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 plumes of unfractionated mantle which produce volcanoes, propel lithosphere plates, and are compensated by subduction. Long-lasting hot cores were dogmatized for Venus and Mars also, but with a different stagnant-lid conjecture for each based on conflicting interpretations of surface imagery.

Physics, empirical data, and planetary imagery contradict those models, and support a different and shared early evolution of Earth, Venus, and Mars. Radiogenic heat, ~5x greater than now, forced magma-ocean fractionation of each. This produced thick mafic protocrusts, concentrated radioactivity at shallow depths, and permanently depleted lower mantles, by ~4.5 Ga. On Earth, the protocrust lay directly above refractory dunite, in turn above pressure-varying deeper fractionates. The shallow concentrations of radioactivity allowed mantles 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,in the garnet stability field to make Archean, and possibly Hadean, felsic crust. Densified garnet-rich residues of protocrust delaminated, sank through the low-density dunite, and began upper-mantle re-enrichment. Archean cratons were stabilized where sinking of the residua left derivative felsic crust directly upon buoyant sterile dunite. Where some protocrust remained, Proterozoic crustal activity ensued. This was mostly in the form of basin-filling atop Archean felsic crust, followed by radioactively heated metamorphism and partial melting of basement plus fill. Top-down re-enrichment of the upper mantle by evolving processes reached the critical level needed for plate tectonics only ~0.6 Ga. Surficial plate motions are driven by top-down cooling and densification of asthenosphere to lithosphere and resulting subduction. 3-D circulation is closed within the upper mantle.

The inner planets may have received most of their liquid water in a barrage of icy bolides ~4 Ga, best dated on Mars and Venus but in accord with terrestrial and ambiguous lunar data. Earth's new water may have enabled the formation of Archean hydrous TTG from protocrust. The increasing downward cycling of water and CO_2 into the upper mantle ever since may have been essential to continuing tectonism and magmatism.

INTRODUCTION

This report summarizes evidence that Earth, Venus, and Mars all underwent synaccretionary melting, and fractionation of thick mafic protocrusts that contained most of each planet's U, Th, and K, and also its light-ion lithophile elements (LILE). Venus and Mars quickly chilled to internal inactivity because of the shallow concentrations of their heat-producing elements. Only Earth, far larger than Mars and with twice the K content of Venus, generated enough protocrustal heat to fractionate felsic crust, begin downward recycling of densified residual protocrust, and progress through distinctly different stages of Archean and Proterozoic tectonism and magmatism, and into plate tectonics shortly before

Phanerozoic time.

This model is opposite to the popular models for the three planets, which violate thermodynamics and ignore radioactivity. The popular models are extrapolated from 1970s and 1980s speculations regarding Earth: all three planets are still only partly fractionated and have perpetually hot cores that maintain whole-mantle convection. Divergent conjectures have been added for each planet. Earth is commonly assigned a bottom-up convective drive that has maintained plate tectonics throughout all or most of geologic time. Venus is assigned a much more vigorously circulating mantle, but beneath a thin unbroken lithosphere that was transformed by plume-generated vertical tectonism a half-billion years ago. Venusian topography then generated has since been precisely maintained dynamically by rising plumes and sinking antiplumes with constant configurations and velocities and no new effects. Mars is assigned a permanent stagnant lid, punctured intermittently by plumes that produce megavolcanoes but little vertical or horizontal surface effect. The assumed shared mechanism for these three mutually incompatible chains of speculations is not supported by viable evidence from any of the planets. Thousands of published papers have nevertheless based geologic and geophysical interpretations on the divergent chains of speculations.

The objectives of this paper are to show that the conflicting speculative popular models are false, and to present evidence in support of an alternative unifying model. Popular models of ongoing geologic activity in Venus and Mars do not accord with morphological evidence, as is shown by imagery included here. Much of the surface of Venus is saturated with pre-3.8 Ga impact craters and basins, and impact-melt constructs, and not with products of commonly postulated young plumes and diapirs. On Mars, ancient impact structures are universally recognized, and plume speculations are based on the mistaken assumption that the huge Martian “volcanoes” resemble incrementally constructed Hawaiian composite shield volcanoes, which further are wrongly assumed to be formed by a plume. Imagery instead requires each Martian “volcano,” including giant Olympus Mons, to have formed from a single sluggishly spreading batch of melt explicable only by a large impact.

Earth, by contrast, remained active because it had enough radioactivity to generate felsic crust from protocrust, followed by sinking into the upper mantle of densified residual protocrust. Re-fertilization of the upper mantle by this downward recycling, which may have included voluminous water and CO_2 only after ~4.0 Ga, ultimately enabled plate tectonics. This model is opposite to the slow core-driven fractionation and uniformitarian behavior postulated by conventional explanations.

The popular models do not accord with either physics or empirical information. Widely accepted concepts consist of rationales devised to fit obsolete terrestrial speculations that are now recognized in the primary literature as false, yet are retained as dogma in textbooks and secondary research papers. Radioactivity, even now the major source of Earth’s heat, was ~5x greater in the young planet, 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 assumptions are widely accepted.

This paper builds on prior syntheses. Hamilton (2007a and 2011) described a model of terrestrial plate tectonics as 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. Hamilton (2007b, 2011, 2013) argued that plate tectonics was lacking during most of Precambrian time, while other tectonic modes evolved. Archean felsic crust was derived by partial melting of synaccretionary protocrust, and Proterozoic orogens developed atop Archean felsic crust not yet stabilized by complete delamination and sinking of protocrust densified by removal of its felsic components. Gradual re-enrichment of upper mantle in LILE, volatiles, and heat producers *from the top* enabled plate tectonics in, and since, the late Proterozoic. 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, was presented by Hamilton (2005, 2007c, 2011, and 2013). All of these papers present evidence against plume-driven whole-mantle circulation.

Mercury must have had an exceptional history. Its core is outsize, its orbit is highly eccentric, and it is much stressed tidally by the nearby Sun. It is not considered further here.

EARTH

The 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 about Earth's surface that define plate tectonics. The new proof did not define either absolute motions or mechanism, but most then-new mobilists endorsed speculation that plate motions were bottom-driven responses to whole-mantle convection. This was soon dogmatized, along with geologic and geochemical conjectures about "plumes," "primitive lower mantle," and "depleted upper mantle." 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, such as 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 migrating hinges.

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 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). Anderson (2013), Anderson and Natland (2014), Foulger (2010) Hofmeister (2010, 2014), and Hofmeister and Criss (2005, 2012, 2013, 2015) are among those who have long raised similar, and other, objections to popular speculations regarding Earth.

The shared popular-model starting assumption of Earth's hot-core drive is thermodynamically unsound. It postulates that 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 on route, thereby superheating the core and leaving an otherwise unfractionated mantle. (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 colder higher-density iron.) In alternative popular models, Earth's mantle fractionated magmatically, but then was re-homogenized by solid-state convection, which has continued ever since. (Both variants of starting speculations ignore the overwhelming effect of radiogenic heat.) Earth's core is kept eternally hotter, by perhaps 500°C, than the adjacent mantle by a combination of retained original heat plus latent heat of crystallization. (Retention of primordial 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. Latent heat can delay cooling, but it cannot produce or maintain superheat.) This core heat is concentrated in spots along the core-mantle boundary (another Second Law violation), from which hot plumes rise toward the surface. This is an imaginary Earth, so the plumes are narrow and 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. (Substitute real-Earth properties, and any rising lower-mantle masses would be broad, sluggish, reactive, losing heat, and most unlikely to cross the 660.)

These and many derivative speculations are widely misrepresented as fact. In Earth, rising plumes are credited with producing volcanoes and magmatic provinces, heating and refertilizing asthenosphere, and driving lithosphere plates. The plumes of Venus are postulated to be far more vigorous than Earth's but to have almost no horizontal effect at the surface, which instead they deform vertically. Extremely active Venusian plumes have dynamically maintained precisely the same topography for a half-billion years. On Mars, plumes generate long-term volcanism, mostly in one region, but otherwise do not visibly affect the lithosphere. Very long-range migration of Martian basal mantle has fed one plume on Mars for ~4 billion years. On all three planets, negative-buoyancy plumes take cooled material back down to the core-mantle boundary, where it is reheated by hot cores and recycled. Lower mantles maintain mostly primitive compositions by mixing, whereas upper mantles are slowly depleted by net growth of crust. Support for all of this comes only from circular rationalizations.

Contrary evidence is overwhelming. Hofmeister and Criss (2013) documented how measurements of oceanic heatflows and of thermal conductivities of rocks are disregarded in the popular modeling used to illustrate plume speculations. Global heatflow is increased about 50% above measured values, from an observed 30 TW to a hypothetical ~45 TW, to support desired plume models. The erroneous high value is obtained by substitution for measured age-varying oceanic heat flows of a hypothetical curve based on model assumptions. The curve is demonstrably invalid because it extends to infinite heatflow at zero age. Modelers work around this impossibility by truncating integration under the hypothetical curve where the desired global total of ~45 TW is achieved (e.g., Hasterok, 2013). The fictitious 45 TW is then cited 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 core-separation and unfractionated-mantle speculations of the terrestrial model date from about 1950. Conjectural plumes, unfractionated lower mantle, and depleting upper mantle were added in the 1970s. Criteria were postulated for identifying plumes by "plume tracks," and for demonstrating their basal-mantle origins by geochemistry and isotopic geochemistry. These and other conjectural criteria have since all been disproved. For example, suggested markers of origin from the core-mantle-boundary in the He, W, and Os isotope systems have been discredited (White, 2010). Further, 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 plate interiors and spreading centers.

Advocates retain the plume concept despite falsification of the sole original basis for designation of plumes. Morgan (1971) speculated that the Emperor-Hawaiian chain of volcanoes and seamounts formed sequentially as the Pacific plate passed over a narrow vertical plume rising from the deep mantle. He then assumed that igneous features elsewhere that could be rationalized to define progressions, on the Pacific and other lithosphere plates, that were compatible in Euler geometry with a fixed Emperor-Hawaiian plume recorded analogous age progressions caused by other vertical plumes beneath moving plates. Most of his Pacific and North American examples, including the Emperor half of his type example, and many elsewhere, have since been tested and their predictions disproved. Morgan and Morgan (2007) acknowledged the misfits, and speculated that plumes tunnel horizontally for thousands of kilometers from their vertical deep sources and erupt volcanoes anywhere at any time. Other plume advocates dealing with disproved plume tracks recognized that even this is not enough, and rationalized that plumes further rise at any angle, merge, split, and corkscrew, and are blown about by "mantle winds." There is no "hotspot reference frame." Advocates thus retain the plume concept despite falsification of the sole original basis for designation of plumes. All early speculations regarding plume heads, tails, "large igneous provinces," and other features also have been disproved, by advocates as well as skeptics, and those failures also are rationalized away. New disproofs keep coming. For example, the Canary Islands and seamounts, originally attributed to a "plume track," range in age from 142 to 0 Ma, and fit no possible spatial or chronological progression (van den Bogaard, 2014).

Lithosphere is proved to be an insulating lid, so the hypothesis that plumes are needed to add heat for magmatism is unnecessary (Hofmeister and Criss, 2013). Asthenosphere is ~200°C hotter than assumed in plume theory.

Seismic tomography cannot image mantle convection, but does show subducting slabs lying down on the seismic discontinuity ~660 km deep (Foulger et al., 2013; Hamilton, 2011). Purported depictions of slabs and plumes in the lower mantle are illusory artifacts of inappropriate processing unconstrained by essential crossfire rays.

Plume conjectures have failed all tests, but there has been little seeking of 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).

Synaccretionary magmatic fractionation

Earth's bulk composition cannot be as popularly assumed. Many geochemists favor a type of carbonaceous chondrite that does not contain nearly enough iron and has oxygen isotopes that mismatch Earth's. "Pyrolite" is favored by some geophysicists, although it is merely an arbitrary mixture of basalt and peridotite. Mixtures of meteorites, including enstatite chondrite as a major component, appear to be required, and would have yielded a lower mantle markedly more refractory than the peridotitic upper mantle (e.g., Hofmeister and Criss, 2013).

Thermal conductivities of mantle rocks preclude retention of ancient heat, and require that global heat loss approximately equal 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), 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 ~5x greater in the young Earth (Hofmeister and Criss, 2013). Those three heat producing elements all partition selectively into melts, so 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 required by similar arguments for Mars and Venus, even though Mars is much smaller, and therefore faster cooling, and although Venus has only half as much absolute ^{40}Ar in its atmosphere as does Earth and so likely has only half as much solid-planet potassium. The enormous early radioactive heat is commonly overlooked. Thus, Elkins-Tanton (2012) invoked brief heating by short-lived ^{26}Al as contributing to early melting in terrestrial planets, but overlooked long-lived heat-generating isotopes. Griffin et al. (2014) did not consider radiogenic heat while assuming the early mantle to have been homogenized and primitive.

Upper mantle and crustal evolution

Very early separation of a thick mafic protocrust from a magmatically-depleted mantle is indicated for Earth by the greatly increased knowledge 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 Moon, Venus, and Mars by apparent lack of mantle rocks within even their deepest impact excavations, and by other features. The analysis that follows is the opposite of the conventional assumptions of slow, and still largely incomplete, depletion of Earth's mantle of fusible and melt-affinity components through geologic time. However, all petrologic, geologic, and geophysical data are still commonly attributed to the obsolete models with special pleading.

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 seismically subuniform felsic and intermediate crust (mostly tonalite, trondhjemite, and granodiorite, TTG) from nearly uniform 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. The 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, 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 (Ziaja et al., 2014, add new data) to require derivation of Archean TTG by moderately hydrous partial melting of mafic rock under P/T conditions that left much garnet in the residue, or by recycling from felsic rock thus derived. 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-cratonic TTG and dunite (Figure 1, and xenolith studies; for documentation of the following petrologic 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, provides 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 deeper into the upper mantle. Neither the present basal-crustal 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 that is indicated by the flat Moho and constant crustal thickness of Figure 1, and by 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 more ferrous olivine plus orthopyroxene plus various ultramafic combinations with clinopyroxene and garnet or spinel. The transformations were accomplished by variable metasomatism, reconstitution, and obliteration of primary mineralogy. In these terms, mafic protocrust was a synaccretionary fractionate above uniform dunite, and the protocrust sourced both TTG and the subordinate mafic volcanic rocks of Archean crust.

Stabilization of the cratons resulted from the complete delamination and sinking of densified residual protocrust, which left TTG buoyed up by light 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 2.4 Ga. Archean crust floated, and maintained semiconstant thickness, on the buoyant dunite, 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 known 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. 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 averages of sample suites range 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 outside the dunite. These trends are confirmed and mapped in 3-D by seismic tomography (Artemieva, 2009) that quantitatively discriminates varying mantle thermal perturbations (*Vs* decreases much more than does *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 likely strongly dominates 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 the separation of a since-vanished mafic protocrust above it. The refractory dunite is not compatible with incremental separations of small batches of mafic melt from a mantle that has been depleting gradually for 4.5 billion years.

By contrast, the Moho beneath Proterozoic and Phanerozoic terrains 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 Figure 1). Proterozoic crust commonly is deeply eroded yet often still quite thick, and has a Moho that is highly irregular and often indistinct. Proterozoic crust and uppermost mantle obviously 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 crust 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 progressively younger mantle rocks show progressively greater re-enrichment in more fusible components, and that upper mantle has been enriched, not depleted, since Archean time. 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_{92} 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. 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.

Rare xenoliths and xenocrysts, commonly inverted and reconstituted to lower-pressure minerals, are inferred to record origins in deeper parts of the upper mantle, above the 660 km discontinuity, and possibly even lower mantle. Present 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.

The oldest proved TTG is ~3.9 Ga old. Direct evidence for the existence of older terrestrial intermediate and felsic rocks comes from zircon xenocrysts and cores, as old as ~4.2 Ga, enclosed in such post-4.0 Ga TTG, and from clastic zircons, to a maximum proved age of almost 4.4 Ga in Archean sandstone (Valley et al., 2014). Although the pre-3.9 Ga zircons have commonly been ascribed to ancient TTG, trace elements and other features of the zircons support the contrary interpretation that they came instead from fractionated large impact melts (brief review by Griffin et al., 2014). Impact specialists have long emphasized that the early Earth must have been heavily bombarded. I argue below, as in prior reports, that large Hadean impact-melt constructs are widespread on Venus and are present, but less extensive, on Mars. Such constructs on Earth would have contributed erratic fractionation and irregularities, but as mechanically and petrologically recycling transients, not in everlasting form above effectively rigid mantle as on Venus.

The youngest large impacts on the Moon are dated as ~3.9 or 3.8 Ga. Many Archean, hence younger, beds of impact spherules are documented in Australia and South Africa. The spherules often contain mafic material (Glikson, 1999), I presume mostly from protocrust, although Glikson presumed oceanic sources. Locations and local products of those impacts are not known. Proved major Precambrian impact-melt structures include Sudbury, Ontario, 1.8 Ga, and Vredefort, South Africa, 2.05 Ga. I regard apparently shock-injected breccias in the floors of the great fractionated magma lakes of Bushveld, South Africa (which is the same 2.05 Ga age as the remnants of the adjacent Vredefort melt sheet) and of Stillwater, Montana (2.7 Ga) as also indicative of impact-melt origins. Exposures of Archean lower-crustal gneisses include in many regions large sheets of dismembered highly calcic anorthosites (low pressure fractionates, almost uniquely Archean), often with other identified mafic and ultramafic rocks indicative of formation in layered complexes. These might ha/ve formed in impact-melt lakes of Hadean(?) and Archean age. I expect thick 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 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 above moving lower crust. 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 often is misused by Precambrian specialists, many of whom claim it to require a young Earth controlled by the same plate tectonic and plume processes that they postulate for the modern planet. Earth's radiogenic heating was still 2.5x greater at 3 Ga than at present, and it is not possible that internal distribution of radioactivity, heat, and dynamic processes could have been similar to the modern situation, nor does anything observed in the geology suggest they were. The only basement rocks ever seen depositionally beneath Archean mafic and ultramafic lavas are older TTG. There is no indication of oceanic crust and mantle. No ophiolites, subduction mélanges, oceanic or continental magmatic arcs, oceanic crust, or other evidence for plate tectonics, or for oceanic lithosphere, older than about 1 Ga have been documented, Modern-style plate tectonics is indicated only after ~0.6 Ga (Hamilton, 2007b, 2011, 2013). Nevertheless, plate tectonics is popularly assumed to have operated throughout most of Precambrian time.

Most Precambrian papers of the last 20 years contain highly speculative assignments to plate-tectonic and plume settings of rocks and associations that bear no similarity to those in the purported modern analogues. No geologic or petrologic data suggest operation of plate tectonics, and so selected ratios of ratios (not absolute amounts) of a few trace elements are widely cited as requiring many Precambrian mafic lavas to have formed as 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 trends 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 melts rose through older TTG crust. Ratios of high-field-strength to rare-earth elements are widely used as such discriminants. The regional continental flood-lava sheets of late Archean ferroandesites (rocks with few or 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), and would be asserted to prove such a setting were their minor granite-and-greenstone deformation severe enough to disrupt their vast regional stratigraphic continuity. Ratios of ratios of trace elements nevertheless continue to be used as tectonic discriminants, with little or no incorporation of petrology, geology, geophysics, or Sphysics. Thus, Furnes et al. (2015) use the ratios to assign a dozen precise plate-tectonic and plume settings, plus further imaginative mixtures and sequences thereof, to mafic rocks in about a hundred volcanic suites throughout the world's Precambrian, and to postulate uniformitarian tectonics and geodynamics throughout geologic time.

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 have been demonstrated. The orogens 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 discussions of some of the voluminous published data. Exposed contacts between Proterozoic orogens and Archean cratons are marked by Proterozoic strata lapping onto the cratons, often thrust cratonward during metamorphism, plutonism, and inversion of the basin fills. Where both sides of Proterozoic orogens are exposed, both are of this type. For example, both north and south margins of the early Proterozoic Limpopo orogen show typical Archean Mohos (Figure 1). The deeply eroded interior of that orogen exposes abundant recycled Archean basement as well as plutonized Proterozoic fill. No boundary of a Proterozoic orogen by indicators of subduction, either beneath the adjacent cratons or beneath the Proterozoic materials, has been demonstrated. Archean basement has now been proved in the deeply eroded interiors of many Proterozoic orogens previously assumed to be oceanic. Sediments sourced from cratons are now known to be voluminous within many Proterozoic orogens. 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 by sedimentation-buried basement and sediments is adequate to account for the metamorphism and plutonism. Many Proterozoic orogens contain very high temperature mid-crustal rocks, explicable with the concentrations of radioactivity beneath low-conductivity upper crust. I infer the much-subordinate TTG of Archean type in Proterozoic orogens to record derivation from synaccretionary protocrust still beneath the Archean basement.

As 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., Figure 1), and have voluminous lower-crustal mafic rocks.

Modern-style plate tectonics (see the next section) began only about 600 million years 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 assumed in much geochemical work (see Hamilton, 2011, 2013, for documentation). The relative homogeneity of ocean-floor basalts in limited areas records mixing of melts from diverse sources, not source uniformity. 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 upper mantle has become more enriched with time, not progressively depleted as conjectured by popular models.

Arithmetic devices, such as epsilons and T_{DM} dates, used in isotope geochemistry to define "juvenile" (mantle) origins of TTG and other igneous rocks, and the times of their separation from the mantle, are based on obsolete, but still popular, assumption of a progressively depleting upper mantle and of derivation of crustal rocks directly from subjacent mantle. They cannot apply to the documented ancient lithospheric mantle, which is far too refractory to be complementary to crustal rocks. The purported indicators may have utility, however, in relating Precambrian igneous rocks to time of separation from synaccretionary protocrust.

The preceding synthesis posits much distributed horizontal transport during the mobile-crust Archean era, but does not attempt to define horizontal motions within Proterozoic orogens in now-coherent Precambrian shields, let alone between shields. Details may ultimately be defined with paleomagnetic data, but currently available data are too erratic for confident analysis. Problems of inadequate sampling, ages of rocks, age, stability, and history of magnetization in mostly-altered rocks, paleohorizontals, flattening of inclinations in compacting sediments, rotations and lateral motions between nuclei, and too many large jumps and rotations are all formidable obstacles. Three recent broad reviews, by Buchan (2013), Piper (2014), and Schmidt (2014), integrate and evaluate voluminous Precambrian paleomagnetic data from different viewpoints and generate largely incompatible conclusions.

Plate tectonics

Continued recycling of protocrustal derivatives ultimately allowed Earth to enter its present dynamic mode of plate tectonics. Addition of abundant water to Earth ~4.0 Ga is suggested subsequently to have been essential also. The oldest known complete suites of indicators of subduction and seafloor spreading are ~600 Ma, although transitional parts of the array may have formed from ~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 now. Sample corroboration comes from a new global compilation of blueschist ages by Tsujimori and Ernst (2014). Low-pressure epidote-glaucophane blueschists are entirely 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 the biological development of multicellular animals, slow and taxonomically limited from ~600 to 540 Ma and then ballooning to include almost all extant phyla by ~515 Ma, was coincident with the plate-tectonic expansion of Earth's marine habitats and nutrient-enriching processes.

As surficial plate tectonics is characterized by the skittering about of plates of lithosphere above weak asthenosphere that is close to its solidus temperature, a global asthenosphere also may have first formed ~600 Ma. Only then had enough protocrustal materials and volatiles been recycled downward through the upper mantle so that the increasingly fusible composition allowed even the decreasing radiogenic heating to form an asthenosphere beneath a stiff lithosphere. There is much evidence against the presence of asthenospheres in Mars and Venus, for example the strong non-Earthlike correlation of long and middle wavelength Venusian topography and geoid, although asthenospheres are commonly assumed by plume advocates merely because Earth has one.

Comprehension of plate tectonics has long been hampered by dominance of the concept of a "hotspot reference frame" as defining "absolute" plate motions with Morgan's (1971) disproved vertical-plumes speculation. Plate motions make no kinematic sense in that frame, and this lack has encouraged the mistaken assumption that plate propulsion is produced by deep-mantle processes. This has contributed to the common false assumption that trenches and spreading ridges are mostly fixed. Even brief examination of a map of seafloor ages, with the positions of subducting and spreading plate boundaries in mind, shows that although any one boundary segment might be regarded as fixed, almost all other boundaries must move relative to it. In addition, 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 slots, as commonly depicted. Instead, hinges retreat, and slabs sink more steeply than their transient dips as defined by seismicity and tomography. Sinking of subducting 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° or so beneath fronts of overriding plates, and well back under them inflects in broad curves to inclinations commonly between ~30° and 80°. The thin fronts of both oceanic island-arc and Andean continental-margin plates commonly bear forearc basins of minimally deformed strata, which show those thin leading edges to have been uncrumpled during the duration of basin sedimentation, which commonly is at least tens of millions of years. The very thin, but often broad, accretionary wedges that form where voluminous sediments are present in the trench or on the 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 ~50 Ma when they begin to subduct are plated down on the great seismic discontinuity at ~660 km depth, which may be a chemical boundary as well as a thermodynamic one. This requires another rolling hinge at the lower limit of slab sinking. These 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 must be overpassed, although with yet-undefined geometry, by overriding plates.

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 age up to ~60 Ma. Upward migration of recycled fusible components into the deepening lower lithosphere must enrich the lithosphere. 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 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 and when 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 readily integrated into a model of plate-tectonic circulation, driven by top-down chilling, slab pull, and lithosphere-mass push, that is closed within the upper mantle, above the 660-km discontinuity (Figure 2; Hamilton, 2007a). Subduction, with migrating hinges at both the 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 the 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. Very slow spreading is accomplished primarily by extensional faulting of exposed pre-existing lithospheric mantle. 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.

Given that subduction controls plate motions, including spreading, it follows that Antarctica, almost wholly surrounded by retreating oceanic spreading ridges, may be 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 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. The lack of such involvement invalidates the common assumption of terrestrial whole-mantle circulation that provides the sole basis for assuming whole-mantle stagnant-lid convection in Mars and Venus.

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 and long-duration migration of small subducting arcs into or through confined spaces (e.g., the Banda, Caribbean, Scotia, Carpathian, and Rif arcs) require self-propulsion and mass transfer. The bathtub configuration of lithosphere plated down on the 660-km discontinuity as the New Hebrides and Tonga arcs diverge is another effect. Collisions of arcs with each other, or with subducting or stable continental margins, require the top-down and mass-transfer control, as does the prompt polarity reversal of subduction to the outsides of collided masses. That active subduction occurs beneath only one side of an internally stable plate at a time defies analysis with popular models that assume fixed boundaries and, in some cases, all-around subduction.

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 million years. 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).

Terrestrial crustal dichotomy?

In the following section on the Moon, 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 protocrustal materials. 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.

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 mantle? The core-mantle boundary temperature is presently constrained only within a range perhaps as broad as from 3000 to 5000 K, primarily because the light-element component of the liquid portion of the outer core is undefined (although it is extremely unlikely to be radioactive potassium). However, even the low end of that temperature range presents a problem. Effects that may be implicated include frictional heating by lunar and solar tides, and by gyroscopic transfers of angular momentum back and forth between core and mantle in response to migration of the planet through its spin axis as mass distributions are changed by plate tectonics and other processes. Perhaps magnetic-polarity reversals, the wandering of the magnetic-dipole axis, and the present slight westward drift of the non-dipole component of the core field also are related to gyroscopic transfers. Analysis depends upon assumptions of rheology, and other properties, that are poorly constrained.

Arrival of water

Whatever Earth’s early-accretionary water, it may have been lost during early high-temperature fractionation. Present water, both internal and external, may record primarily late-accretionary additions. Extensive delivery of water to Mars and Venus, mostly ~4.0 Ga, is deduced in following sections. Permissive support for about the same timing comes from Earth from the age 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 pillow basalts and by waterlaid sandstones, was certainly present by 3.6 Ga, and ages as old as 3.9 have been suggested, although poorly documented. Hadean zircons, older than ~4 Ga, formed in felsic or intermediate igneous rocks, and the zircon compositions arguably record low-water impact-melt fractionates rather than endogenic hydrous melts.

THE MOON

The surface-saturating late-accretion bombardment of the Moon (Figure 3) occurred between ~4.5 and 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 ~4.5 Ga may still be in view on the Moon, Venus, and Mars. Some quantitative treatments of comparative cratering rates invoke “capture cross sections” calculated merely from planetary sizes and masses. These are invalid: bolide orbits are overwhelmingly controlled by the Sun’s gravity, and the whirling Moon must intercept much more debris than do the planets, relative to their sizes (Anne Hofmeister, various reports). I do not attempt to integrate this constraint.

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 not until the mid-1960s receipt of optical images from some of the one-way Ranger rockets, which showed obvious impact cratering down to meter scale, did majority opinion change. Dietz also argued long ago that the maria are filled by impact melts. He was broadly correct in my view, although popular opinion now favors mostly endogenic melts.

Origin by fission from Earth?

A fission origin of Moon from Earth when Earth had reached essentially full size, had a metallic core, and still had a magma ocean, thus no later than ~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 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, hydrogen, 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), 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 Earth late in the main accretion phase, after separation of Earth’s core. This conjecture appears to be incompatible with constraints (1) and (2), however, and can account for only (3). Elkins-Tanton (2013) 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 the giant impact, but did not consider options. A recent Royal Society meeting on origin of the Moon generated 19 papers (Philosophical Transactions, v. A-372, no. 2042, 2014), all of which noted problems with the giant impact hypothesis, but none of which supported an alternative.

Fission of the Moon from Earth also has problems but warrants rigorous evaluation. Fission was advocated long ago by Darwin (1902), and in detail subsequently by Wise (1963, 1969) and Durisen and

Gingold (1986). The hypothesis now requires that Earth was spinning rapidly, its day less than 4 hours 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 by self-compression of the growing Earth. (Early rotation, and much else, cannot be explained with the popular models that begin with a spinning 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 Sun and planets. This dramatically changes angular-momentum considerations.) A fission proposal appears compatible with the three listed constraints, and with the magma-ocean argument presented earlier.

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 using tiny rock fragments in Apollo samples of polymict shock breccias, postulates prolonged crystallization of a magma ocean, 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 added much information about composition, topography, and gravity. Figure 3 shows the surface concentration of orbitally mapped thorium, one indicator of magmatic fractionation.

The surface-saturating bombardment of the Moon by large bolides is bracketed between ~4.5 and 3.9 or 3.8 Ga. Studies of radiogenic products of short-lived radioisotopes indicate condensation of Solar System materials to have begun by ~4.567 Ga (references in Hamilton, 2013). The Moon had essentially its present size, and all or most of its fractionated crust, by ~4.46 Ga (the age of the oldest lunar crustal rocks yet dated with a ^{147}Sm/^{143}Nd isochron) or ~4.42 Ga (the oldest zircon well dated by U/Pb; Nemchin et al., 2009). An earlier date of ~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, 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.

There are no known exposures of mantle ultramafic rocks on the Moon (Greenhagen et al., 2010). The largest and deepest impact excavation, South Pole-Aitken depression, about 2000 km in diameter, in the south part of the farside hemisphere, displays a substantial Th anomaly (Figure 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 regarding lunar evolution and gravity-topography-density relationships, from which only very thin crust is calculated for this and the other large, deep craters (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 of the Moon is an even larger quasicircular topographically low region of high anomalies of Th (Figure 3) and other magmaphile elements, the KREEP-Procellarum region. 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 pre-impact thick protocrust.

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

Impact melts are limited largely to glass within impact breccias in most lunar interpretations. I suspect that complete impact melts were more common than usually inferred. Even mare "basalts" (a rock name applied more broadly on the Moon than on Earth) are commonly assigned to endogenic melting, with or without contributing impact effects. Age determinations of basalt fragments in Apollo and Luna breccia samples scatter down to 3.2 Ga (Stöffler et al., 2006, Table 5.8). Lunar impacts were still generating abundant shock breccias with impact-melt glass at that time (Fernandes et al., 2014, fig. 8), and the impacts were also producing heat for post-breccia melting (Fernandes and Artemieva, 2012). Thermal conductivities require that if tiny Moon indeed remained hot through much of geologic time, it must have been a result of tidal heating, not retained heat. The extremely high titanium contents of some lunar "basalts" may provide evidence for the proposal by Hofmeister and Criss (2014) that Earth's lower mantle is titaniferous.

What formed the large highland regions of the Moon? Garrick-Berthell et al. (2014) removed calculated effects of large impact basins from topographic and gravity datasets and subjected the residual fields to spherical-harmonic analysis. They deduced degrees 2 to 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. A few petrologists and geochemists have long argued for such multiple sources. 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 situ in fragments of norite and of granophyre (rapidly crystallized from high-T granite melt), scatter with decreasing abundance from ~4.4 to ~3.8 Ga (Pidgeon et al., 2010). These also might date fractionated impact melts. However, the relatively low velocities of lunar impacts would have minimized melts, and no surviving topography defines obvious large igneous constructs, either endogenic or exogenic, so if such were formed their definitive morphology was obliterated by subsequent bombardment. Below, I argue 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., Figure 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 are of the central uplift (4A) in the floor of Tycho, a relatively large young impact crater, and of a raised block (Figure 4B) in the SE rim of Mare Imbrium. The Tycho layering follows the quasiconical central uplift, and must have been approximately horizontal before the impact. Layered rocks exposed in the left shoulder of the uplift are about 1.5 km thick. In this Tycho case, spectroscopy from orbiter Clementine is interpreted to define the uplift as of layered mafic and calcic igneous rocks (Tomkins and Pieters, 1999), which I would assign to an impact lake rather than to the conventional late endogenic intrusion.

The 800-m section of layered rocks in the Imbrium-rim uplift (Figure 4B) must be older than 3.92 Ma, the age of the 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, and such crossings indeed occur within Figure 4B. However, the thick rubble-covered parallel slope-and-cliff layers that dominate Silver Spur cannot be illusory, and their parallelism with much of the apparent thin-layer outcrop-striping throughout much of that picture provides evidence for the stratigraphic reality of those thin layers also. Further, a number of narrow canyons in lunar maria (e.g., Hadley Rille at the Apollo 15 landing site) that are conventionally ascribed to collapse of deep lava tubes have patterns suggestive of rapid aqueous cutting, perhaps by flash floods from single 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 waterlaid sediments should be present within some of the Imbrium ejecta blanket. Such materials can be inferred. Wilshire and Jackson (1972) described petrographically the lithic clasts in Imbrium ejecta sampled at the Apollo 14 site. Most are very small, shocked, and thermally metamorphosed, and primary fabrics have mostly been obliterated. Most lithic clasts are of rocks that were finely comminuted before the climactic Imbrium impact. Many obviously are shattered igneous rocks, but many others could have been poorly sorted fine-grained sediments provided they were washed in quickly from already-comminuted impact assemblages of mafic rocks. (Wilshire and Jackson did not make this inference, but that apparently is what the lander-sampled plains sediments of Venus represent.) Many lunar rocks and glasses are now known to contain small amounts of water (<300 ppm; e.g., Hui et al., 2013). The deuterium/hydrogen ratio in this water is similar to that in terrestrial rocks and in carbonaceous chondrites (Hui et al., 2013). Although both lunar and terrestrial water is commonly assumed to be primordial, it is suggested in this report that most of this water was added by a barrage of icy missiles from the then-outer part of the main asteroid belt, which arguably accords with the chondritic data. Perhaps a landscape analogous to the heavily sedimented one of much of Mars is hidden beneath the space-weathered rubbly impact-recycled surface of the Moon. If so, the causative lunar deluge, and presumably those of the terrestrial planets, was older than the 3.92 Ga Imbrium impact.

POPULAR MODELS FOR EARTH, VENUS, AND MARS

The disproved 1970s assumption that Earth’s dynamics are dominated by fixed vertical plumes was exported to Venus and Mars, for which it has been retained in its dogmatized 1970s form. Core-driven plumes are now widely postulated to control the internal dynamics of Earth, Venus, and Mars, but with strikingly different effects on each. The contrast between these three postulates of utterly unlike products of a single process underscores the implausibility of all three. Earth is still widely regarded as having plume-driven plate tectonics. Venus and Mars obviously lack plate tectonics, and are popularly assigned stagnant-lid lithospheres that respond to fixed vertical plumes in quite different ways. Venusian lithosphere is speculated to have undergone intricate vertical deformation from beneath by plumes, without disruption, a half-billion years ago, and the resulting topography to have been maintained dynamically ever since by plumes of constant configuration and buoyancy. Plumes are conjectured to have fed long-continuing large-volcano magmatism on Mars, much of it concentrated in one region, while producing little horizontal or vertical deformation.

Geologic and geophysical interpretations of Venusian and Martian imagery are force-fit to those speculations. Counter interpretations of imagery, including impact effects, are provided in the 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 billion years. They had thick mafic crusts before late-accretion saturation bombardment of their surfaces. They display no viable evidence for plumes, either long- or short-lived, 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 surface of Venus is saturated with ancient impact structures and impact-melt constructs, that the conventional speculation that the thousands of observed circular structures were produced by plumes and diapirs is specious, and that Venus has been relatively immobile internally since chilling after very early fractionation of thick crust. Conventional Venusian specialists, by contrast, consider Venus to have even more active core-driven plume circulation than they assume for Earth, but confined beneath a thin fixed lid, and to have plumes that have been precisely fixed in position and dynamics for an enormous length of time.

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. No such 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 1.5 billion years) as does that of Earth. Solid Venus likely contains proportionately less heat-generating K. A solid metallic core provides the likely explanation for Venus' lack of a magnetic field, and eliminates the heat source popularly speculated to drive Venusian plumes. Further, 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 despite its relatively high temperature.

See no impacts

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 accepted as such by many observers. Solomon and Head (1982) and Solomon et al. (1982) stated, however, that the evolution, thermal structure, physical properties, and internal dynamics they assumed for Venus, by analogy with popular speculations regarding Earth and including no analysis of the Venusian structures, precluded preservation of ancient surface features, and therefore only young features could still be visible on Venus. Those conjectures were quickly accepted, without scrutiny. Impacts disappeared from discussions in favor of endogenic processes even before high-resolution radar imagery was obtained by orbiter Magellan in 1990-1994. Hypothetical plumes were soon dogmatized as the causes if circular structures. Vita-Finza et al. (2005) and I are almost alone in emphasizing that Venusian imagery displays thousands of obvious large impact structures.

Hamilton (2005, 2007c, 2011, 2013) presented Magellan radar backscatter-brightness images, and nadir-radar topographic images, of hundreds of the disputed circular structures at all scales. Representative images are presented in this paper. These images show saturation bolide bombardment of both highlands and large parts of lowlands. Small to huge individual or cookie-cutter superimposed impact structures are widespread. 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, or simply ignored, is arbitrary and inconsistent within a broad continuum. There are rimmed basins, resembling lunar maria but up to 2000 km in diameter, and also poorly preserved large, deep quasicircular depressions to 2500 km in diameter.

Slant-radar backscatter imagery is printed in grayscale and superficially resembles optical photography, but contains quite different information. Backscatter brightness, unlike optical albedo, increases with surface roughness, on approximately centimeter-to-meter scale for Magellan's radar wavelength; with increasing perpendicularity of slope to the slant-look direction; and with surface electrical conductivity. Features can be imaged beneath surficial deposits meters thick. The cross-flightline horizontal dimension of backscatter maps is proportional to slant range, not to optical angle, and is draped on a generalized topographic model, 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, although these present a different array of misleading topographic illusions. Magellan low-resolution nadir-radar altimetry shows many critically important features (e.g., Figures 7 and 9) invisible in backscatter, but it is disregarded in most conventional work. The Magellan maps in this paper were processed by the U.S. Geological Survey, and such images are available, at any scale and for almost the entire planet, on request.

Aramaiti "Corona" (Figure 6) is only one of many hundreds of rimmed circular structures that preserve apparent impact morphology, but is unusual in having been repeatedly singled out in conventional literature for detailed interpretation as formed by a plume. At least five mutually incompatible plume explanations of Aramaiti have been published (e.g., Lang and López, 2013, and Stofan and Smrekar, 2005). These postulate deformation of thin lithosphere above a plume by delamination, inward-directed overthrusting, collapse, or other structural processes, none of which account for what I see in the imagery. Aramaiti is, for me, a young structure formed by a shallow-sea impact (see below) into sediments that had buried the impact-saturated basement of that area (compare with Figure 7, of a different area).

The only conventionally accepted impact structures on Venus are small, sparse craters that are arbitrarily designated "pristine." All of the thousands of other circular structures, most of which are much larger, are claimed to be products of plumes and associated diapirs because they are not "pristine." That most of the assumed "pristine" craters in fact are much modified (see next section) has been ignored. Further, something like 80% of all visible but pre-"pristine" circular craters and basins, including at least 95% of those in the lowlands (where plumes cannot easily explain their abundance), are simply omitted from conventional maps and discussions. Only about a thousand "non-pristine" circular structures, and clusters thereof, selected mostly in the highlands, are given specific plume explanations. Speculations by different groups are often mutually incompatible, and one's rising plume can be another's sinking antiplume. The consistent circularity and impact morphology of the structures of all sizes are ignored in interpretations. A typical approach (e.g., Jurdy and Stoddard, 2005, Figure 4) is to sketch irregular blobs outside single rimmed circular structures, or around clusters of circular structures with cookie-cutter overlaps, and then to interpret the blobs as products of plumes and diapirs without considering the circles. Another approach uses a "perspective image," wherein low-resolution large-pixel topography is exaggerated vertically by 20 or 30x. This has been done, for example, to Aramaiti. The resulting enormously high and lumpy image bears no resemblance to the actual structure, and is cited to support structural explanations that are unique to Venus. Models of plume-raised landforms, involving variously intrusive magmatism, surface overthrusting or underthrusting or other deformation, and collapse into hidden plumes and diapirs, mostly without surface volcanism, are proposed to explain circular craters and basins with rim diameters from 10 to 2000 km. Intricate classifications of exotic postulated plume products, none of which either have terrestrial analogues or account for the consistent 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 (Figure 7). Many lesser clusters of old structures also are obvious on the plains in backscatter images alone. Where only relatively young structures are exposed, there commonly are many more "non-pristine" than "pristine" ones. Figure 8 shows a wide range in preservation and modification of impact structures formed during and after, and possibly before, sedimentation and erosion in a transient ocean.

Estimation of the maximum age of the craters arbitrarily classed as "pristine," and thereby the age of the popularly postulated plume-generated global surface constructed shortly before the relatively few accepted impact structures, incorporates huge uncertainties. These involve not only bolide flux and sizes but, because of the superdense atmosphere, also bolide types and their destruction. The maximum age that can thus be calculated for "pristine" craters varies with those poorly constrained assumptions from ~0.3 to almost 3.9 Ga, the latter number coming from lunar dating. About 0.5 Ga is popularly assumed because a young limit provides the fewest problems for the plume model. This is commonly asserted to be the time of a resurfacing of the planet by a great surge of plumes and countersinks that contorted the raised highlands, but with little volcanism, while flooding the lowlands with basalt flows.

See no water erosion and sedimentation

Another component of Venusian popular dogma is that because the surface temperature under the dense CO_2 atmosphere now averages ~460°C, which is true, and because all landscape features are assumed to be young, anything that appears to record past aqueous erosion or sedimentation must instead be a product of some high-temperature anhydrous process. It is on this basis that only unmodified small "pristine" craters were accepted to be of impact origin, although most craters so designated in fact are substantially modified. Herrick and Rumpf (2011) showed that only a small fraction of them preserve radar-bright breccia fills of craters and are in fact "pristine," and that crater fills and ejecta blankets of most have been variably covered by smooth radar-dark plains material. These they assume to be smooth unearthlike basalt flows, whereas I regard them as sediments. Variable modification is shown also on many of my published images, including some in the present paper. Many of these images display erosion of components. Faint ejecta lobes about many likely include radar visibility through thin cover. The distinction between pseudo-pristine craters and the many more circular features that form a continuum with them is wholly arbitrary, but is applied as an absolute discriminant between exogenic and endogenic origins throughout the conventional literature.

Both eroded bedrock canyons and distributary channels across the lowlands demonstrate past erosion, both subaerial and submarine, and sedimentation (Jones and Pickering, 2003). This and other conspicuous evidence for fluvial features and oceanic sedimentation has yet to be acknowledged in any conventional report. The radar 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. Altimetry invaluably supplements backscatter imagery, but is not considered in most conventional work. Figure 9 shows canyons, obvious in altimetry but inconspicuous in backscatter, 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. Figure 11 shows channels in the upper left part of the map area. These lowland channels have semiconstant rectangular cross sections, like those of terrestrial submarine distributaries of turbidites (Jones and Pickering, 2003). One such channel is continuous for almost 7000 km with a semiconstant cross section. Plume advocates have explained it, and the myriad lesser channels, as collapsed lava tubes, or as channels melted by eternally superheated lava flowing across basalt plains.

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 basalt, the conventionally assumed surface material. Optical-scanner images from Soviet landers, reproduced in `Hamilton (2005), show the plains to consist of smooth horizontally platy material, as expected of strata statically metamorphosed at greenschist facies by the hot, dense atmosphere. No pictures suggest ropy, blocky, or clinkery lavas resembling terrestrial basalts. There are no plausible eruption sites for the 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) and if so record dewatering of underlying sediments. The conventional view of the plains as formed of vast flood basalts is not easily combined with the simultaneously advocated conjecture that the plains are topographically low because they are pulled down by cold, sinking plumes.

Venusian plains display huge 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, but are commonly said to be cooling joints in very thin flows of basalt. The obvious terrestrial analogue is instead polygonal faulting, which is now known from 3-D seismic profiling to be widespread in marine basins of fine-grained sedimentary strata (Cartwright, 2007). Venusian and terrestrial examples are shown in Figure 10. Terrestrial ones are produced by subsurface dewatering by compaction. Venusian ones are seen on the surface, and, like the associated apparent mud volcanoes, presumably record top-down dewatering as the sediments dried out following evaporation of seawater.

Venusian and Martian seas appeared at or a little before the end of saturation bombardment by large bolides, hence ~3.9 or 4.0 Ga if the age of lunar Imbrium applies as an end of mega-impacts to Venus and Mars. The time of hydration was deduced previously to have been before ~3.9 Ga on Earth, and before 3.92 Ga on the Moon if it was similarly deluged, so simultaneous delivery may have affected all of them. The source of the water is suggested in the final section of this essay.

Venusian mantle rigidity

Geodetic evidence supplements the geologic interpretation that refutes young-surface speculation and instead requires long-lasting stability of topography and structure. Venusian topography and geoid show strong direct correlation at all wavelengths between about 1500 and 12,000 km (Steinberger et al., 2010; see also maps by Weiczorek, 2007, or the contrasting maps of Venus and Earth by Catherine Johnson and David Sandwell reproduced in Hamilton, 2007c and 2013). 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, e.g., sea level, and the planetary ellipsoid, minus the rotational gravity term. This derivation requires that at very short wavelengths the geoid, like closely related free-air gravity, correlates directly with topography on a scale shorter than that of isostatic compensation, whereas, on a large scale, Earth's continents, oceans, and mountain systems are almost invisible in Earth's geoid because they are balanced isostatically in hot, weak upper mantle, and the dominant geoid signal reflects deeper density variations.

The obvious explanation for the striking Venusian correlation between topography and geoid is that the topography of Venus is supported by strong, rigid upper mantle, and that the hot and highly mobile mantle, asthenosphere, and very thin lithosphere of Venusian plume hypothesis do not exist. Geodesist Kaula (1995) recognized the correlation to 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 of the planet's 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, and is due to dynamic uplift and subsidence of thin lithosphere by positive and negative plumes, vastly more vigorous than Earth's hypothetical plumes, which overwhelm the isostatic constraint that dominates the geoid calculation. Barnett and McKenzie (2000), Basilevsky and Head (2007), Dombard et al. (2007), Herrick et al. (2005), P.B. James et al. (2010), Sotin and Smrekar (2011), and Steinberger et al. (2010) are among those who regard the geoid as a proxy for direct dynamic control of topography by rising and sinking plumes and antiplumes.

The *same* topography of modern Venus is attributed to formation by plumes a hypothetical half-billion years ago, so the size, configuration, thermal structure, buoyancy, and motions of those rising and sinking plumes are postulated to have remained constant since then, without producing further changes recognizable at the surface. That the assumption of a planet suffused with super-vigorous but unchanging plumes needs evaluation is not considered.

In my view, the correlation of geoid and topography has survived for four billion years because the mantle has been cool, strong, and lacking an asthenosphere since very early in planetary history.

A corollary of the popular speculation that long-wavelength Venusian topography was produced, and has since been maintained, by steady-state thermal processes is that circular structures produced by plumes 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). This overlooks the inconsistency that the purported vast plume-fed basaltic floods in the lowlands formed above cool downwellings. I regard the purported surface plume constructs as instead products of ancient impacts, and see the lowlands as saturated with impact structures, variably obscured by sediments (e.g., Figure 7). The arbitrary exclusion of the myriad lowland structures from conventional maps is mis-cited as evidence for their non-existence.

The popular substitution of assumed extreme mobility for the geodetic constraint on Venusian 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. Geodesist Kaula (1995, p. 1463) termed this “wish fulfillment.” Thus, Smrekar and Sotin (2012) stated that Venusian plumes require a mantle much hotter and wetter than Earth’s—which does not increase the plausibility of their simultaneous proposal that plumes and thermal columns are fixed through vast geologic time and maintain precisely constant dynamic topography. Modelers who do acknowledge that their models are based on speculations do not evaluate those assumptions or consider alternatives. Herrick et al. (2005, p. 11) properly noted that their modeling 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” of global thermal and viscosity structure.

Detailed published calculations and maps of Venusian crustal thicknesses are based on the assumption that the Venusian geoid can be disregarded because it is maintained dynamically. This allows modelers to chain assumptions of compositions, thermal and rheological structures, average thicknesses, and densities as needed to calculate desired features of thin crust and isostatic balance.

Large impact-melt constructs

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

Figure 11 illustrates many features of Venusian geology in a region about the size of North America. Low uplands of old rocks display abundant impact structures 100-600 km in rim diameter. Lowland impact structures are less conspicuous in this imagery, but the few that are obvious 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 rim breaks in an impact basin 1500 km in diameter, formed from impact melts generated near the end of main bolide accretion. Direct lunar analogy would date these as ~3.9 Ga because they have been only sparsely pocked by subsequent small impact structures, both “pristine” and pre-“pristine.” In contrast to this interpretation, everything in the area of Figure 11 is conventionally assumed to be endogenic and perhaps a half-billion years old, except that sparse tiny misnamed “pristine” craters, barely visible at this scale, are accepted as recording subsequent impacts.

Some Venusian “volcanoes” are enclosed in, or overflow, circular rims that I attribute to impacts, whereas these combinations are conventionally termed “volcano-corona hybrids” and attributed to unusual plumes that erupted at the surface. Most are concentric to their rims, and the eccentric one in Figure 11 was formed by a low-angle bolide in my model. Venusian “volcanoes” are randomly scattered about the planet, and range in diameter from ~500 to 1000 km. They have far larger areas than terrestrial volcanoes, but all have unearthlike gentle slopes, typically ~1°. Mainline papers show them in pseudoperspective cartoons with enormous vertical exaggerations to suggest analogy, otherwise obscure, with terrestrial volcanoes (Figure 12). They have single summits, commonly broad, often with very large shallow collapse calderas that require extremely extensive unearthlike melt at shallow depth. No Venusian “volcano” shows the complexities of prolonged growth of terrestrial volcanoes and igneous provinces. None show multiple summits, nested volcanoes, rift zones, unambiguous flank eruptions, or any of the other features that characterize terrestrial volcanoes. All appear instead to have formed in single mobilization events. 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” (Figures 9, 11, and 13) are larger, ~1200 to 3000 km in diameter and a few kilometers high, and also are conventionally attributed to plumes. They too show a broad range in disruption by large and small bolide structures (e.g., large impact craters cut the “tessera” remnant in the NE part of Figure 7), so they also formed throughout the bombardment era. Direct evidence for impact is provided by the broken and partly emptied melt-filled impact basin of Figure 11, outflow from which produced a partial plateau with diagnostic “tessera” flow structures. “Tesserae” have convex-upward profiles, very broad summit plateaus, have continuous structures that indicate spreading as single batches of mobile material, and display no incremental growth. The 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 (Figures 11 and 13). The enormous viscous-magma pancakes spread sluggishly outward, compressing radially and expanding tangentially, in continuous single events, and were not produced by long-continuing magmatism. Hansen (2006) reiterated my impact-melt evidence and interpretation (Hamilton, 2005, p. 803-805 and figs. 18 and 19). (Her previous papers had explained “tesserae” first by different processes, all endogenic,for different examples, but later [Hansen et al., 2000] by the single process of deformation of thin crust from beneath, plus magmatic augmentation, by huge plumes from deep mantle.) Thermal emissivity of the nightside surface of Venus, as measured at very low resolution through the near-infrared 1.02 μm window in atmospheric absorption by the European Venus Express satellite, is lower from tesserae than from plains. Such emissivity increases with content of ferrous iron in rocks, so this may indicate tesserae to be surfaced by felsic rocks (Haus and Arnold, 2010). This is consistent with fractionation in single-event magmatic constructs.

Venus discussion

The preceding information accords with 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 ~3.8 Ga. Earth’s Hadean evolution is poorly constrained, but its post-impact-saturation history was explained with a similar thick, but more radioactive, protocrust. This generated secondary TTG felsic crust and thereby inaugurated downward recycling of some radioactivity and fusibles 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 an analogous progression.

Many 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 any possible early asthenosphere had disappeared. 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 shifted the mass equator, and with it the spin equator, erratically through time. 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 migrated through its axis to keep its mass equator close to its spin equator. The rift zones typically follow broad ridges with very gentle side slopes. These ridges are drawn with enormous vertical exaggerations (e.g., Jurdy and Stoddard, 2007, fig. 3) to support interpretations of plume uplift and collapsing arches that cannot be made with actual geometries.

The Hadean Earth must have had similar exogenic complications superimposed on whatever was happening due to its presently undefined endogenic processes.

MARS

Almost all investigators of solid Mars, like those of Venus, assume their planet to have been much modified by plumes permanently active beneath a "stagnant lid," but, in a manner unique to Mars, producing volcanism concentrated in one region, rather than global crustal deformation by non-erupting plumes, as conjectured for Venus, or by plate motions, as speculated for Earth.

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.

The argument of Hofmeister and Criss (2013) that radiogenic heat must have induced voluminous synaccretionary melting, and upward concentration of long-lived heat sources, applies also to little Mars, and there also precludes thorough remixing of the radionuclides back into the lower mantle. This is substantiated 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 ~4.55 Ga, and formation of protocrust, or of secondary melts derived therefrom, by ~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 erratic products of shock recrystallization (El Goresy et al., 2013) and aqueous alteration (Bouvier et al., 2008). Mars is commonly inferred to have a thin and highly variable crust in accord with the thermal assumptions of the popular model of long-continued vigorous convection. It has much thicker crust if more objective data sets are integrated (Baratoux et al., 2014). Mars, like Venus, now has no dipole magnetic field, but local remanant 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 well before ~4 Ga, with no heat available for driving hypothetical plumes. (The surface temperature of Venus is almost the Curie temperature, so any remanance once there in crustal rocks was long ago obliterated.)

Figure 14 shows the topography of Mars. The origin of the north/south lowland/highland dichotomy is debated, although an origin in a huge impact before final saturation bombardment is likely the most plausible of popular suggestions. I suggest that this happened during synaccretionary magma-ocean time, and that the northern lowlands are low because they received a thinner protocrust. (I noted earlier that formation of Earth's Moon may have produced a similar terrestrial dichotomy that was long ago obliterated.) The mass equator is near the hemispheric boundary. Migration of the planet, or some large fraction thereof, through its spin axis to move that boundary to the spin equator may have caused some of the minor structural deformation recognized on the surface. The southern highlands display widely varying thicknesses and continuities of sediments, and comparably varying degrees of burial and exposure of age-varying impact structures. This makes determination of basement ages by traditional crater-counting methods ambiguous, but a basement almost everywhere saturated by impact structures seems indicated. The northern lowlands and Tharsis plateau have thicker sediments, but detailed topography shows many mostly-buried craters in them also, and their bedrock surfaces may mostly be equally old (Frey, 2007; Frey et al., 2002). Frey's northern-lowland topographic images of craters resemble those of Venusian lowlands in Figure 7. The Tharsis plateau, and the high igneous constructs on and near it, are, however accepted as plume products by most Martian specialists.

The Hawaii fallacy

The assumptions that Martian "volcanoes" closely resemble the composite shield volcano of Hawaii, and that therefore (a non sequitur) all early plume assumptions regarding Hawaii should be applied to Mars, was made by Carr (1973). They have since been repeated, and applied, hundreds of times. Both geologic interpretations of Mars and the entire geophysical model for Martian plume-driven evolution are based on those assumptions. Disproof in the primary literature of the 1970s plume proposals for Hawaii by both empirical evidence and physical principles was discussed above, but has yet to be considered in the Martian literature. Here, I show that the claim that Hawaii and the Martian constructs are similar is false.

Figure 15 illustrates the profound dissimilarity between Martian "volcanoes," exemplified by Arsia Mons, and the largest terrestrial volcanoes, exemplified by Hawaii. Huge Arsia is shown at a slightly smaller scale than is Hawaii. Like other Martian "volcanoes," Arsia is a broad single-peak construct with circular-concentric structure indicating single-event mobility. Its enormous shallow caldera is as large as the entire above-water island of Hawaii, and 1000 times the area of the largest caldera on Hawaii. The caldera requires a comparable area of simultaneous melt beneath very thin cover. Irregular Hawaii is a composite of 5 volcanoes in the present surface, and just the surface rocks span a million years of incremental volcanism. In the next section, Arsia and all other Martian "volcanoes" are explained as products of bolide impacts.

Numerous reports claim that many Martian "volcanoes" have erupted densely overlapping or widely scattered small lava flows. I see the illustrations in these reports as showing instead depositional and erosional features of aqueous and mass-wasting processes, the latter often cryogenic, which bear no resemblance to terrestrial volcanic features, such as Hawaiian lavas erupted mostly from dike-fed rifts radiating from individual volcanic centers.

Martian geologists assume that anything that can be construed as a volcano must have been produced by a core-heated plume. Some of the most conspicuous "volcanoes" are concentrated in a fraction of one hemisphere. Several are speculated to have been active throughout much, even most, of Martian history. A single permanent plume is often invoked, despite the Second-Law problem of concentrating core heat. Zuber (2001) proposed that heat from the core has been concentrated by continuous subhorizontal flow of the entire lower mantle into a single rising plume. Sekhar and King (2014) speculated that ancient heat is accumulated in the mantle and released to plumes as needed. They deduced that two dozen or so core-driven plumes could now be active beneath the stable lithosphere. Only Ruedas et al. (2013) found that they could not justify a permanently hot core, and avoidance of mantle fractionation, on small Mars—but they accepted geologists' plume conjectures, and proposed that unknown processes maintained similar circulation after the core chilled long ago. No Martian modelers have regarded problems with such conjectures as warranting evaluation of the assumption of plumes on Mars, or on Earth.

Large constructs of impact melt, not plumes

Purported Martian volcanoes share features that I regard as requiring origins as impact-generated melts. Like Arsia, they are broad circular single-peak structures, and the higher ones show concentric circular morphology. Their gross shapes accord with single events of magma generation and variably sluggish spreading. Most Martian "volcanoes" of all types have broad, shallow summit calderas that require huge shallow 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," they commonly are illustrated with large vertical exaggerations, usually unmentioned. Sediment-mantled circular-concentric topography extends far out around some "volcanoes," including Pavonis and Ascraeus Montes, and may record hidden 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 “volcano” (Figure 16), 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 partly above, and partly just inside, the rimcrest of the impact basin in which melt was generated. Like other Martian “volcanoes” of all types, Tyrrhena has no multiple summits or rift eruptions or other signs of incremental magmatism to indicate an endogenic origin rather than a single impact event. An incremental origin from an intermittent plume nevertheless is conventionally assumed.

Giant Olympus Mons, “the largest volcano in the Solar System,” is the favorite plume product for Martian specialists. I interpret it to be a large impact-melt construct mostly contained within its impact basin. The top image of Figure 17 shows the circular Mons and its rim, and the middle plots are true-scale topographic profiles. The Olympus construct is indeed enormous, although much gentler than commonly depicted. The shading of the digital topography makes the bounding outer slope look like a basal cliff. It is instead a slope, gentler and lower where the initially circular outer rim has not slumped out (along most of the west side, and much of the southeast margin), and higher and steeper where the original rim was destroyed by slope failure. The slumped-out sectors produced debris flows and fans are seen in the image to extend as far as 200 km from the southwest and northeast ruptures, and from the short broken sector due west of the summit caldera. The Olympus construct, like Arsia, has circular symmetry. Like the impact constructs of Venus, it appears to record a single event, not protracted incremental growth, and lacks the features expected by analogy with terrestrial volcanoes, which are much smaller than this. There are no multiple peaks and nested volcanoes, rift zones, or obvious flank eruptions. Olympus has a huge caldera, ~65x80 km, on its single broad summit.

Martian plume advocates nevertheless infer long-continued incremental growth. Isherwood et al. (2013) deduced that most of Olympus formed gradually between 3.7 and 2.5 Ga but that low-volume activity has continued intermittently to the present. Their evidence for the purported generations of lavas in their published imagery is to me highly dubious. Such interpretation are, however, commonly made for Martian “volcanoes,” and so postulate that a plume pipe from the core-mantle boundary refilled many times over a billion or more years, each time delivered new melt to the volcano, within which it migrated several hundred kilometers laterally, and then commonly erupted only a small new flow.

The lower image of Figure 17 places Olympus Mons in the context of its vast surrounding “aureole” of a double layer of unusual sheet deposits of far-traveled material, which I take to be impact breccias. The sheets are well exposed clockwise from SW to NE around the mountain, and are discontinuously exposed around the other half. The sheets predate the fans and mass-wasting materials that extend as far as ~200 km from the mountain rim and cover contacts between sheets and rim. The lower, and more extensive, sheet traveled as far as 850 km NW down a pre-Olympus slope of about 0.2° to end with an almost circular front. The exposed part of this sheet shows here mostly in the duller green altitude tint. Overlying this, and not extending as far, are huge lobes of rougher-textured material. The well-exposed parts of both sheets are minimally pocked by subsequent impact craters, so direct lunar analogy suggests an age of ~3.8 Ga. Both sheets show tendencies toward concentric ridging near their termini but less regular structure further back.

What are those sheets? Some investigators have inferred them to be lavas, or pyroclastic flows, from Olympus, although if so they were phenomenally fluid for the short periods implied by their continuities, and they have no apparent sources or terrestrial analogues. The sheets more commonly have been termed mass-wasting or landslide debris from the Olympus rim. This is implausible in terms of their vast extent and gentle slopes, and also because the obvious debris from the broken rim moved only a relatively short distance. De Blasio (2011) likened the sheets to the submarine megaslides from collapsed terrestrial oceanic-island slopes. The best relevant bathymetry is of the many such slides around the Hawaiian Islands, but those are typified by multikilometer blocks that do not extend nearly as far as the

Olympus materials (Figure 15; Eakins et al., 2003).

Given an impact origin for the circular Olympus-basin rim, the sheets should represent an impact-ejecta apron. The actual apron lacks the radial streaking and narrow lobes expected for the usual impact into dry rock. The impacted target appears to have been thick sediment. Could the unusual apron be the result of voluminous intergranular water ice, ± CO_2 ice, in the target, and perhaps also of underwater deposition? Weiss and Head (2014) explained distinctive two-layer ejecta of small Martian craters in terms of impacts into surficial water snow and ice. I do not have a well-formed notion of how this might have operated on the scale of Olympus.

Alba Mons, formerly Alba Patera, the huge sediment-blanketed quasicircular upland centered at 41°N, 250°E (Figure 14), is another obvious impact candidate. It is very low, almost flat, and commonly is depicted with great vertical exaggeration. I infer that its huge apron, ~2000 km in diameter, is a sediment-covered ejecta blanket because it everywhere ends, like the well-exposed one of Olympus Mons, at a broadly curved front (Carr, 2006, fig. 3-11). Surficial deposits commonly cover nearly all of what I predict to be ejecta aprons

Subtract the superimposed and neighboring "volcanoes," impact-melt constructs, and the rest of Tharsis may consist of several impact-melt constructs akin to Venusian "tessera plateaus."

Martian mantle rigidity

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, fig. 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 a much thinner crust in the low northern hemisphere. The huge, deep, and ancient Hellas impact basin, centered near 70°E, 40°S, can be seen in the geoid but is inconspicuous, and hence likely is mostly compensated.

Whereas the geoids of Earth and Venus have a total relief of only ~200 m each, that of Mars has a relief of 3000 m, and geoid and topography correlate through much of the non-dichotomy wavelength spectrum (Wieczorek, 2007, fig. 5). The correlative topography and geoid are dominated by the Tharsis upland and by nearby and superimposed "volcanoes." Tharsis is about the same size as the Tibetan Plateau and flanking ranges on Earth, which, in stark contrast, is inconspicuous in the geoid (Wieczorek, 2007, fig. 1). Tharsis overwhelms with symmetry artifacts spherical-harmonic renditions of the Martian geoid for degrees ≤9 (wavelengths from 2400 to 21,000 km; Grott and Wieczorek, 2012). This confuses illustration and complicates analysis if those low-degree terms are dropped (as is usually done), for not only is by far the largest signal discarded with the artifacts, but also the truncation forces artifacts into renditions of retained higher degrees (shorter wavelengths). At the other end of the wavelength spectrum, spherical harmonic expansions are commonly truncated at short wavelengths where data resolution deteriorates, about 350 km for Martian gravity, which forces other artifacts into that end of the retained spectrum. Problems are multiplied when harmonics are used in serial transformations, as is often done in deducing possible planetary crust and mantle configurations and properties.

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 Ga, and that a very thick protocrust that existed early has been recycled by impacts but little influenced by internal processes. Mars lacks apparent indicators of terrestrial-style shallow compensation, involving either a warm Moho region or an asthenosphere, in topography and gravity. There are no apparent topographic moats around Olympus Mons (Figure 17) or other large Martian "volcanoes" (U.S. Geological Survey, 2002), in contrast to the conspicuous moat along, for example, the topographically simple northeast side and southeast end of the Hawaiian Islands (Eakins et al., 2003). Earth's great canyons, such as the Grand Canyon of Arizona and the Salmon River Canyon of Idaho, are centered on broad, low anticlines that compensate with isostatic rise for the erosional excavations, but such anticlines are not apparent flanking the even-larger Martian canyons (U.S. Geological Survey, 2002).

Martian geophysicists (e.g., Wieczorek and Zuber, 2004) commonly dismiss the possibility that a cold, strong mantle is indicated, and assume that Mars must instead have a hot mantle and shallow isostatic compensation of crustal loads because geologists postulate plumes. As emphasized above, that postulate relies on the invalid comparison of Martian "volcanoes" with Hawaii, and on the assumption that a plume produced Hawaii. Martian geophysicists mostly omit the spectacular Tharsis geoid correlation from consideration, and select densities, thicknesses, and rheologies of crust and mantle that force calculation of shallow compensation. Geologists accept such calculations as confirmation of hot mantle and plume activity.

Mars discussion

Martian plume explanations, like the quite different ones for Venus, are circular rationales extrapolated far beyond terrestrial speculations. The sole purported evidence for Martian plumes consists of analogies of Martian "volcanoes" with utterly different terrestrial constructs. That core-heated plumes do not exist on Earth was discussed extensively early in this paper.

The obvious extensive Martian aqueous erosion and deposition mostly postdate saturation bombardment of the surface (Carr, 2006), and floodwaters may have been delivered by impacting bolides (e.g., Toon et al., 2010

AFTERWORD

None of the popular-model speculations argued against in this paper have been confirmed by viable evidence from any planet. The conflicting conventional internal-dynamic models for Earth, Venus, and Mars were developed independently by adding flawed local speculations to the starting mistaken assumption that all are driven by long-lasting very hot cores. The resulting mutually incompatible models were inappropriately dogmatized before most current researchers entered the scene.

A diametrically opposite general model of terrestrial-planet formation is preferred. Earth, Venus, and Mars were all partially melted by synaccretionary radiogenic heating, and all fractionated with thick crusts that concentrated most of their radioactivity at shallow depths. Venus and Mars quickly chilled into internal immobility, and have been passive targets for bolides for more than 4 billion years. Only Earth contained enough radioactivity to evolve through different stages of continuing internal mobility and, ultimately, to plate tectonics.

The origin of Earth's water has long been contentious. Was it exhaled by a fractionating planet, or added late? The data reviewed here from Earth, Mars, Venus, and Moon permit the inference that oceans of water came to all of them primarily from an icy bombardment centered about 4.0 Ga. A mass expulsion of icy asteroids, from beyond the snowline in the initially graded main belt between Mars and Jupiter, might explain such a deluge. (For current concepts of the chaotic internal evolution of the asteroid belt as planets migrated, see DeMeo and Carry, 2014.) Mars and Venus were inert before the deluge, and, unprotected by core-produced magnetic fields, lost their new water as it was dissociated by the charged particles of the "solar wind." Hydrogen escaped; oxygen may have mostly oxidized CO to CO_2. On Earth, increasing downward recycling of some of this new water, presumably with accompanying 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. I am unaware of any prior integration of such geologic timing into the discussion, but the suggestion here appears compatible with more theoretical arguments (cf. Fritz et al., 2014).

Historical shifts away from disproved paradigms have typically been abrupt and long delayed, like those a half-century ago from terrestrial stabilism to mobilism, and from lunar plumes to impacts. The hold that plume conjecture presently has on planetary evolution is likely to be overturned with similar abruptness. Evaluations of plume theory are not, however, to be expected soon in NASA-supported studies. The 2014 report, *Goals, objectives and investigations for Venus exploration* (www.lpi.usra.edu/vexag/), by NASA's Venus Exploration Analysis Group, recommends that work be funded to further elaborate plume products.

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ILLUSTRATIONS

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 TTG 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, fig. 2); reproduced by permission.

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-upper mantle toward the slab. The slab is plated down on the 660-km discontinuity, which transfers shrinking-ocean mantle to beneath the overriding plate, balancing the spreading that enables its advance. From Hamilton (2007a, fig. 17).

Figure 3. Top: topography of front and back hemispheres of the Moon, illustrating saturation of the surface by impact structures between ~4.5 and 3.8 Ga. Bottom: thorium content of surface materials. Diameter of Moon is 3500 km. Clementine and Lunar Prospector maps provided by NASA.

Figure 4. Layered rocks in lunar uplifts. A: quasiconical central uplift, ~2 km high, in 110-Ma Tycho Crater. Lunar Reconnaissance Orbiter photograph from Arizona State University. B: Silver Spur, a raised block in SE rim of Mare Imbrium, relief ~600m, 70 mm Apollo 15 photograph AS15-11250, from Lunar and Planetary Institute. Spectroscopy indicates Tycho rocks to be igneous fractionates. Silver Spur is unsampled, and might be either pre-3.9 Ga layered fractionates or sediments.

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 shown by shading. Maps by U.S. Geological Survey.

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. Pseudoperspective view, backscatter brightness draped on low-resolution topographic model with vertical exaggeration 3x, by Trent Hare, U.S. Geological Survey. Aramaiti has been repeatedly interpreted in conventional literature as a product of lithosphere deformation by a plume.

Figure 7. Nadir-radar topographic image of the mostly-plains region from about 5° to 25° S, 30° to 50° E, light = high, dark = low, total relief ~3 km, nonlinear scale. 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.

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, rimcrest diameter 175 km, filled by smooth sediment; outer parts of its lobate debris apron and its long runout to SE 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 and 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 only 1, 3, and 5 as impact structures, classify 4 and 8 as plume-formed, and overlook the others.

Figure 9. Paired images of eroded impact-melt Alpha Regio "tessera plateau." Left, east-look radar backscatter; right, nadir-radar altimetry, light = high, dark = low, nonlinear scale. Quasicircular spreading pancake of impact melt rises 3 km above plains, and is dissected by broad valleys obvious in altimetry, but seen in backscatter only as small patches of smooth (radar-dark) sediments. Submarine impact crater Eve "corona" postdates plateau; note its circularity in altimetry, and lobate ejecta blanket in reflectivity. Outer parts of both structures are covered by plains sediments. Only one small "pristine" impact crater, and several possible older small craters, are preserved on the eroded plateau, so it is likely no older than ~3.8 Ga. Conventional view: plateau and "corona" are plume products, and no aqueous activity is recorded on Venus

Figure 10. Polygonal faulting on Venus and Earth. Left: Polygonal faulting of radar-dark oceanic sediments of Venusian plains, ~29° N, 43° E. Low circular hills in north are mud volcanoes. Circular-arc fractures through east half of image likely overlie buried rim of large impact basin. (Conventional interpretation: a plain of thin basalt flows shows thermal-contraction joints, the smooth low hills are basalt cones, and no sediments or impact basins are present on Venus.) Right: Polygonal faulting in subsurface of marine sedimentary basin, offshore Norway. Margins of nested polygons of various sizes are small faults produced by dewatering of fine-grained marine sediments; small circular structure at bottom center is a mud pipe that fed a mud volcano preserved on a buried surface higher in section. Horizontal slice through 3-D seismic-reflection model, from Cartwright (2007), reproduced by

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Figure 11. Part of northern hemisphere of Venus, altitude shown by color, radar backscatter brightness by shading. The many circular structures, rim diameters 100 to 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 SE, but melt slumped out to the W, NW, and N, and formed “tessera” megaflow plateau. A broad “volcano,” only ~2 km high (largest brown area west of 270° 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 approximately 180º E, 71º N; 0º E, 55º N; 313º E, 28º N; and 243º E, 42º N.

Figure 12. Perspective illustrations of Maat Mons, with radar backscatter brightness draped on topographic model. Top: Image as published by Roth and Wall (1995, fig. 3.1) of “tallest shield volcano on Venus,” vertical exaggeration 23x. Bottom, same image, without vertical exaggeration. The single-peak construct is huge but very low, shares no features with terrestrial volcanoes, and is regarded here as an impact-melt construct.

Figure 13. Ovda Regio highland, a composite of three “tessera plateaus” (mostly reddish map colors), constructs from three large impact melts like the Lakshmi one (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.

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 250° E and 10° S). Mars Orbital Laser Altimeter (MOLA) Map from NASA.

Figure 15. Martian impact-melt construct Arsia Mons compared with one of Earth’s largest volcanic edifices, Hawaii island. Each rises ~9 km from its base, Arsia from Tharsis Plateau, Hawaii from Pacific Ocean floor. Top: Arsia Mons “volcano.” Its huge shallow caldera is about the size of the island of Hawaii above sea level, and sagged into the enormous mass of monogenetic shallow melt. Circular concentric structure defines flow as a single event. Arsia is centered at about 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, red; ocean depths colored downward to magenta, ~5.5 km. Hawaii is a composite of 5 volcanoes at the surface and presumably more in the subsurface; the edifice grows by frequent small increments of magma, and just its surface rocks record about a million years of that growth; shallow subsurface melt never had a large area, and the largest caldera is only ~4 km across. Map segment from Eakins et al. (2003). The claim in numerous Martian papers that Arsia Mons and other Martian “volcanoes” closely resemble the composite shield volcano of Hawaii island, added to the assumption that Hawaii sits atop a plume from deep mantle, provides the basis for the popular geodynamic model of Mars..

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 gentle-sided (~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 only by small, scattered impact craters. Location 22.5° S, 106.5° E. MOLA topography, color scale same as Figure 14, from NASA.

Figure 17. Olympus Mons. Top, Shaded MOLA topography of Olympus Mons and its variably slump-broken impact-basin rim. Middle, Topographic profiles across Olympus Mons, no vertical exaggeration, provided by J.C. Andrews-Hanna. Bottom, Altitude-colored MOLA topography of Olympus Mons and, mostly in green, its ejecta blanket. The west edge of Tharsis Plateau is the red region along the east side. Altitude color scale same as Figure 14.

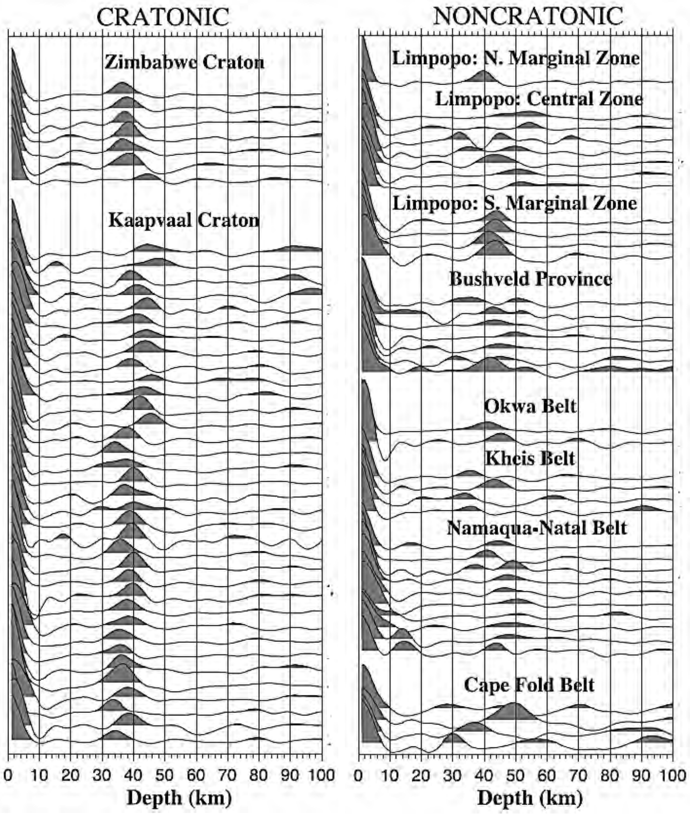

Figure 1

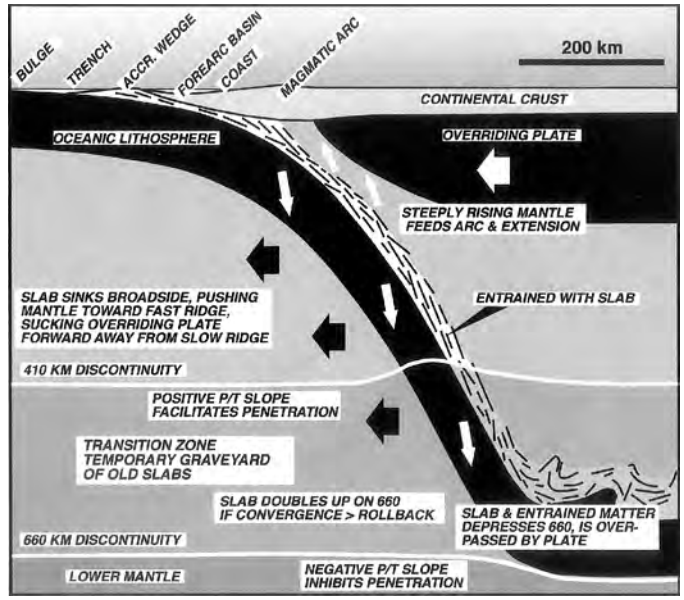

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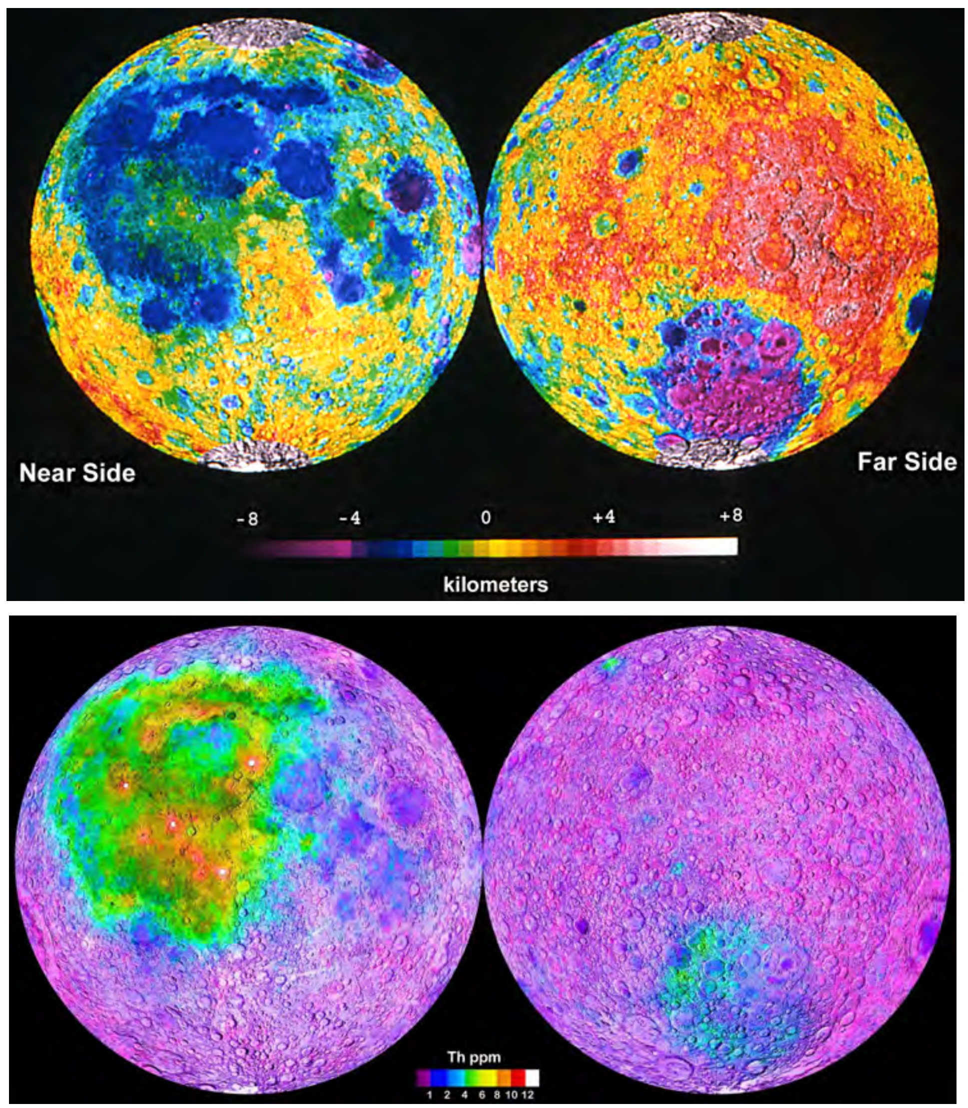
Figure 3



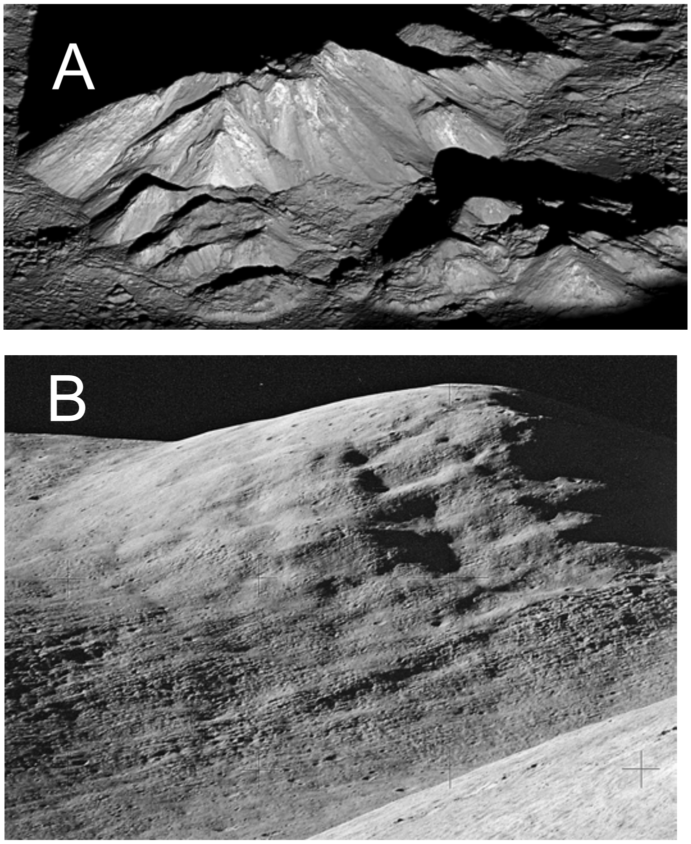
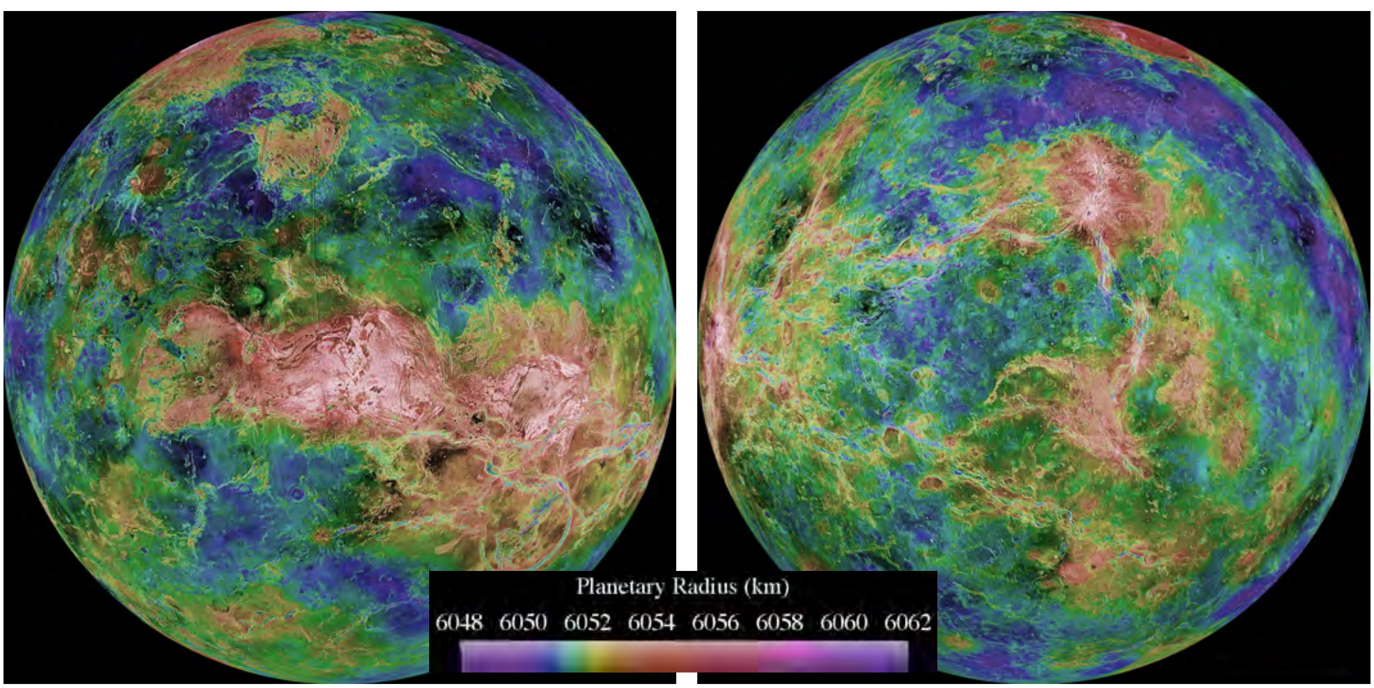


Figure 4



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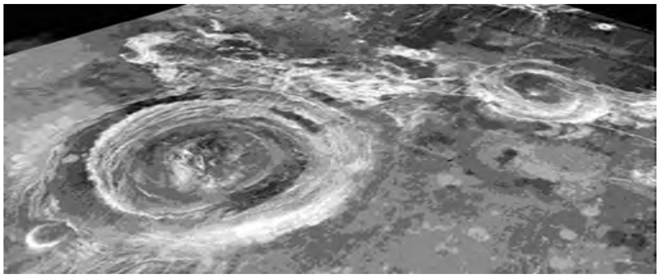

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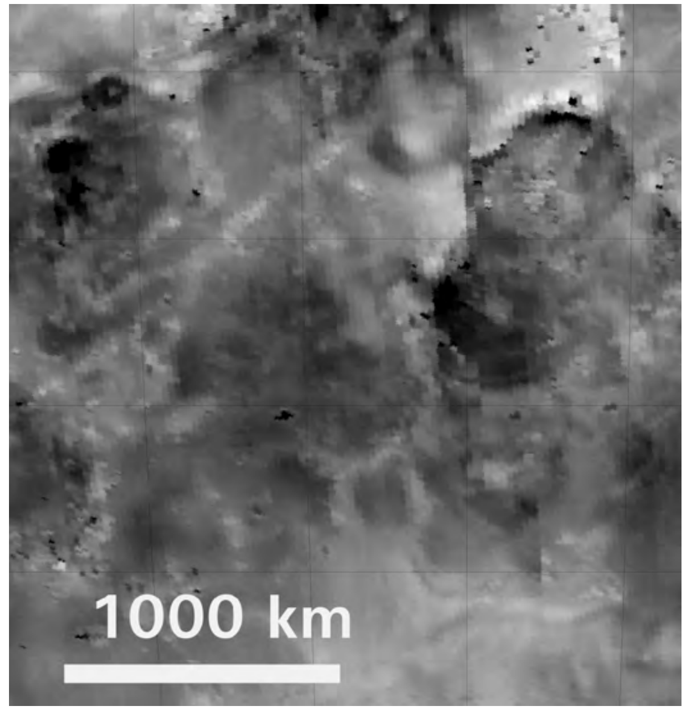

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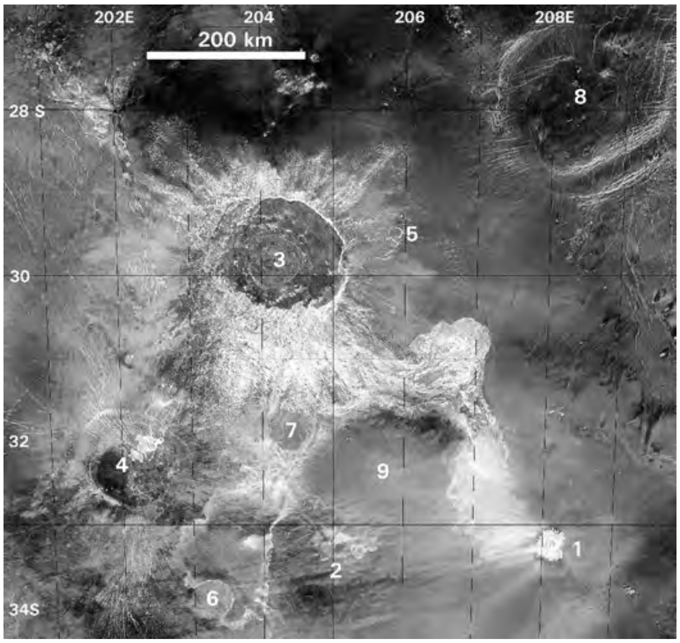

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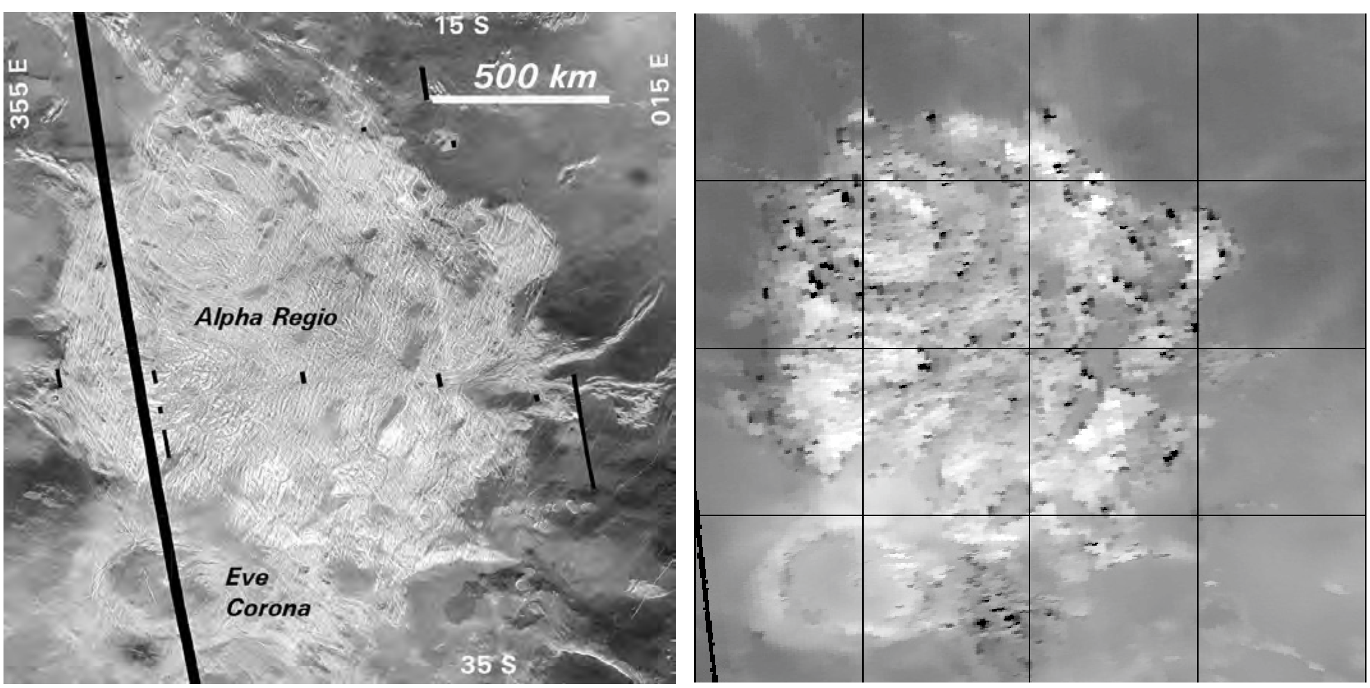

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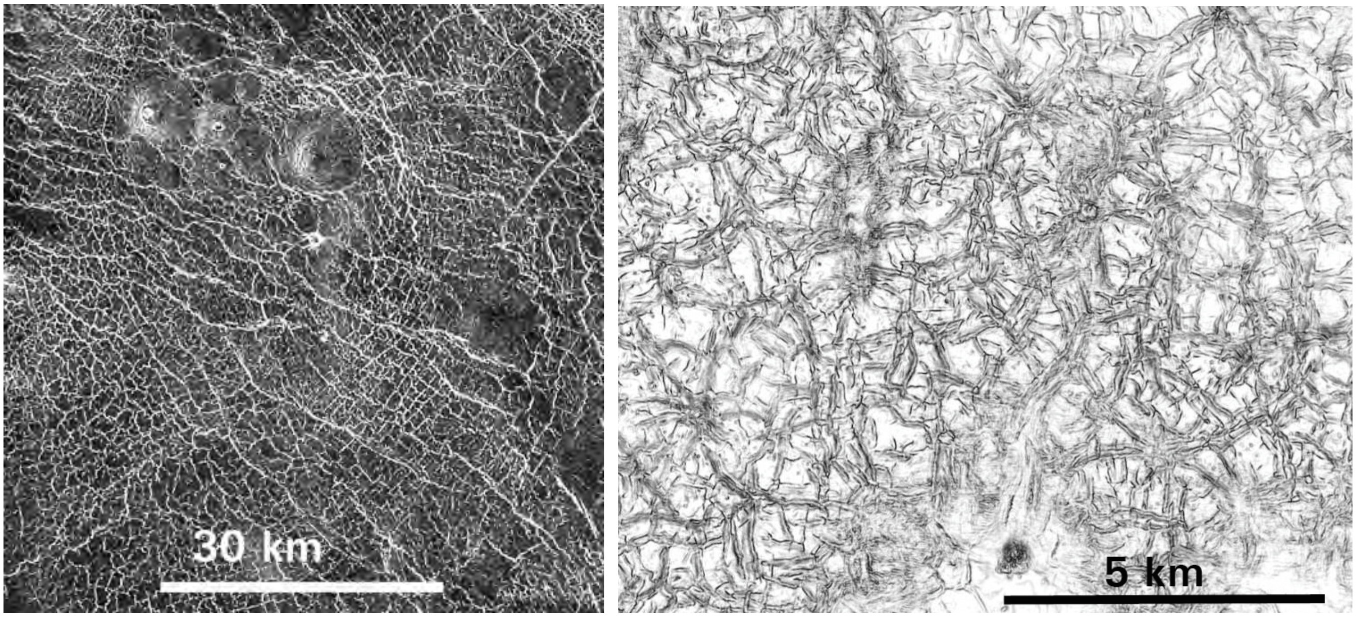

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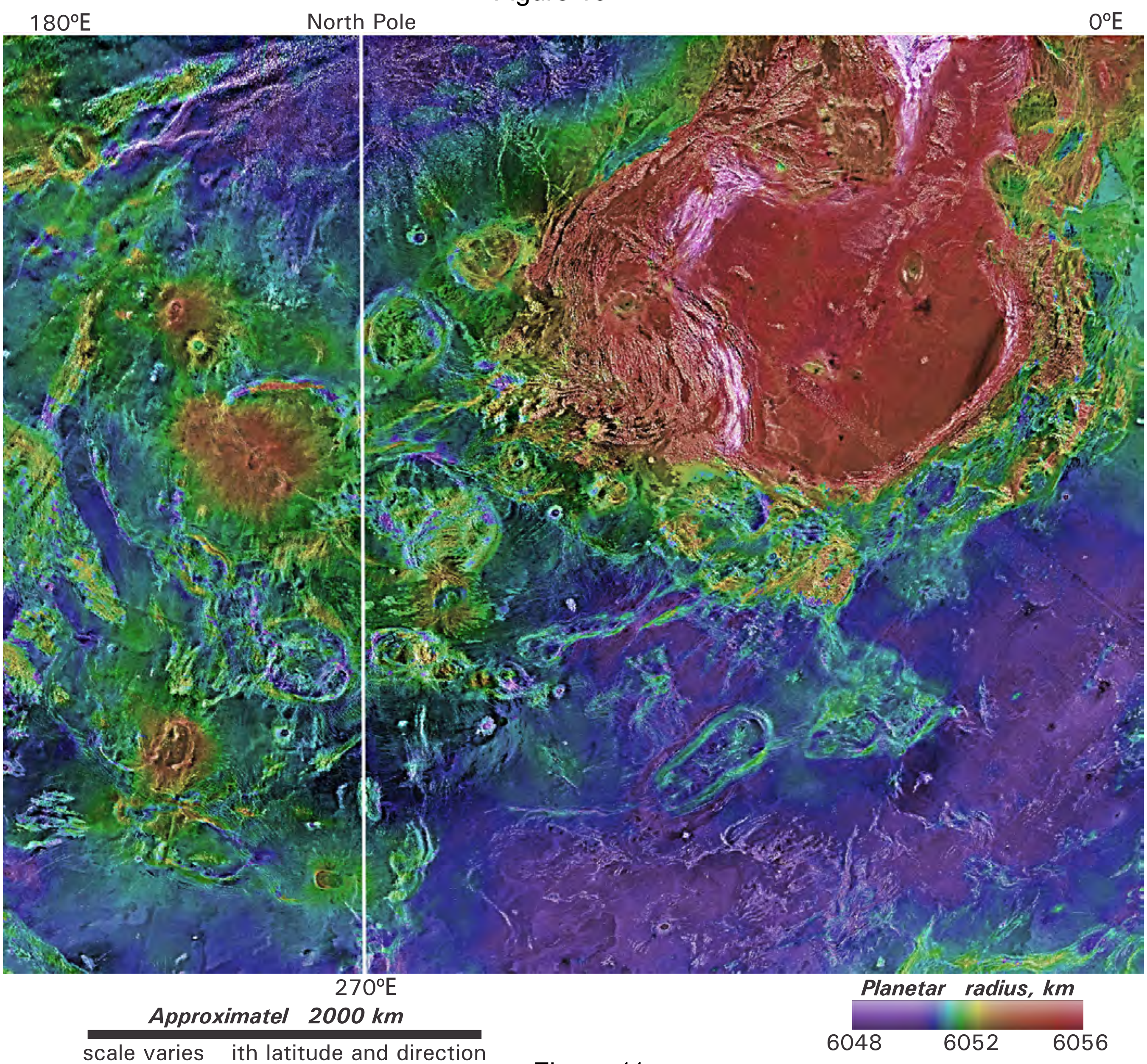

Figure 11

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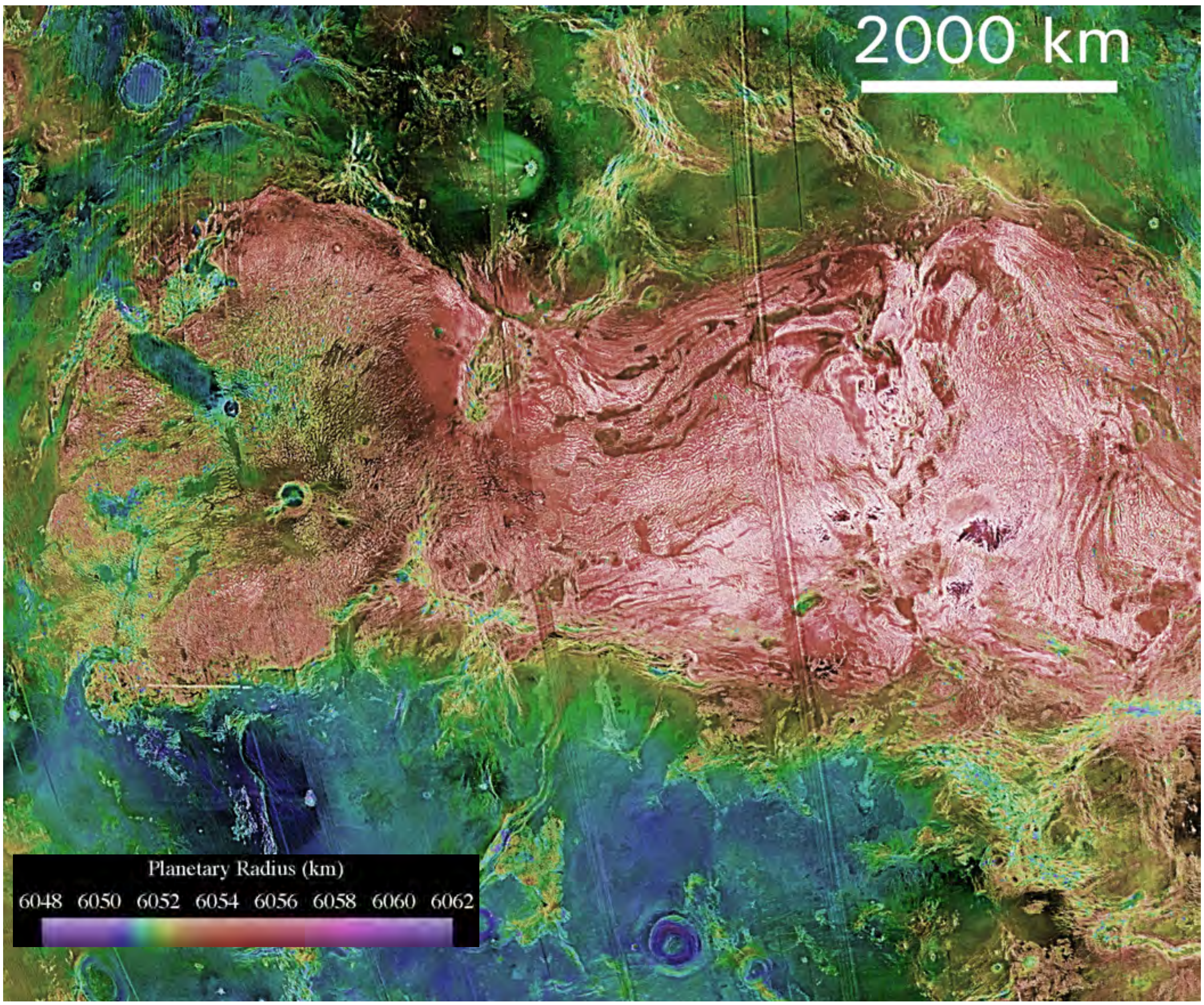

Figure 13

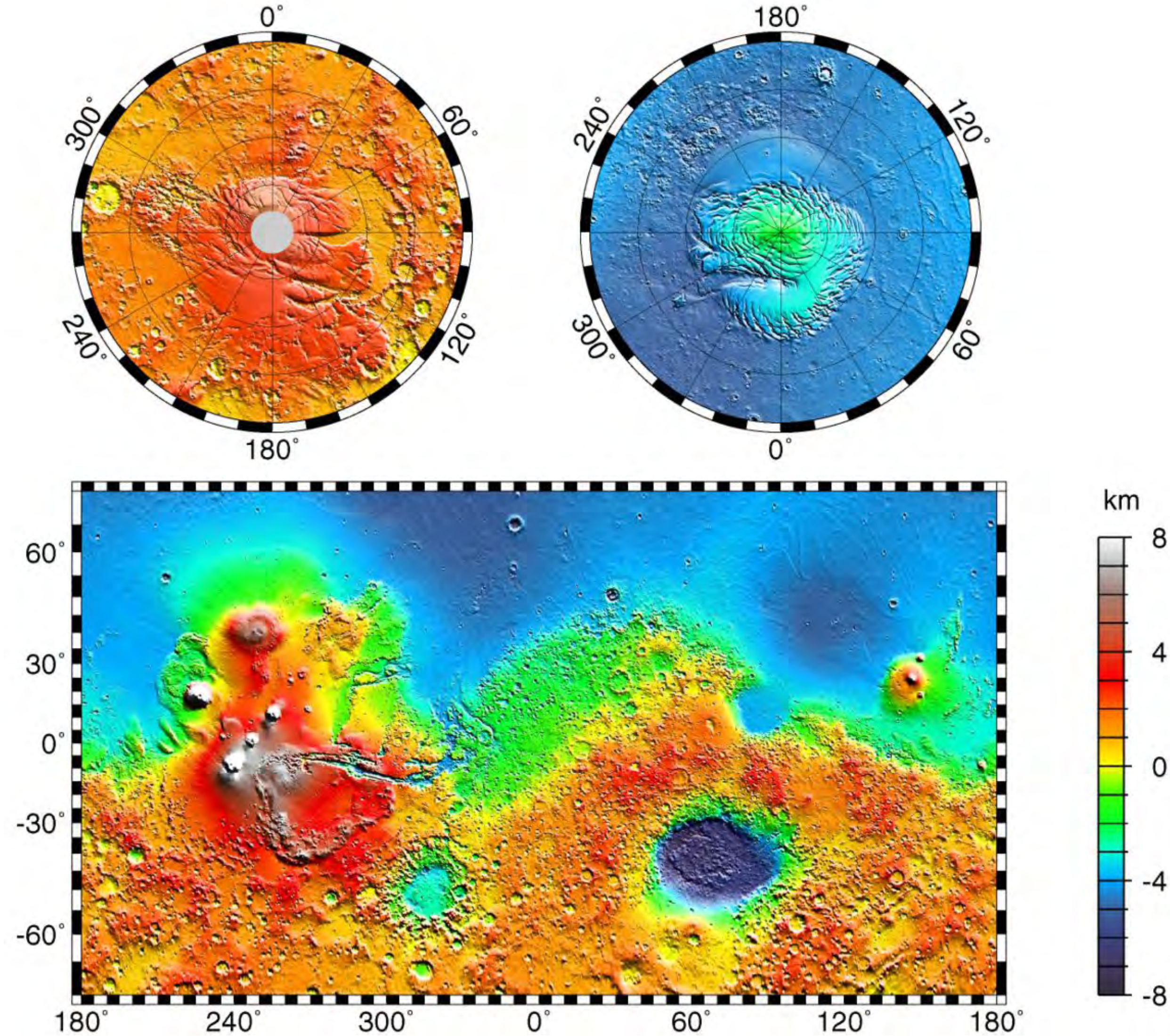

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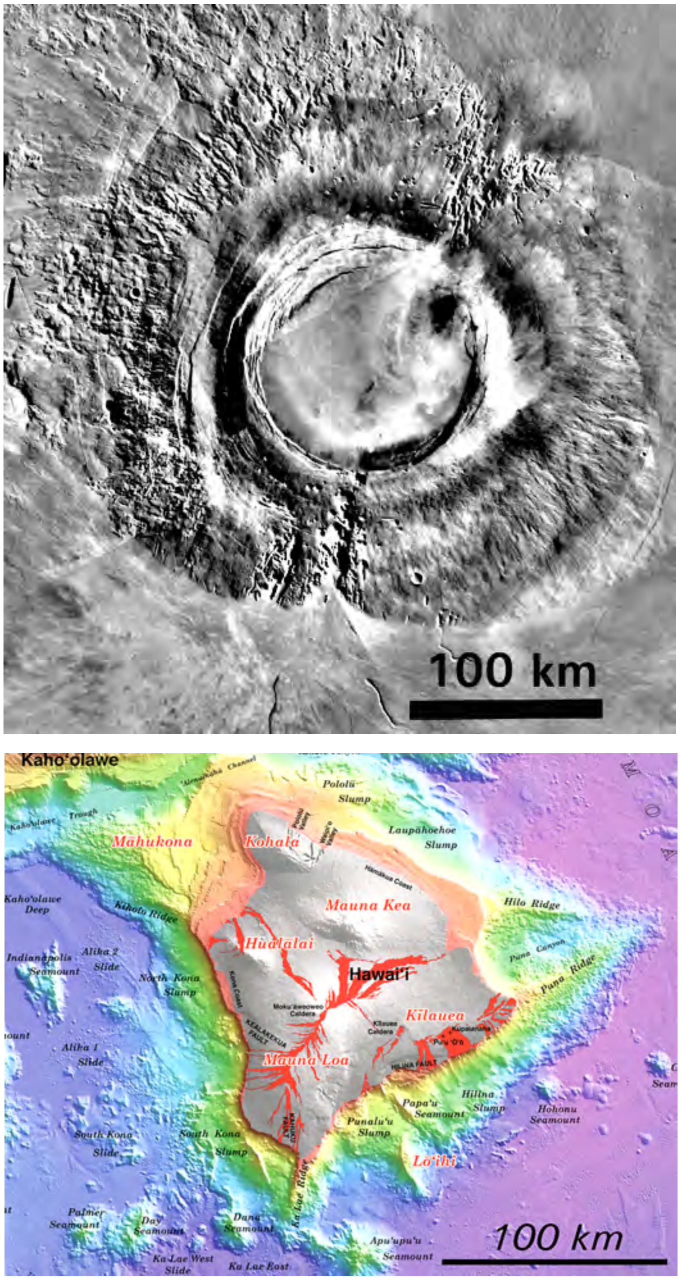
Figure 14



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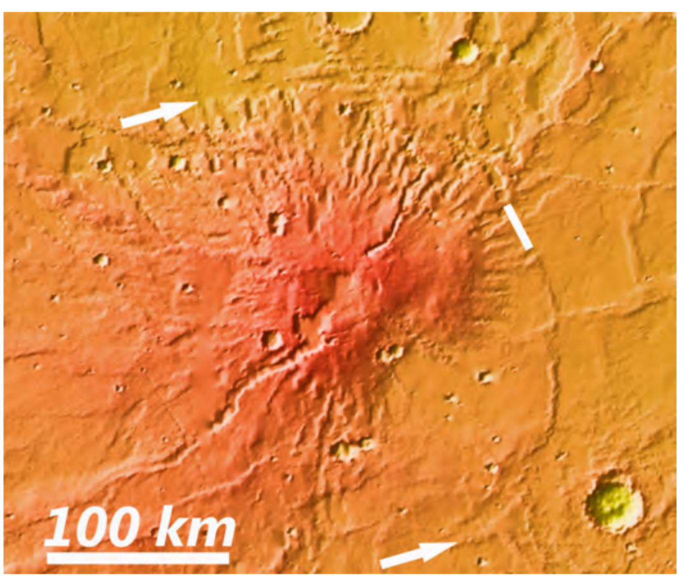

Figure 16

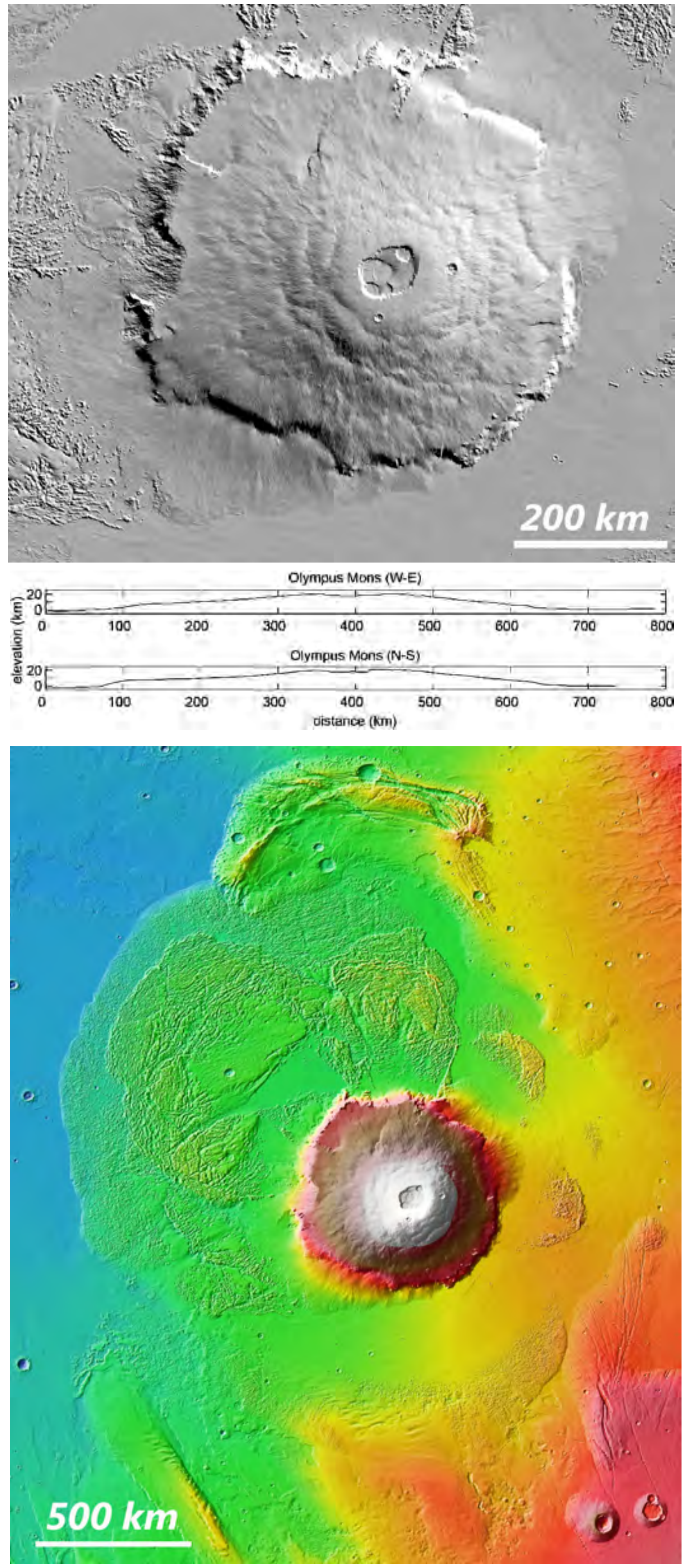

Figure 17