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. Without plate tectonics, Earth likely could not form its present balance of plateaus and strike-slip boundaries, implying that crustal plateaus are key to understanding early Earth. 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, suggesting some analogs that Earth’s early geologic history might stand in for Earth’s.

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.

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.

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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; 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
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


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, Arizona to Alaska. She spent endipitously 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 did her desire for exogenic processes. Venus rewarded for 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 geologic 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.