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Review

# Did large volcanic channel systems develop on Earth during the Hadean and Archean?

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The vestiges of large volcanic channels are preserved at the surfaces of the Moon, Venus, Mercury, Mars, and Io. The largest of these systems have widths of tens of kilometers and lengths of thousands of kilometers. Component channels were incised by voluminous low-viscosity lava flows, and are the surface expressions of magmatic systems that helped to dissipate internal heat accumulated through processes of accretion, differentiation, tidal interactions, and radioactive decay. Past development of large volcanic channels on these bodies suggests the possible formation of analogous systems on the Earth during the Hadean or Archean, a time frame of heightened internal temperatures and eruption of low-viscosity magmas. More generally, the geological record of the inner solar system suggests a predisposition of all rocky planets for early incision of large volcanic channels.



**Contents**



## 1. Introduction

Large volcanic channels exist at the surfaces of the Moon, Venus, Mercury, Mars, and Jupiter's moon Io (Wilhelms, 1987; Komatsu et al., 1993; Leverington, 2004, 2011; Schenk and Williams, 2004; Jaeger et al., 2010; Hurwitz et al., 2013a,b; Byrne et al., 2013). 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 (Hulme, 1973; Baker et al., 1997; Williams et al., 2000; Jaeger et al., 2010; Hurwitz et al., 2012; Stockstill-Cahill et al., 2012). The remarkable sizes of these channels, and their inferred past roles in the resurfacing of planetary landscapes, render them of considerable geomorphological interest (Jaeger et al., 2007, 2010; Garry and Bleacher, 2011; Leverington, 2011; Byrne et al., 2013; Hurwitz et al., 2013a,b). These systems are also of geochemical and petrological interest, since they likely developed as the surface expressions of deeply-rooted magma systems (McGetchin and Smith, 1978; Wilson and Head,

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1981; Komatsu et al., 1993; Jaeger et al., 2010; Head et al., 2011; Leverington, 2011; Stockstill-Cahill et al., 2012) and their attributes should thus reflect the character of interior materials and processes.

Formation of large volcanic channels on four rocky bodies of the inner solar system implies a commonality in ancient volcanic processes across these bodies (Leverington, 2011). This paper describes the basic properties of large volcanic channels, and outlines a hypothesis for early development of analogous features on the Earth. Estimates of the capacities for incision of early low-viscosity lavas are presented for terrestrial conditions. On the basis of the attributes expected of large rocky bodies in other solar systems, the hypothesis for early development of large volcanic channels on Earth is extended to all planets composed predominantly of silicates and metals.

## 2. Large volcanic channels of the solar system

Large volcanic channels exist at the surfaces of all major rocky bodies of the inner solar system beyond the Earth, and on Io (Fig. 1). Though the largest modern lava channels on Earth characteristically have widths of less than 50 m and lengths of only tens of kilometers (e.g., Fornari, 1986), the largest of the volcanic channels of other bodies have widths of tens of kilometers and lengths of thousands of kilometers. These channels are believed to have developed as a result of high-volume effusive eruptions involving lavas with viscosities orders of magnitude lower than those typical of modern Earth. Though the absolute timing of landform development on Venus is poorly constrained, the volcanic channels of the Moon, Mercury, and Mars formed mainly in the first ∼1.5 billion years of solar system history. Formation of large volcanic channels on Io is likely to have occurred in the recent geological past.

### 2.1. The Moon

Lunar channels are sinuous in character and typically have few or no tributaries (Schultz, 1976; Wilhelms, 1987; Hurwitz et al., 2013a). Many channels commence at prominent topographic depressions that mark the sites of ancient voluminous effusions of low-viscosity fluids (Fig. 2). Though originally hypothesized as aqueous systems (Urey, 1967; Peale et al., 1968; Lingenfelter et al., 1968), these channels were later confirmed as volcanic on the basis of geological and geochemical attributes of the lunar surface (Oberbeck et al., 1969; Goles et al., 1970; Greeley, 1971; Weill et al., 1971, 1972; Wilhelms, 1987; Papike et al., 1991), including those of the Rima Hadley system visited by the Apollo 15 astronauts (Swann et al., 1972) (Fig. 1). The geomorphic features of lunar channels include terraces, inner channels, levees, anastamosing reaches, streamlined erosional residuals, and typical longitudinal slopes of less than 1° (El-Baz et al., 1972; El-Baz and Roosa, 1972; Schaber, 1973; Hulme, 1974; Schultz, 1976; Strain and El-Baz, 1977; Zisk et al., 1977; Wilhelms, 1987; Leverington, 2004, 2011; Garry and Bleacher, 2011). Of the more than 200 lunar channels identified to date, the longest system is Rima Sharp (566 km) and the widest is Vallis Schröteri (4.3 km) (Hurwitz et al., 2013a) (Fig. 2). Most lunar channels were incised into terrain units formed between ∼3 and 3.75 Ga before present (Hurwitz et al., 2013a). Channels are hypothesized to have developed through eruption of low-viscosity lavas of mafic and ultramafic composition (Murase and McBirney, 1970; Hulme, 1973; Williams et al., 2000), with maximum sustained flow rates of at least 4000 $m^3$/s (Hurwitz et al., 2012).

### 2.2. Venus

Though characterized by a much wider range of size and complexity, the more than 200 volcanic channels of Venus share many basic attributes with lunar systems (Baker et al., 1992; Head et al., 1992; Komatsu et al., 1993; Ivanov and Head, 2013). Most fundamentally, Venusian volcanic channels typically commence in regions of topographic disturbance or at extensive volcanic plains, and terminate in basins mantled by deposits that have properties consistent with those expected of volcanic flows (Baker et al., 1992; Komatsu et al., 1993). As with many lunar systems, the narrowest volcanic channels of Venus generally have a sinuous character and low channel order (Komatsu and Baker, 1994) (Fig. 3). Some narrow Venusian systems (the "canali") are characterized by extraordinary lengths; the longest, though only ∼3 km wide, is at least 6800 km in length (Komatsu et al., 1992) (Fig. 1). The largest volcanic systems have widths of up to ∼30 km, anastamosing channel patterns that define large streamlined erosional residuals, and longitudinal slopes of well under 1° (Baker et al., 1992). Among the largest Venusian systems are Kallistos Vallis (Baker et al., 1992) (Fig. 1) and a remarkably complex system located northeast of Ozza Mons (Komatsu et al., 1993) (Fig. 4).

Alternative aqueous origins have previously been hypothesized for the canali (Jones and Pickering, 2003), but development of channels on Venus is instead generally believed to have involved Mg-rich lavas or possibly more exotic types of flows such as sulfur-rich fluids (Baker et al., 1992; Komatsu et al., 1992), flowing with low viscosities at rates of up to $\sim 5 \times 10^7$ $m^3$/s (Baker et al., 1997). Properties of the Venusian surface, including the character of the preserved impact record, indicate that the planet has been resurfaced since the heavy bombardment period (Phillips et al., 1992). Though narrow temporal constraints on landform development are not available (Campbell, 1999), impact features and stratigraphic relations suggest that current landforms on Venus mainly developed within the past ∼0.5–1.0 Ga, and that a global volcanic resurfacing event may have taken place ∼300 Ma before present (Strom et al., 1994; Basilevsky and Head, 1995; Price et al., 1996).

### 2.3. Mercury

At least 10 prominent channel systems have recently been discovered in the high northern latitudes of Mercury, on the basis of moderate-resolution images generated by the ongoing MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) mission (Head et al., 2011; Byrne et al., 2013). The smallest of these systems are relatively sinuous and narrow, with lengths of up to 161 km and average widths of 3–9 km (Byrne et al., 2013). Though characterized by lengths no greater than 102 km, the four largest Mercurian channels have average widths of 19–28 km, and appear to have acted as major inter-basin conduits for flood lavas emplaced across adjacent lowlands (Byrne et al., 2013; Hurwitz et al., 2013b) (Fig. 5). Extensive volcanic mantles currently preclude determination of the forms of channel floors, but longitudinal slopes of less than 1° are expected (Byrne et al., 2013). As with lunar and Venusian systems, several of the Mercurian channels host streamlined erosional residuals (Head et al., 2011; Byrne et al., 2013) (Fig. 1). The Angkor Vallis system has terraced channel margins, and several of the Mercurian systems are associated with furrow-like features along component channels and adjacent uplands (e.g., at Timgad Vallis) (Byrne et al., 2013). Channel incision on Mercury is hypothesized to have occurred through mechanical and thermal incision by Mg-rich basalts erupted with low viscosity at maximum effusion rates on the order of $\sim 10^6$–$10^8$ $m^3$/s (Stockstill-Cahill et al., 2012; Byrne et al., 2013; Hurwitz et al., 2013b). The flood lavas associated with the Mercurian channels are estimated to have been emplaced ∼3.7–3.8 Ga before present, during the Calorian Period (Head et al., 2011).