THE QUEST FOR EXTRATERRESTRIAL CRATONS

Vicki L. Hansen[1,2]

DOI: 10.2138/gselements.20.3.152

Here I explore our Solar System's rocky planetary bodies as possible Archean craton (AC) analogs. Why? If other bodies host AC-like features, we might learn things about early Earth that we cannot learn from Earth itself. Typically, we look to Earth for planetary analogs. I propose the reverse—let us look to other planets for Earth analogs. Planets are likely most similar in their *early* histories. Earth developed plate tectonics, but this elegant global cooling process destroyed most of Earth's early geological record. No other planets developed global plate tectonics and, therefore, might preserve records of early global processes that shed light on our own planet's workings.

First, we need to define 'Archean craton' so that it is clear what we are looking for. Second, we will abandon strict uniformitarianism (the concept that Earth has always changed in uniform ways and, hence, that the present is the key to the past), which bolsters familiar concepts but stifles novel ideas. Third, we will formulate thought experiments armed with first-order scientific principles and being mindful of operative boundary conditions (i.e., primary variables that control processes we wish to explore).

Archean cratons (quasi-circular masses of ancient lithosphere ≥500 km in diameter) consist of coupled crustal granite-greenstone terrains (GGTs) and strong, buoyant cratonic lithospheric mantle (CLM). GGTs owe their preservation to CLM, without which GGTs would be recycled to the mantle by subsequent plate tectonics. Coupled GGT-CLMs formed contemporaneously and likely by a uniquely Archean process, although ACs were variably modified over geologic time by plate tectonics. Eroded GGTs expose a snapshot of mid-crustal processes and evidence of once higher-standing terrain. Models to explain the formation of ACs, and their planetary analogs, if such exist, must address 1) their large size and high-standing, quasi-circular shape; 2) their unique crustal signature and buoyant mantle root which formed together; and 3) their ability to survive for billions of years.

Regional topographic highs can be supported in three different ways: 1) thermally, 2) by mantle upwelling, and 3) by compositionally lower bulk density. The first two form domical topography with gradual surface slopes, indicative of the role of flow (heat and material, respectively), and represent contemporary processes. These actively supported features are not good analogs for ACs due to their transient nature (remove heat or flow and topography decays). Compositionally supported topography, typically marked by steep sides and flat tops (plateaus), is more resilient and will not decay over time, as needed for ACs. Erosion, a dominant process on Earth (but not on all planets) might modify an AC, exposing the mid-crust as in Earth's GGTs.

Many Solar System bodies *lack* geomorphic features appropriate to be AC analogs. Mercury and the Moon have no AC-like features; impact craters dominate both bodies. Among Jupiter's moons, volcanically dominated Io is much too young. Europa hosts small quasi-circular 'chaos terrain' surfaces crisscrossed with overlapping lineaments of seemingly random orientations cut by sharp breaks that leak material from below, like broken ice refrozen on a pond; their small size and low topography are not AC-like. Ganymede and Calisto also lack fitting geomorphic features; again, impact craters dominate both. Saturn's moons Enceladus and Titan likewise lack features resembling ACs. And despite new data for Pluto, no AC-applicable features stand out.

Although none of those bodies host plausible AC analogs, Mercury and the Moon's vast ancient impact basins remind us that large bolides traversed the early inner Solar System. Bolides, bodies of unspecified composition—stony, metallic, gaseous, or a combination—form large craters upon collision with target bodies and are a principal driver of exogenic (versus endogenic) processes. Mars also preserves gigantic ancient impact basins. These three bodies—all smaller than Earth and hence cooling significantly faster—developed thick target lithospheres. The high crater density on their impact-basin fills, resulting from subsequent pummeling by smaller bolides, confirm the ancient ages of these enormous impact basins. Large ancient bolide impacts are therefore something we should bear in mind for early Earth.

Mars, bigger than Mercury and the Moon, preserves a richer geologic history, including potential AC analogs. The Tharsis bulge (~5000 km in diameter and 7 km high) and Olympus Mons (~1600 km in diameter and a whopping 22 km high) are extensive highland features meeting some of the AC-analog criteria. However, their domical forms and gradually sloping topography indicate thermal topographic support and relative youth, consistent with their young glacial and volcanic surfaces marred by only a few small impact craters (Neukum et al. 2004). Rather, Tharsis and Olympus Mons, potentially the longest-lived volcanic provinces in the Solar System, seem more analogous to Hawaiian volcanoes underlain by a deep mantle plume than to ancient cratons.

This leaves Venus. Venus is considered Earth's sister planet due to its similar size, density, bulk composition, and heat budget—all factors critical to planetary differentiation and first-order dynamic endogenic cooling processes. Like siblings, these planets were most similar at 'birth', yet Venus now differs dramatically from Earth. It is hotter (~475 °C) and drier, therefore with stronger silicate rocks and little erosion, has a dense atmosphere, and it never developed plate tectonics. Without plate tectonics, evidence of early lithospheric processes could have been preserved such that Venus' early geologic history might stand in for Earth's.

Venus and Earth lack the vast impact basins seen on other planets; their largest impact craters are a mere ~300 km in diameter. Why? Surely, they must have experienced the same early large-bolide impacts recorded on Mercury, the Moon, and Mars, and their larger masses should have attracted even more numerous and larger bolides. But because Venus and Earth are bigger, they cooled more slowly, resulting in early thin, hot lithospheres, and lithosphere thickness plays a critical role in bolide-impact response. A large bolide impacting thick lithosphere forms a crater, whereas a large bolide impacting thin, hot lithosphere can generate millions of cubic kilometers of melt, which forms in the mantle, not in the crust; thinner lithosphere, larger bolides, and hotter mantle each contribute to greater melt volumes (Jones et al. 2005; Elkins-Tanton and Hager 2005).

Venus hosts two types of quasi-circular craton-sized features—volcanic rises and crustal plateaus—both >1500 km in diameter and ~4 km above mean planetary radius. Volcanic rises are domical with extensive lava flows reflecting contemporary thermal support by large mantle plumes, making them unlikely AC analogs. In contrast, crustal plateaus are characterized by steep sides and flat tops that host distinctive tessera terrain (see Box 1); tessera is widely accepted as Venus' oldest surface. A plateau shape indicates compositional support which, together with tessera surfaces, imply ancient formation. Crustal plateaus on Venus are therefore a viable AC analog. But how did they form? Tessera may provide critical clues. Distinctive tessera fabric consists of parallel-trending short- and medium-wavelength folds (~1 to 5 km) that record thin-layer shortening and orthogonal periodic ribbon structures (1–3 km spacing) formed by thin-layer extension. Venus' lowlands host isolated tessera inliers that display coherent fabric patterns across 1000s of kilometers, interpreted as remnants of collapsed crustal plateaus.

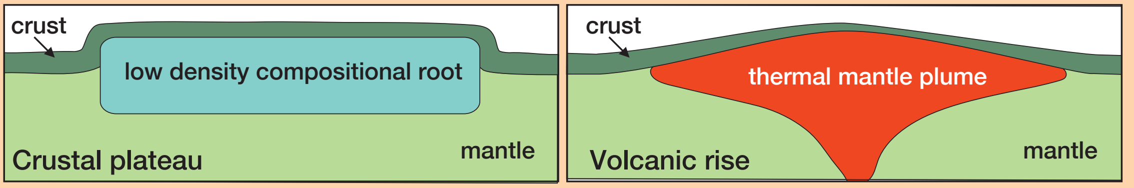
---

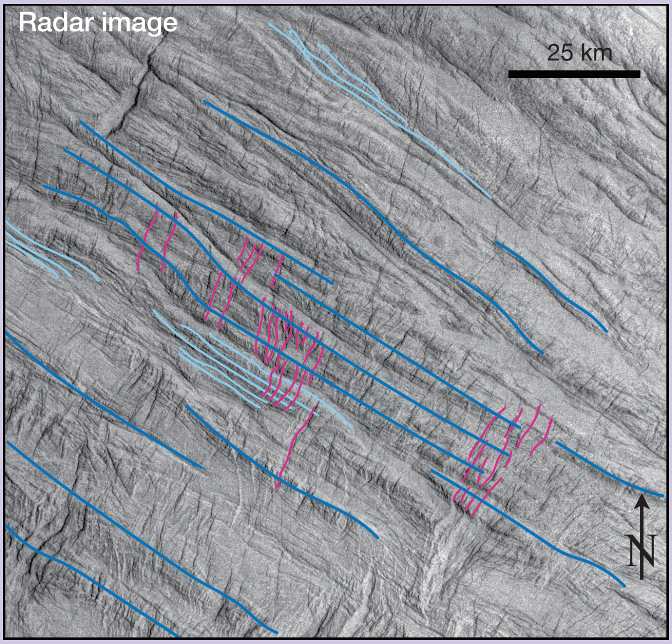
[1] Department of Earth and Environmental Sciences
University of Minnesota Duluth
Duluth, MN, USA
E-mail: vhansen@d.umn.edu

[2] Planetary Science Institute
Tucson, AZ, USA
E-mail: vhansen@psi.edu

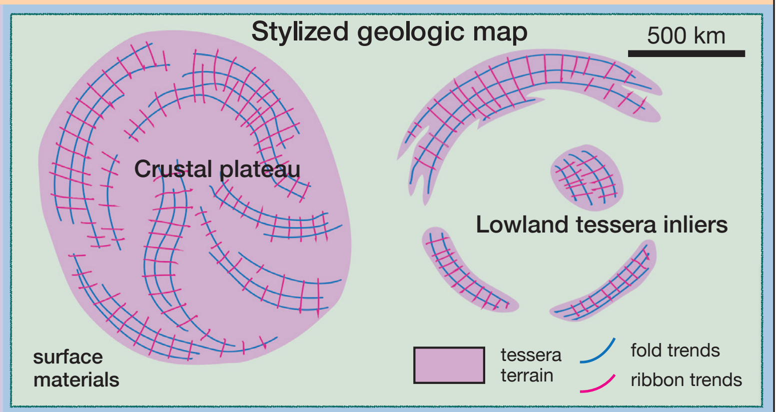
Plateaus and rises

Cartoon cross sections of crustal plateaus and volcanic rises. Ancient crustal plateaus are compositionally supported by low density roots, whereas contemporary volcanic rises are thermally supported by active mantle plumes.

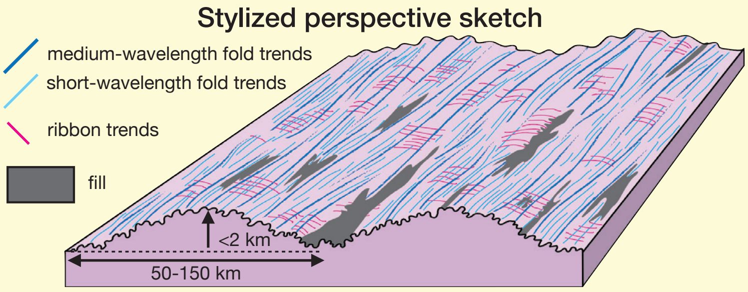




This inverted NASA Magellan Mission SAR (synthetic aperture radar) image illustrates the distinctive surface of tessera terrain. Image appears illuminated from the right. In this example, folds—which record layer shortening—trend NW-SE, and periodic ribbon structures—which record layer extension—trend NE-SW. Selected structures are highlighted to guide the eye: short-wavelength folds in light blue, medium-wavelength folds in darker blue, and ribbon structures in magenta. At any given location all fold trends are parallel, whereas folds and ribbons are perpendicular to one another.



Stylized geologic map showing tessera terrain fabrics as they are exposed on crustal plateaus and lowland tessera inliers.



Stylized perspective sketch illustrating tessera fabrics (not to scale). Parallel short- and medium-wavelength folds piggyback on long-wavelength warps. The slopes of broad-scale warps have extremely gentle slopes, generally less than 2°. Volcanic fill occurs in local topographic lows.

Box 1 CHARACTERISTICS OF VENUSIAN CRUSTAL PLATEAUS AND THEIR DISTINCTIVE TESSERA TERRAIN.

Crustal plateaus are supported by a compositionally low-density root. Tessera terrain, defined by perpendicular folds and ribbon structures, decorates all crustal plateaus and also occurs as lowland inliers thought to represent the remnants of collapsed crustal plateaus. Note the disparate scales of tessera fabrics and crustal plateaus (see radar image and geologic map).

Crustal plateau formation is highly debated. I focus here on a mind-stretching bolide impact hypothesis (Hansen 2006), contending that tessera fabric, so characteristic of individual crustal plateaus, evolved as the 'scum' of a vast lava pond (1500–2000 km in diameter and perhaps >5 km thick), which formed due to a large bolide impact on Venus' early hot, thin lithosphere. Bolide impact resulted in extensive high-temperature, high-fraction partial melting (30% to >50%) in the mantle; juvenile mantle melt rose to form an immense lava pond (>1.77 × 10^6 km^2) on thin lithosphere. As the pond solidified, progressive formation of tessera ribbons and short- and intermediate-wavelength folds recorded increasingly thicker pond scum. As the pond melt crystallized, differentiated melts (as opposed to juvenile melts) leaked through to the surface, embaying local structural lows in the developing tessera scum. Petrologic evolution of such a huge igneous province would result in a wide range of melt compositions; this complexity, however, has yet to be modeled. In the mantle, melt residuum formed a strong and compositionally buoyant sublithospheric root (e.g., Jordan 1981). Residuum strength resulted from its extremely high temperature of melting and dry nature (fluids would concentrate in the melt), while residuum buoyancy resulted from it being chemically less dense than the surrounding mantle. This melt-residuum root ultimately uplifted the partially solidified lava pond, producing a crustal plateau decorated with tessera. Each crustal plateau represents a separate large bolide impact event. Tessera that lost its buoyant residuum root (e.g., via mantle convection) could be locally buried, forming lowland tessera inliers. Tessera coupled to its buoyant residuum would escape burial, preserved atop a crustal plateau. Subsequent secular cooling and thickening of the global lithosphere would 'lock' resilient low-density residuum roots in place, assuring geologic preservation of crustal plateaus. Lowland tessera inliers could be subsequently uplifted above a mantle upwelling, but would not fit the definition of a crustal plateau.

What are the implications for Earth? Can we extrapolate directly from Venus to the early Earth? Let us start with what early Earth and its neighborhood were like, and what might result. During the Archean, large bolides that struck Earth's thin, hot lithosphere would cause massive fractional (i.e., partial) melting of the mantle (30% to >50%), instantly creating two new reservoirs—juvenile melt and strong buoyant residuum (Hansen 2015, 2018). Some melt, lost to a vapor-rich ejecta plume (Jones et al. 2005), would rain down as vapor-condensate spherules (Lowe et al. 2003; Glass and Simonson 2012). Neither melt nor residuum reservoirs would communicate chemically with their parent mantle. The melt reservoir, concentrated with parent-mantle components that chemically partitioned into the melt (radiogenic elements, fluids, precious metals, etc.), would rise, forming a vast crustal igneous province. Igneous evolution would form rock types spanning the entire spectrum from ultramafic to felsic compositions, and intrusive to volcanic rocks, further enriching the evolved melts. The residuum—a buoyant, isolated solid mantle reservoir—would remain unchanged.

I suggest that Venus' crustal plateaus represent plausible analogs of Earth's ACs. Both could have formed as a result of large bolide impacts on ancient hot, thin lithosphere—an exogenically driven process leading to rapid, simultaneous formation of distinctive GGT-type crustal igneous complexes coupled with low-density mantle melt-residuum roots (CLM). The ensuing evolution of Venus' and Earth's igneous complexes would differ as a function of the ancient environmental boundary conditions of each planet. A bolide impact/melt mode of GGT-CLM formation appears consistent with isotopic signatures related to formation of one of Earth's oldest cratons, the Pilbara (Kemp et al. 2023; Petersson et al. 2023) indicating 1) linkages between mantle–crustal processes throughout craton history; 2) coupled evolution of granites and greenstones; 3) felsic rocks formed mostly by differentiation of juvenile mantle material; 4) little evidence for remelting of Hadean crust; and 5) a distinctive style of Archean crust production. A bolide impact/melt hypothesis for Archean craton formation hence seems worthy of consideration.

Seemingly outlandish hypotheses can lead us to consider unforeseen implications, surprising connections, and novel solutions. In this case, the Venus perspective 1) challenges geologists to reconsider the importance of bolides in Earth's early evolution; 2) presents a mechanism by which Archean cratons (like crustal plateaus) are the product of large bolide impacts on ancient thin lithosphere during a unique period in Earth history; 3) explains how a GGT could lose its CLM root and be recycled to the mantle; and 4) accounts for Earth's (and Venus') lack of gigantic impact basins. Further, it 5) potentially addresses the uniqueness of Archean mineral deposits; 6) suggests that ancient GGT topography might be supported, at least in part, by mantle melt residuum, not solely by thick silicate crust; and 7) stimulates us to consider other implications stemming from processes and conditions not usually envisaged for the early Earth.

Is mind travel between Earth and other planetary bodies relevant to better understanding the formation of terrestrial Archean cratons? Because Earth offers geochemical clues, whereas other bodies, like Venus, preserve rich geological and structural evidence the equivalent of which has been lost on Earth due to plate tectonics, I believe it is. Given that the early (Archean) Earth's lithosphere was thin and large bolides traversed the heavens, logic tells us that large bolides hit the early Earth. Spherule layers in the geological record represent the vapor-plume ejecta of impact events and provide evidence of large Archean events, despite the lack of corresponding crater basins (Lowe et al. 2003; Glass and Simonson 2012). Geochemical, isotopic, and geophysical data combined with modeling (see Table 1 in Johnson and Melosh 2012) provide timing (3.5–2.5 Ga), bolide size (11–58 km), and velocity (18–25 km/s) of these Archean impact events. Modeling further suggests that large bolide impact with thin lithosphere yields extremely high-fraction (30% to >50%) partial melting in the mantle, and that just a 50 °C increase in the potential temperature of the mantle leads to the production of 2–3 times more melt volume (Jones et al. 2005; Elkins-Tanton and Hager 2005). Mantle potential temperature, a theoretical concept geologists use to compare mantle temperatures in different situations, is the temperature of the mantle if it ascended to the surface without melting. Imagine the amount of melt a hot Archean mantle could generate! Voluminous high-fraction melting would also leave behind a substantial low-density residuum (see Box 3 in Pearson et al. 2021).

Implications often lead to new questions, or new thought experiments. Three immediately come to mind. 1) *What would happen if a bolide 50 km in diameter struck hot, thin Archean lithosphere overlying mantle with a high potential temperature? How much melt volume would result and what would be the chemical composition of that melt?* 2) *Given Archean mantle and environmental conditions, how would this large melt pool evolve physically and chemically during solidification? Would evolution differ under Venus conditions?* 3) *Would melt evolution be different if there were two or more spatially adjacent, but temporally distinct, large bolide impacts?*

In closing, we should ask '*What happened* when *large bolides impacted Earth's early thin lithosphere?'*—not *if*. Geologically, Earth is not a closed system, particularly during its early phase in the larger Solar System, so it is important to consider the influence of exogenic processes on geodynamics and, likely, the origin of life.

REFERENCES

Elkins-Tanton LT, Hager BH (2005) Giant meteoroid impacts can cause volcanism. Earth and Planetary Science Letters 239: 219-232, doi: 10.1016/j.epsl.2005.07.029

Glass BP, Simonson BM (2012) Distal impact ejecta layers: spherules and more. Elements 8: 43-48, doi: 10.2113/gselements.8.1.43

Hansen VL (2006) Geologic constraints on crustal plateau surface histories, Venus: the lava pond and bolide impact hypotheses. Journal of Geophysical Research Planets 111: E11010, doi: 10.1029/2006JE002714

Hansen VL (2015) Impact origin of Archean cratons. Lithosphere 7: 563-578, doi: 10.1130/L371.1

Hansen VL (2018) Global tectonic evolution of Venus, from exogenic to endogenic over time, and implications for early Earth processes. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 376: 20170412, doi: 10.1098/rsta.2017.0412

Johnson BC, Melosh HJ (2012) Impact spherules as a record of an ancient heavy bombardment of Earth. Nature 485: 75-77, doi: 10.1038/nature10982

Jones AP, Wünemann K, Price GD (2005) Modeling impact volcanism as a possible origin for the Ontong Java Plateau. In: Foulger GR, Natland JH, Presnall C, Anderson DL (eds) Plates, Plumes, and Paradigms. Geological Society of America Special Paper 388, pp 711-720, doi: 10.1130/2005.2388(40)

Jordan TH (1981) Continents as a chemical boundary layer. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences 301: 359-373, doi: 10.1098/rsta.1981.0117

Kemp AIS, Vervoort JD, Petersson A, Smithies RH, Lu Y (2023) A linked evolution for granite-greenstone terranes of the Pilbara craton from Nd and Hf isotopes, with implications for Archean continental growth. Earth and Planetary Science Letters 601: 117895, doi: 10.1016/j.epsl.2022.117895

Lowe DR and 5 coauthors (2003) Spherule beds 3.47–3.24 billion years old in the Barberton Greenstone Belt, South Africa: a record of large meteorite impacts and their influence on early crustal and biological evolution. Astrobiology 3: 7-48, doi: 10.1089/153110703321632408

Neukum G and 11 coauthors (2004) Recent and episodic volcanic and glacial activity on Mars revealed by the High Resolution Stereo Camera. Nature 432: 971-979, doi: 10.1038/nature03231

Pearson DG and 8 coauthors (2021) Deep continental roots and cratons. Nature 596: 199-210, doi: 10.1038/s41586-021-03600-5

Petersson A and 6 coauthors (2023) Response of Sm–Nd isotope systematics to complex thermal histories: a case study from 3.58 Ga gneisses of the Pilbara Craton. Earth and Planetary Science Letters 620: 118346, doi: 10.1016/j.epsl.2023.118346

ABOUT THE AUTHOR

Vicki Hansen is a structural geologist with a strong belief that important questions (and answers) lie in the field. Her initial inquiries focused on the North American Cordillera from Arizona to Alaska. She serendipitously ventured to Venus, experiencing geologic 'field mapping' and structural analysis at global scales, made possible through incredible NASA Magellan high-resolution radar data. New collaborations further expanded her world from planetary crusts and lithospheres to mantle dynamics and core–mantle boundaries. Her appreciation of deep endogenic processes grew, as it did for exogenic processes. Venus research led Hansen back to Earth—particularly early Earth—motivated by global-scale evolution of 4.5-billion-year-old planetary systems, and driven by questions that start with geological relationships embedded in planetary crusts. Hansen is Emeritus Professor at University of Minnesota Duluth, USA, and Senior Scientist with the Planetary Science Institute, Arizona, USA.