.g., Jurdy and Stoddard, 2007, their figure 3) to illustrate interpretations of plume uplift and collapsing arches that cannot be made with actual geometries.

The Hadean Earth must have had similar impact products. I presume, from meager evidence such as the zircon Lu-Hf data, that impact was then the dominant means of reworking of terrestrial crust, and that it was not superimposed on large-scale endogenic remelting of protocrust.

## MARS

I concur with Martian specialists that most of the surface was saturated by early bolide bombardment, and that the surface underwent great erosional and depositional modification by both running and standing water, source debated, and by wind. The compilation of Martian imagery at all scales, along with geologic descriptions by Carr (2006), illustrates the complexities and problems of Martian surficial geology. I disagree, however, with almost all investigators of Martian dynamics and magmatism. They assume their planet to have continuously active plumes beneath a "stagnant lid," which, in a manner unique to Mars, produce volcanoes rather than vertical crustal deformation by non-erupting plumes, as conjectured for Venus, or horizontal deformation by erupting plumes, as speculated for Earth. Details of popular speculations vary widely, but probably most common is the rationale that Mars heated slowly, and that its crust formed progressively from a mostly solid mantle by upward migration of partial melts (e.g., Zuber, 2001).

The argument by Hofmeister and Criss (2013) that radiogenic heat must have induced voluminous synaccretionary melting, and upward concentration of long-lived heat sources on Earth, applies also to little Mars, and there also precludes thorough remixing of the radionuclides back into the lower mantle. Empirical evidence is given by the large $^{182}$W and $^{142}$Nd anomalies, from short-lived Hf and Sm isotopes, of crustal meteorites from Mars. These indicate extremely early separation of core from mantle, likely by ca. 4.55 Ga, and formation of protocrust, or of secondary melts derived therefrom, by ca. 4.50 Ga (e.g., Symes et al., 2014). Such meteorites have long been cited as also recording crustal-crystallization ages throughout most of geologic time, and thus as requiring continuing Martian endogenic volcanism. Those purported dates, however, vary within single specimens depending on the isotopes used, and petrographic and other evidence shows them to be products of shock recrystallization (El Goresy et al., 2013) and aqueous alteration (Bouvier et al., 2008a). Popular models also incorporate the assumption that the crust has grown slowly through geologic time, as is imagined to be the case for Earth, whereas I infer formation of a thick protocrust by primordial fractionation, followed by impact reworking. Mars, like Venus, now has no dipole magnetic field, but local crustal remanent magnetization, detected by satellite, may be the product of such a field early in the period of surface-saturating bombardment. The core has likely been solid since soon after the planet reached essentially full size, with no heat available for driving hypothetical plumes.

Figure 14 shows the topography of Mars. I infer that the north-south lowland-highland dichotomy resulted from a huge impact during synaccretionary magma-ocean time, and that the northern lowlands are low because they received a thinner protocrust after loss of early fractionates. (I suggested earlier that formation of Earth's Moon produced a similar terrestrial dichotomy, long ago obliterated by horizontal tectonics.) This differs greatly from the common giant-impact explanation that the dichotomy represents a huge but shallow impact basin in a solid planet; Zuber (2001) argued against that option. The planetary mass equator is near the hemispheric boundary. The Tharsis upland, largest surface load on the planet, straddles the spin equator. Migration of the planet through its spin axis to move the mass equator to the spin equator may have caused some of the minor structural deformation of the surface.

Both the northern lowlands and southern highlands have similarly ancient bedrock surfaces, despite their widely varying covers of sedimentary materials. The bedrock surfaces of both are largely saturated by mid- to large-sized impact craters, to ~3000 km in diameter, visible in detailed topography where not obvious in optical and near-optical imagery (Frey, 2006). The craters are mostly buried in the northern lowlands, where they resemble the mostly-buried craters of the Venusian lowlands (Fig. 7 of this report). They are variably buried in the southern highlands, where conventional methods of counting little-modified craters have deduced illusory young basement ages. (Absolute ages on Mars are conventionally assigned by size/frequency statistics of young impact structures, in precise accord with assumed rates of bolide accretion, which has led to a wide range in inferred basement ages; but the less-conspicuous ancient craters have mostly

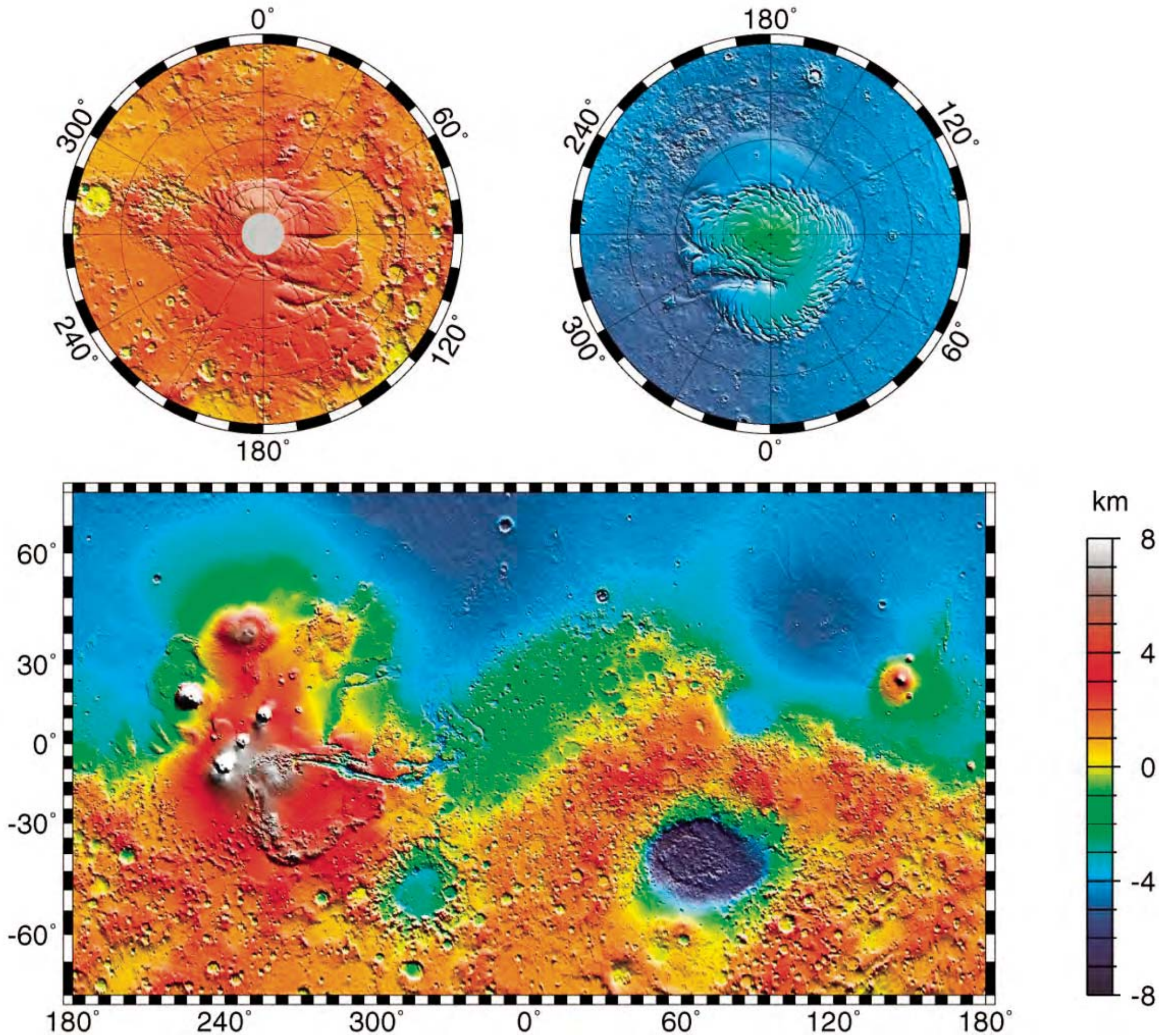


Figure 14. Topographic map of Mars, diameter ~6800 km. Three general topographic types are apparent: the mostly northern lowland plains, the mostly southern uplands with abundant obvious impact structures, and Tharsis plateau (region of high topography, red on map, and "volcanoes," centered near 10°S and 250°E). Mars Orbital Laser Altimeter (MOLA) map from National Aeronautics and Space Administration.

been omitted from analysis.) The Tharsis upland and young "volcanoes" are the dominant non-sedimentary features that postdate this ancient impact-saturated basement (Frey, 2006). Popular assumptions of slow growth and endogenic modification of Martian crust are invalid.

### The Hawaii Fallacy

The popular notion that Martian evolution has been dominated by core-driven plumes is based on the assumptions that Martian "volcanoes" so closely resemble the composite shield volcano of Hawaii island that the (now disproved) early plume speculations regarding Hawaii must be applied to Mars. Those assumptions were expressed by Carr (1973), and have been repeated by many authors (e.g., Greeley and Batson, 1996; Hiesinger et al., 2007; Werner, 2009). Martian "volcanoes," exemplified by Arsia Mons, and Hawaii, in fact are so profoundly different (Fig. 15) that they cannot share similar origins. Like other Martian "volcanoes," Arsia is a broad single-peak construct with concentric structure indicating single-event mobility. Its enormous shallow caldera is as large as the entire above-water island of Hawaii, and has an area 1000 times that of the largest caldera on Hawaii. Arsia's caldera requires a vast area of simultaneous melt beneath thin cover, which has never occurred at Hawaii. Irregular Hawaii is a composite of five volcanoes at the surface, and its exposed rocks span almost a million years of volcanism. The false analogy has been repeatedly asserted to require the Martian constructs to have formed by incremental eruptions of plumes from deep mantle active for long periods (summary by Werner, 2009). In the next section, I explain Arsia and the other Martian "volcanoes" as products of bolide impacts. Numerous reports claim that Martian "volcanoes" have erupted densely overlapping, or widely scattered, small lava flows over long periods (e.g., Carr, 2006; Isherwood et al., 2013; Platz and Michael, 2011; summary by Werner, 2009). I see the relevant imagery as showing instead non-volcanic deformation and depositional and erosional features of aqueous and mass-wasting processes, the latter often cryogenic. The features bear no resemblance to terrestrial lava flows, such as Hawaiian flows erupted from dike-fed rifts radiating from individual volcanic centers (Fig. 15). (For a well-illustrated conventional analysis of Arsia Mons as having had a long history of magmatism, which I reject, see Garry et al., 2014.)

Some of the most conspicuous Martian "volcanoes" are concentrated in a fraction of one hemisphere. Several are speculated to have been active throughout much, even most, of Martian

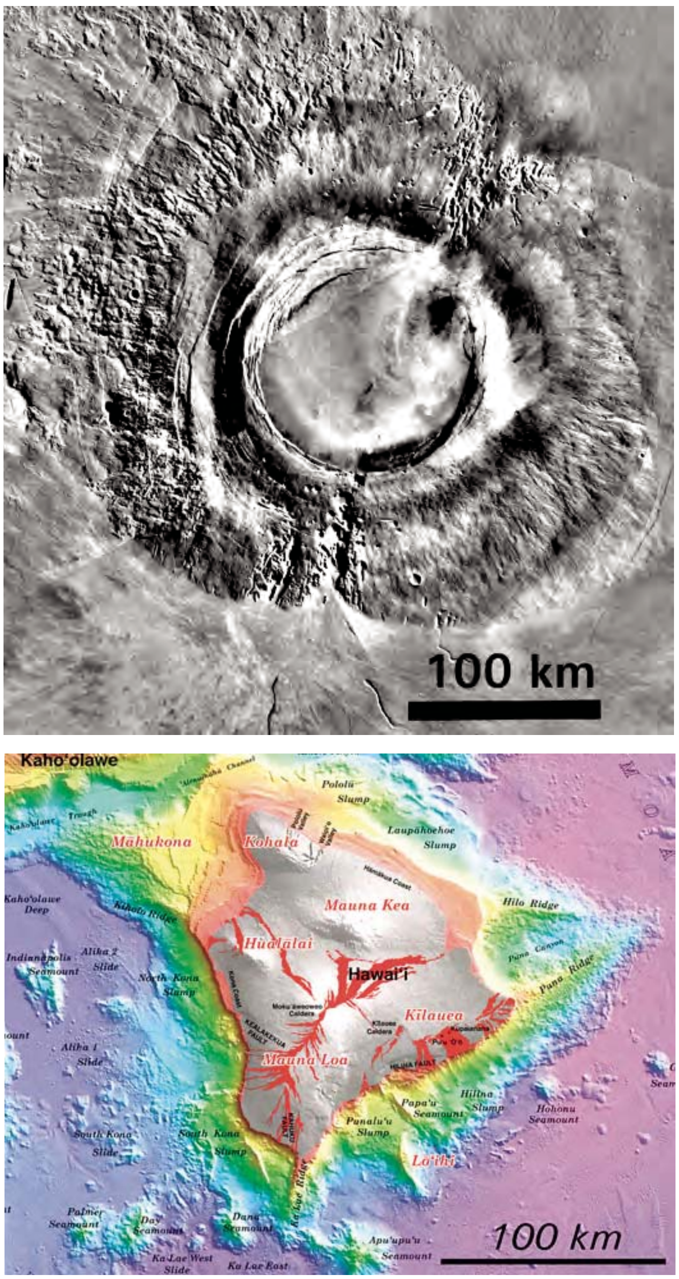


Figure 15. Martian impact-melt construct Arsia Mons compared with Hawaii, one of Earth's largest volcanic edifices. Each rises ~9 km from its base, Arsia from Tharsis plateau, Hawaii from Pacific Ocean floor. Top: Arsia Mons "volcano." Its huge shallow circular caldera is as large as the area of irregular Hawaii is above sea level, and sagged into the enormous mass of shallow melt. Concentric structure further defines flow as a single event. Arsia is centered at ~9°S, 239°E. Viking Orbiter imagery from U.S. Geological Survey. Bottom: Island of Hawaii, gray above sea level; historic lava flows, mostly from dikes along lateral rifts, are in red; ocean depths are colored downward to magenta, ~5.5 km. Hawaii is a composite of five volcanoes at the surface and presumably more in the subsurface, and grew by frequent small increments of magma (historic ones are colored red); shallow subsurface melt never had a large area, and the largest caldera is only ~4 km across. Edges of map are at ~154.2°W and 156.8°W longitude, and 18.5°N and 20.5°N latitude. Map segment from Eakins et al. (2003). The claim in numerous papers on Mars that Arsia Mons and other Martian "volcanoes" closely resemble Hawaii, added to the assumption that Hawaii sits atop a plume from the deep mantle, provides the basis for the popular geodynamic model of Mars.

history (e.g., Carr, 2006; Isherwood et al., 2013; Werner, 2009). A single permanent plume is often invoked. Zuber (2001) proposed that core heat was long concentrated by continuous subhorizontal flow of the entire lower mantle into a single rising plume. Sekhar and King (2014) speculated that, on the contrary, ancient heat accumulates in the mantle and is released to plumes as needed, and that two dozen core-driven plumes may now be active beneath non-deforming lithosphere. Both approaches violate the second law of thermodynamics. Only Ruedas et al. (2013), among dynamic modelers, found that they could not justify a permanently hot core and avoidance of mantle fractionation, but they nevertheless accepted geologists' plume conjectures, and speculated that unknown processes maintained similar circulation after the core chilled. I know of no Martian modelers who have regarded problems with such conjectures as warranting evaluation of the assumption that plumes operate on Mars, or on Earth, or who have discussed the physical-principles and empirical problems with the early-1970s terrestrial speculations that they illustrate for Mars.

## Large Constructs of Impact Melt, Not Plumes

Purported Martian endogenic volcanoes share features that I regard as requiring them to be impact-generated melt constructs. Like Arsia, they are broad circular single-peak structures. The higher ones show concentric morphology consistent with sluggish spreading of voluminous single-event melts. Most Martian "volcanoes" of all types have broad, shallow summit calderas that require huge near-surface magma accumulations. They lack intergrown volcanoes and eruptive rift zones. Incremental and peripheral volcanism is often postulated but nowhere well documented. Flank slopes of many are only a degree or so, and slopes of high ones are only moderate. Like Venusian "volcanoes" (Fig. 12), they often are illustrated with large vertical exaggerations that enhance analogies with terrestrial volcanoes (e.g., figures 3.3 and 3.10 of Carr, 2006). Sediment-mantled concentric topography extends far out around some "volcanoes," including Pavonis and Ascraeus Montes, and may hide ejecta blankets.

Low-domiform "tholus volcanoes," and still lower "patera volcanoes," also are almost circular, also are single-summit masses, and also lack terrestrial analogues. Low Tyrrhena Patera (Fig. 16), for example, in the southern highlands, has extremely gentle slopes. It is centered within a narrow circular-ring ridge or depression 300 km in diameter, which I presume to be expressed in sediments deposited partly above, and partly just inside, the rim crest of the impact basin in which melt was generated. Like other Martian "volcanoes" of all types, Tyrrhena has no multiple summits, rift eruptions, or other signs of incremental magmatism to suggest an endogenic origin rather than a single impact event, although feeding by a long-active plume is conventionally assumed.

Giant Olympus Mons, considered the largest volcano in the Solar System, is the favorite plume product for Martian specialists. I regard it as an impact-melt construct mostly contained

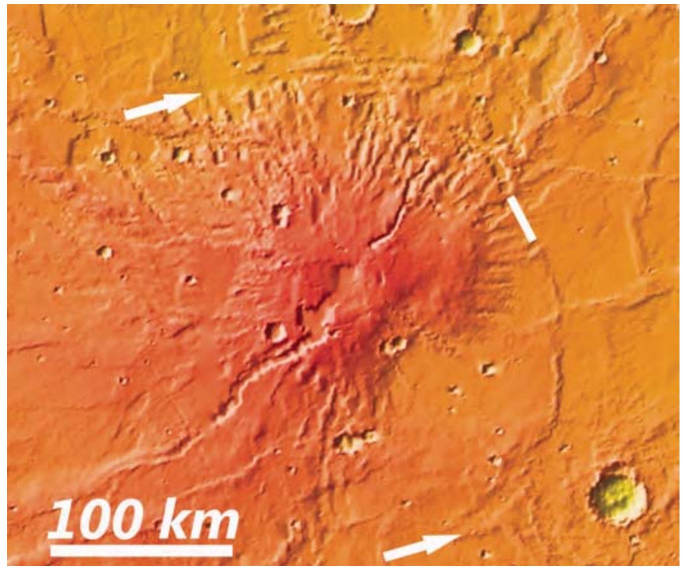


Figure 16. Tyrrhena Patera, Mars, a broad conical rise commonly assumed to be a volcano although it is far too low (~1500 m high) and gentlesided (~1°) to have a terrestrial analogue. It is in the center of a half-circle narrow trough and ridge, marked in white, in sediments inferred to overlie the rim and inner scarp of the impact basin in which the melt formed. Thick blanketing sediment is postdated by small, scattered impact craters. Location 22.5°S, 106.5°E. Mars Orbital Laser Altimeter topography, color scale same as Figure 14, from National Aeronautics and Space Administration.

within its impact basin. The top image of Figure 17 shows the circular mons and its enclosing rim, and the middle plots are true-scale topographic profiles. The Olympus construct is enormous, although much gentler than usually depicted with vertically exaggerated pseudo-perspective views. The shading of the digital topography makes the slope of the bounding outer slope look like a cliff. It is instead a low and gentle slope where the initially circular outer rim has not slumped out, along the west side and much of the southeastern margin, and higher and steeper where the original rim was destroyed by slope failure. The slumped-out sectors produced debris flows and fans, clearly shown on the image, that extend 200 km from the southwestern and northeastern ruptures, and from the short broken sector of the rim due west of the summit caldera. The Olympus construct, like Arsia, has concentric symmetry. Like other Martian "volcanoes" and Venusian impact constructs, it appears to record a single event, not incremental growth, and lacks the features expected by analogy with terrestrial volcanoes, which are much smaller than this. Olympus has a huge caldera, ~65 × 80 km, on its single broad summit.

Martian plume advocates assume their "volcanoes" to have grown by small increments of lava erupted over long periods, and assume eruption rates based on a hypothetical 1970s-style Hawaiian plume. Pipes from the core-mantle boundary are thereby deduced to have filled many times, even over billions of years, each time delivering new melt that migrated hundreds of kilometers laterally in a volcano and beyond and then erupted small flows. For example, Isherwood et al. (2013) inferred that Olympus Mons volcanism began ca. 3.7 Ga, and that incremental plume volcanism in the region continues to the present. Their paper focuses on a single conjectural young lava flow, source unknown, expressed as an irregular low contour-parallel ridge along the convex-upward frontal slope of the regional apron of Alba Mons, 175 km upslope from its base and 450 km from Olympus Mons. It is to me only a small part of the concentric topography of that vast apron. I see no evidence in imagery or topography that, as Isherwood et al. assume, the ridge is of lava that flowed down a paleoslope in previously unrelated topography that was deformed by Olympus isostatic compensation to become part of a smooth regional slope that trends almost directly away from distant Olympus.

The lower image of Figure 17 places Olympus Mons in the context of its vast surrounding "aureole" of a double layer of sheet deposits of far-traveled material, which I take to be fluidized impact breccias. The sheets are well exposed clockwise from southwest to northeast around the mountain, and are exposed discontinuously around the other half. The sheets predate the fans and mass-wasting materials, noted above, that extend no more than 200 km from the mountain rim and cover contacts between sheets and rim. The lower, and more extensive, sheet traveled as far as 750 km northwest down a pre-Olympus slope of ~0.2° to end with an almost circular front. The exposed part of this sheet is mostly in the duller green altitude tint on the figure. Overlying this, and not extending as far, are huge lobes of rougher-textured material that comprise a higher sheet. The well-exposed parts of both sheets are minimally pocked by subsequent impact craters, so direct lunar analogy suggests an age of ca. 3.8 Ga. Both sheets show concentric and radial ridging near their termini, and less-regular structure further back.

What are those sheets? They commonly are assumed to be mass-wasting or landslide debris from the broken Olympus rim. See Carr (2006) for a list of some of the conflicting detailed speculations. This not only is implausible in terms of the sheets' thinness, vast extents, and gentle slopes, but is disproved because the actual debris from the broken rim moved less than 200 km and covered the near-Olympus parts of the sheets (Fig. 17, top). De Blasio (2011) likened the vast sheets to submarine megaslides from collapsed terrestrial oceanic-island slopes. The best relevant

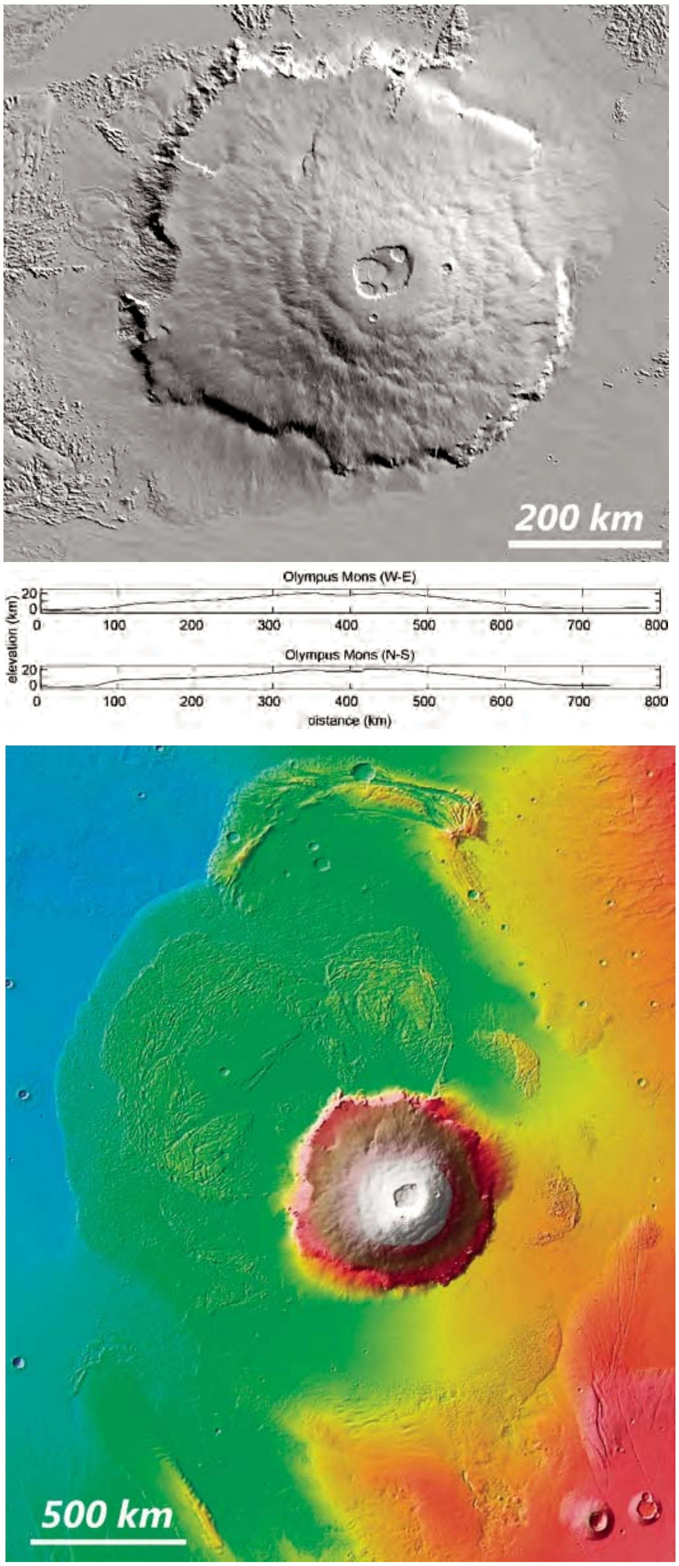


Figure 17. Olympus Mons, Mars. Top: Shaded Mars Orbital Laser Altimeter (MOLA) topography of Olympus Mons and its variably slump-broken impact-basin rim; from National Aeronautics and Space Administration. Middle: Topographic profiles across Olympus Mons, no vertical exaggeration, provided by J.C. Andrews-Hanna, Colorado School of Mines. Bottom: Altitude-colored MOLA topography of Olympus Mons and, mostly in green altitude tint, its fluidized ejecta blanket. The west edge of Tharsis plateau is the red region along the east side. Altitude color scale same as Figure 14. Mercator projection; bounding latitudes equator and 40°N, longitudes 205°E and 240°E; from National Aeronautics and Space Administration.

bathymetry of such is of the many slides around the Hawaiian Islands, which are typified by blocks kilometers in diameter, and do not extend nearly as far as the Olympus materials (Fig. 15; Eakins et al., 2003). Some investigators have inferred the sheets to be lavas or pyroclastic flows from Olympus, although they have neither Olympus vents nor terrestrial analogues.

The sheets obviously formed from fluidized material. They are related to the Olympus impact, in my terms, which occurred after most of the sedimentation of its region. The sheets cannot be deposits of ballistic ejecta from dry targets, for they lack the radial streaking, rays, and narrow lobes of such materials. I presume the sheets to represent ejecta from an impact into thick sediment that contained abundant intergranular, and perhaps also overlying, ices of water and other volatiles that melted on impact. Underwater deposition might also have been involved. The far-traveled basal sheet formed from low-angle ejecta, and the overlying large lobes from higher-angle material. Analogous two-layer ejecta of small Martian craters were explained as products of impacts into surficial snow and ice by Weiss and Head (2014). Slippery clays may also have been a factor (cf. Watkins et al., 2015).

Alba Mons, formerly Alba Patera, the huge sediment-blanketed quasicircular very low upland centered at 41°N, 250°E (Fig. 14), is another obvious impact candidate. I infer its huge apron, ~2000 km in diameter, to be a sediment-covered fluidized ejecta sheet. The sheet terminates, like the well-exposed younger Olympus one, at a broadly curved front (Carr, 2006, his figures 3–11).

The numerous other Martian "volcanoes" are similar to those just discussed, and also likely have impact origins. The three aligned "volcanoes" of Arsia, Pavonis, and Ascraeus Montes, for example, are similar in appearance, preservation, and partial sedimentary covers, and I presume them to be products of a large bolide that disintegrated before impact. I suggest that the much-modified but post-planetary-basement Tharsis Plateau formed as a large impact-melt construct, analogous to the "tessera plateaus" of Venus.

Isolated small young volcanic eruptions also have been inferred by Martian geologists. Thus, Broz et al. (2015) argue that complexly impacted, eroded, and eolianite-covered ancient lake sediments in the southern highlands are overlain in one region by small and widely dispersed lava flows and domes. I see their images and highly exaggerated profiles as instead showing some mud volcanoes (products of top-down dehydration of sediments) and some products of mostly eolian erosion of, and deposition on, horizontal lake beds. The Broz et al. analogies with terrestrial silicic-lava domes in strongly extensional volcanic fields, and as minor eruptions in continental arcs, are rendered irrelevant by both settings and detailed morphologies. (I have seen many of these earthly features in the field.)

Conventional planetary geologists do not consider large impacts capable of producing positive topographic elements, as I advocate here for Venus and Mars, and as Vredefort, Bushveld, and other complexes must have been originally on Earth. Popular models for evolution of the three planets remain anchored to hypothetical plumes, which are speculated to behave altogether differently on each planet.

**Martian Mantle Rigidity**

The correlation, or lack thereof, between surface topography and the geoidal and free-air gravity fields contains invaluable information regarding isostatic compensation and mantle strength, as was discussed primarily in the preceding section on Venus. The method of calculation of those gravity fields, and the empirical example of Earth, require that topographic and gravity fields do not correlate at wavelengths at which topographic positive and negative loads are compensated by isostatic balance high in the upper mantle, for example at the base of the crust or at the low-velocity zone. (The uncertainties and limitations of calculations of the field from the planetary data sets were discussed by Wieczorek, 2007.) Conversely, where the fields do correlate, as they do on Earth only at short wavelengths but on Venus at long and medium wavelengths (which are the only ones tightly constrained by the gravity data), the load is being carried by strength of the outer part of the planet. As noted above, geophysicists who seek to explain Venusian data in terms of mantle plumes rationalize the hypothetical positive and negative plumes to be so vigorous that they override the isostatic term and have long maintained precisely constant buoyancy and dynamic push-up of high topography, and pull-down of low topography. Topography and high-relief geoid correlate even more strongly on Mars. There too, most geophysicists seek to explain this correlation in terms of active plumes, hot mantle, and very thin lithosphere, but do so with quite different speculations than on Venus. I regard both planets as showing no evidence for the existence of plumes at any time in their histories. I see the geodetic data as powerful evidence that both planets have been cold, and have supported large surface loads by their strength, since well before 4.0 Ga.

Martian topography is dominated by the hemispheric dichotomy. Most of the northern hemisphere is ~5 km lower in altitude than the southern. This great contrast is almost invisible in the geoid (Wieczorek, 2007, his figure 5), so the hemispheric topography presumably is isostatically compensated with quite different density profiles of crust and upper mantle. This may indicate an origin in a grazing collision by a planetoid while Mars was in late magma-ocean stage, and subsequent development of much thinner protocrust in the depleted northern hemisphere than in the southern one. The huge, deep, and ancient Hellas impact basin, centered near 40°S, 70°E, can be seen in the geoid but is inconspicuous, and hence likely it too is mostly compensated.

Whereas the geoids of Earth and Venus have total relief of only ~200 m each, that of Mars has a relief of 2000 m, and geoid and topography correlate through much of the non-dichotomy wavelength spectrum (op. cit.). The correlative topography and geoid are dominated by the Tharsis upland and by superimposed and nearby "volcanoes." Tharsis is about the same size as the Tibetan Plateau and its flanking ranges on Earth, which, in stark contrast, are inconspicuous in the geoid (Wieczorek, 2007, his figure 1) because they are compensated at shallow depth. Lowry and Zhong (2003, p. 1) recognized that calculations of compensation, densities, thicknesses, and rheologies of crust and mantle components are dependent on assumptions, but nevertheless can "rule out a predominantly internal load [isostatic compensation]" for Tharsis, and "cannot reject the possibility that Tharsis results from [uncompensated] surface loading alone" and is held up by mantle strength. Most Martian geophysicists (e.g., Wieczorek and Zuber, 2004), however, assume that Mars must have a hot mantle and very shallow isostatic compensation of crustal loads because geologists postulate plumes. They dismiss the spectacular correlation of Tharsis topography and geoid, and assume densities, temperatures, and rheologies of crust and mantle, and average thickness of crust, that force calculation of shallow compensation elsewhere.

I infer that Tharsis and the rest of the non-dichotomy topography of Mars is mostly supported by a mantle that was chilled to high strength long before 4.0 Ga, and that a very thick protocrust that existed early has been recycled by impacts but little influenced by internal processes. The protocrust is the ancient basement identified by Frey (2006) as underlying both northern lowlands and southern highlands. Mars lacks apparent indicators of terrestrial-style shallow compensation, as by a weak Moho region or an asthenosphere, in topography and gravity. There are no apparent topographic moats around the large Martian "volcanoes," except that Olympus Mons, the most concentrated load on the planet, appears to have a discontinuous shallow moat 0–200 km wide (U.S. Geological Survey, 2002; Fig. 17, bottom). Earth's great canyons, such as the Grand Canyon of Arizona (United States) and the Salmon River Canyon of Idaho (United States), are centered on broad, low anticlines that compensate the erosional excavations with broader isostatic rises, but no such rises are apparent flanking even-larger Martian canyons (U.S. Geological Survey, 2002).

### Water on Mars

The powerful evidence for Martian aqueous erosion and sedimentation, partly by enormous floods, has long been obvious (Carr, 2006; Carr and Head, 2010). Aqueous activity apparently began late in the surface-saturating bombardment. Release of volatiles from target rocks in impacts, as deduced here for Olympus Mons, has been advocated by Toon et al. (2010) and others, as has delivery of water by bolides, but dominant explanations (Carr and Head, 2010; Phillips et al., 2001) invoke devolatilization of a slowly fractionating planet, with vast eruptions of accumulated groundwater. I infer instead that Mars was essentially dry after high-temperature magma-ocean fractionation before 4.50 Ga. By this time, Mars had reached essentially full size, and had a thick crust. In these terms, the reason water is not apparent in the geology until late in the saturation bombardment lies not in delayed fractionation but in the near absence of water when Mars reached full size, and that the water obvious in the geology was delivered in a barrage of icy bolides centered ca. 4.1 or 4.0 Ga. This approximate timing comes from my reading of the time of appearance of the water in Martian geologic reports, integrated with bombardment dating for the Moon as discussed in the section on that satellite. The water was catastrophically released on impact, and caused great local and regional floods, erosion, and sedimentation in the southern highlands. Olympus Mons, formed by a large impact (ca. 3.8 Ga?), postdates delivery of major new water, although there was much surface(?) and subsurface ice in the high southern hemisphere, and likely an ocean still in the low northern hemisphere.

## AFTERWORD

None of the popular hot-core speculations argued against in this paper have been confirmed by viable evidence from Earth, Venus, or Mars. The popular internal-dynamic models for the three planets were developed independently by adding local speculations to the assumption that dynamics of all are driven by hot cores. The terrestrial starting model is based on the disproved assumption that intraplate volcanoes form above fixed plumes. The Venusian extrapolation is anchored to the assumption that thousands of large rimmed circular structures cannot be impact products. The Martian derivative stems from the Hawaiian fallacy. The mutually incompatible three models were dogmatized before most current researchers began their work, and data interpretations in nearly all conventional reports are forced to fit the conflicting assumptions. Proponents of those popular models tend to bring about conformity because the majority dominates academic peer review, a process that works to suppress challenges to the status quo.

A diametrically opposite general model of terrestrial-planet formation is preferred. Radiogenic heating partly melted Earth, Venus, and Mars as they accreted, and all fractionated very early with thick crusts that concentrated most of their radioactivity at shallow depths. Venus and Mars quickly chilled to internal immobility, and have been passive targets for bolides for more than 4 b.y. Only Earth contained enough radioactivity to evolve through different stages of continuing internal mobility and, ultimately, to plate tectonics.

Earth has had abundant water since ca. 3.9 Ga, and meager data do not require it earlier. Venus and Mars received abundant surface water between something like 4.1 and 3.9 Ga, to judge by lunar-analogy dating. The compatibility of these tenuous dates permits the suggestion that water may have come to all of them in an icy bombardment centered ca. 4.0 Ga. A mass expulsion of icy asteroids, from beyond the snowline in an initially graded belt of planetoids now between Mars and Jupiter, might explain such a deluge. Current concepts of the chaotic evolution of the asteroid belt as planets, particularly Jupiter, migrated make such a barrage plausible (cf. Batygin and Laughlin, 2015; DeMeo and Carry, 2014). I am aware of no prior integration of geologic timing into the discussion, but the suggestion here appears compatible with theoretical arguments (cf. Fritz et al., 2014). Venus and Mars were internally inert before the deluge, and, unprotected by magnetic fields, lost their new water as it was dissociated by the charged particles of the "solar wind." Hydrogen escaped, and oxygen may have mostly oxidized CO to $CO_2$. Ammonia likely was abundant in the incoming ices, and atmospheric nitrogen is its surviving product (cf. Harries et al., 2015). On Earth, increasing downward recycling of some of the new surficial water and $CO_2$ allowed extensive partial melting of protocrust, and contributed to the tectonic and magmatic progression that led to plate tectonics. The organic compounds that enabled the first life on Earth, in the presence of liquid water, may have arrived with the deluge, or may have been products of reactions involving $NH_3$ (op. cit.). Earth has complex life because of many events, and not only because of its size and distance from the Sun.

Historical shifts away from disproved paradigms have typically been abrupt, but long delayed, like those a half-century ago from terrestrial stabilism to mobilism, and from lunar plumes to impacts. The hold that plume mythology presently has on planetary evolution is likely to be overturned with similar abruptness. Myths, however, are more difficult to displace than are scientific concepts. Dickinson (2003) evaluated plumes and other popular geomyths, and rightly emphasized (p. 856) that "the defining style of mythic thinking is to build selectively upon some particular conjecture that is given privileged status against contradictory observations. Rejecting any myth typically requires more conclusive evidence than its initial invention entailed." Evaluations of plume conjectures are not to be expected soon in studies supported by the National Aeronautics and Space Administration (NASA). The report, *Goals, Objectives and Investigations for Venus Exploration* (Venus Exploration Analysis Group, 2014) recommends that work be funded to further elaborate products of young plumes.

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Notes