DID LARGE VOLCANIC CHANNEL SYSTEMS FORM ON EARTH DURING THE HADEAN AND ARCHEAN?  David W. Leverington, Department of Geosciences, Texas Tech University, Lubbock, TX, 79409.

Introduction: The remains of large volcanic channels exist at the surfaces of the Moon, Venus, Mercury, Mars, and Jupiter’s moon Io [1-10]. These channels commence near sites of past voluminous effusion of lava, terminate at basins mantled by volcanic flows, and show evidence for incision by low-viscosity lava flows. The remarkable sizes of these channels, and their inferred past roles in the resurfacing of planetary landscapes, render them of considerable geomorphological interest. These systems are also of geochemical and petrological interest since they likely developed as the surface expressions of deeply-rooted magma systems, and their attributes should thus reflect the character of interior materials and processes [4,6,10].

Past development of large volcanic channels on all major rocky bodies of the inner solar system beyond Earth suggests the possible formation of analogous terrestrial systems during Earth’s early history, a time frame of heightened internal temperatures and eruption of low-viscosity magmas. More generally, the geological record of the solar system suggests a strong predisposition of all rocky planets for early incision of large volcanic channels.

Large Igneous Provinces: Much of the magma formed on Earth today develops through processes of decompression at divergent plate boundaries and at hypothesized mantle plumes [e.g.,11]. The partial melting of mantle peridotite here is constrained by peritectic compositions rather than by bulk mantle compositions, producing mafic magmas at pressures less than 2 GPa. Earth’s volcanic output during the Phanerozoic has at times been punctuated by geographically restricted effusions that formed the large igneous provinces. These provinces consist largely of mafic units emplaced as continental flood basalts, ocean basin flood basalts, oceanic plateaus, submarine ridges, seamount groups, and volcanic passive margins [12]. The largest igneous provinces of the Phanerozoic had original volumes of millions of cubic kilometers and were in numerous cases mostly emplaced within ~1 Ma [12]. The processes that resulted in development of most flood basalts and oceanic plateaus on Earth are believed to have been related to impingement of the heads of mantle plumes against the lower crust [11,12].

Though well-preserved examples of large igneous provinces are restricted to the Phanerozoic, evidence for earlier emplacement of analogous units may exist in the form of ancient dike systems. Radiating dike swarms are associated with many Phanerozoic continental flood basalts, and the ancient equivalents of these intrusive systems are correspondingly inferred to be mid-crustal remnants of large igneous provinces now lost to weathering and erosion [13]. Radial dike patterns are expected to develop in relation to plume-generated deformation, with points of dike convergence marking positions of maximum uplift, suggesting that Archean and Proterozoic radiating dike swarms formed in association with ancient mantle uplift [13].

Despite the enormous volumes of the large igneous provinces of the Phanerozoic, their emplacement is not known to have favored incision of large igneous channel systems. The relatively high lava viscosities, and slow emplacement of flows through inflation processes, are likely to have hindered formation of large channels.

Early Volcanic Channel Development on Earth: Mantle temperatures and rates of heat production during the earliest eons of Earth history are expected to have been much higher than those of today, resulting in increased rates of mantle convection and magmatism [e.g.,14]. For decompression melting such as that believed to be occurring today at mantle plumes, hotter mantle temperatures favor deeper melting and the production of greater volumes of melt [15]. The higher pressures associated with deeper partial melting should enrich liquids in olivine, producing picritic magmas at pressures of ~3 GPa [11] and komatiitic magmas at pressures of ~3-15 GPa [16].

Generation of komatiites, and related magmas such as basaltic komatiites, was prevalent on Earth during the Archean and Early Proterozoic [15]. Ultramafic magmas will generally have high anhydrous liquidus temperatures (~1400° to >1600° C) [e.g.,16] and viscosities on the order of ~0.1 Pa s [17]. Such viscosities are much lower than the ~80-1000 Pa s typical of modern mafic lavas, and can greatly increase the capacity of a magma for turbulent flow and for mechanical and thermal erosion of a substrate [18,19].

Might voluminous eruption of mafic or ultramafic magma early in Earth history, possibly at plume-like upwellings of the mantle, have resulted in incision of volcanic channels with dimensions comparable to those of other bodies of the inner solar system? Incision rates predicted on the basis of principles summarized in [10] for 10-m-deep lava flows erupted under Earth conditions, across basaltic substrates of intermediate strength and with slopes under 0.25°, are consistent with this hypothesis (Fig.1). Relatively small volcanic channels, with dimensions that nevertheless far exceed those of modern terrestrial systems, are already known for the ancient crust of Australia (2.72 Ga) and Quebec (1.9 Ga) [e.g.,17,20].
Earth's oceans are believed to have existed at least as early as 4.3 Ga B.P. [21]. The pressure and quenching effects of oceans are likely to have facilitated development of large volcanic channels, since: 1) ambient pressures are sufficiently high at deep ocean floors to inhibit explosive eruptions [22] that might otherwise disrupt lava flows; and 2) rapid development of glassy rinds serves to insulate the interiors of submarine lava flows by compelling heat transfer to take place through the relatively slow process of conduction [23].

The best terrestrial candidates for the remains of large igneous provinces of Archean age are greenstone belts that contain thick tholeiite sequences with minor komatitites [24]. If large volcanic channels developed on Earth in the Hadean or Archean, the remnants of associated geological units could conceivably still be preserved in ancient crustal volumes such as these. Relict units could range from lava flows and incised substrates to the deep intrusions hypothesized to have fed early eruptions. Alternatively, it is possible that meaningful evidence for the past existence of hypothesized igneous systems has been largely or completely lost as a result of an early transient character to crustal units, or the later effects of metamorphism, subduction, weathering, and erosion. Identification on Earth of possible geological, geophysical, or geochemical signatures of early igneous systems that might have driven development of large volcanic channels may depend on future detailed investigation of the vestiges of volcanic systems on other bodies of the solar system.

Volcanic Channels on Extrasolar Rocky Planets:
Development of large volcanic channels on at least five rocky bodies of our solar system suggests that formation of such channels is typical of rocky bodies of similar or larger size. The energy sources that drove differentiation and magmatism in our own solar system (e.g., impacts, core formation, tidal interactions, and radioactive decay) should vary in relative importance between individual planets but should nevertheless be common influences on the development of extrasolar rocky planets. The extent to which extrasolar rocky planets have a tendency to form large volcanic channels must ultimately be related to the degree to which these bodies are characterized by compositions and thermal histories that promote voluminous and rapid eruptions of low-viscosity lavas.


Figure 1 Mechanical (A) and thermal (B) incision rates predicted for 10-m-deep lava flows erupted under Earth gravity across basaltic substrates of intermediate strength. Thermal estimates assume a lava viscosity of 1 Pa s. The kilometric-scale slopes of large volcanic channel systems are typically well under 1° [e.g.,6,10,25].