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Palaeoflood-generating mechanisms on Earth, Mars, and Titan

Devon M. Burr

[a] *Earth and Planetary Sciences Department and Planetary Geosciences Institute, University of Tennessee Knoxville, 1412 Circle Dr., TN 37996-1410, USA*
[b] *Carl Sagan Center, SETI Institute, 515 N. Whisman Rd., Mountain View, CA 94043, USA*

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ABSTRACT

Channelized, surface, liquid flow occurs on Earth, Mars, and Titan. In this paper, such fluvial flow is constrained to involve volatiles that can undergo phase transitions under surface conditions and can be stable as liquids over geologically significant periods of time. Evidence for channelized, surface, liquid *flood* flow has been observed on Earth and Mars and hypothesized for Titan. The mechanisms for generating flood flow vary for each body. On Earth, the mechanism that generated the largest flooding is widespread glaciation (e.g. the catastrophic release of water from glacial lakes), which requires an atmospheric cycle of a volatile that can assume the solid phase. Volcanism is also a prevalent cause for terrestrial megaflooding, with other mechanisms producing smaller, though more frequent, floods. On Mars, the mechanism for flood generation has changed over the history of the planet. Surface storage of floodwater early in the history of that planet gave way to subsurface storage as the climate cooled. As on Earth, flooding on Mars is an effect of the ability of the operative volatile to assume the solid phase, although on Mars, this solid phase occurred in the subsurface. According to this paradigm, conditions on Titan preclude extensive megaflooding because the operative volatile, which is methane, cannot as easily assume the solid phase under current conditions. Mechanisms that produce smaller but more frequent floods on Earth, namely extreme precipitation events, are likely to be the most important flood generators on Titan in the recent past.

1. Introduction

The scientific study of palaeoflooding has risen and fallen largely in concert with prevailing scientific paradigms (Baker, 1998). The paradigm in the seventeenth and eighteenth centuries was catastrophism, the idea that the geological record and landscape change is the product of sudden, short, violent events. In palaeoflood science this paradigm was expressed as diluvialism — the view that the Biblical flood was historically accurate and could explain various geological formations and fossil remains. Catastrophism gave way to uniformitarianism, first introduced in 1830, which stipulated that the Earth's formations are the product of slow, gradual change. Under this paradigm, geological formations previously explained by catastrophic (Biblical) flooding were often transmuted into the effects of sustained river flow or glaciation. The Channeled Scabland in Washington, USA, was originally interpreted at glacial in origin, either directly (through flow of glacial ice) or indirectly (through diversion of rivers). Consequently, the proposal by J Harlan Bretz of massive flooding as an explanation for the Channeled Scabland was originally treated as an absurd or outrageous hypothesis (cf. Davis, 1926; Baker, 1978). Decades of study demonstrated the verity of this hypothesis, establishing palaeoflood hydrology and geomorphology as a subdiscipline of geology (e.g. Kochel and Baker, 1982).

During this time, the study of palaeofloods was also extended to Mars. The Mariner 9 and Viking orbiter missions first observed Mars' gigantic flood channels, identified on the basis of their morphological similarity to the Channeled Scabland (Mars Channel Working Group, 1983). Future analysis and spacecraft missions to Mars supported continued study of these and other flood channels (Baker, 1982; Carr, 1996), providing quantitative estimates of discharge and other flow parameters, although with large error bars (Wilson et al., 2004). As a result, aqueous catastrophic flooding was established as an extraterrestrial phenomenon.

The Cassini–Huygens mission to the Saturnian system (Matson et al., 2002) opened up a new frontier in planetary geology. Mission data revealed the surface of Titan, Saturn's largest moon, as having strikingly Earth-like landforms – including aeolian dunes (Lorenz et al., 2006) and lakes (Stofan et al., 2007) – although composed of exotic materials that are uncommon on Earth. In particular, the volatile cycle on Titan involves hydrocarbons, namely methane and the nitrogen dissolved in it. Fluviatile features have been interpreted as river channels (Elachi et al., 2005; Porco et al., 2005; Tomasko et al., 2005), which may have discharges of the order of 10^4 m^3 s^{-1} (Jaumann et al., 2007). Though much smaller than the megaflood discharges on Mars or Earth, such discharges would be large for terrestrial rivers.

This paper compares and contrasts evidence for palaeofloods on these three planetary bodies. In this work, the operative liquid is constrained to be a volatile that can undergo phase change at surface conditions. This constraint derives from using terrestrial aqueous

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E-mail address: dburr1@utk.edu.

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flooding as the template. On Earth, flooding results from the rapid release of liquid water from atmospheric, surficial, and underground reservoirs (O'Connor and Costa, 2004). The conditions for such release are created by atmospheric cycling of this volatile and its ability to undergo phase transitions among solid, liquid, and gas phases at surface temperatures and pressures. Similar conditions have occurred on Mars, where water currently exists as a gas in the atmosphere and as a solid on and near the surface. Ancient valley networks indicate that water has existed as a liquid on the surface in the past (Pieri, 1976, 1980; Carr, 1996; Irwin and Howard, 2002; Howard et al., 2005). The interpretation of gullies on Mars as aqueous flow features (Malin and Edgett, 2000; McEwen et al., 2007) also implies that liquid water may exist on the surface today, if only temporarily and/or in isolation. At Titan temperature (~94 K), water occurs only as a solid, except in limited examples of cryovolcanism (Lopes et al., 2007). By analogy with flooding on Earth and Mars, flooding on Titan would involve liquid methane–nitrogen. As on Earth, nitrogen comprises most (94%) of Titan's atmosphere; methane is the next largest fraction (5%) (Niemann et al., 2005). Methane undergoes phase changes between liquid and gaseous phases at Titan surface pressure and temperature, and gaseous nitrogen dissolves in the liquid methane. In addition to the gaseous and liquid phases, methane–nitrogen may even occur or have occurred in solid form on the surface of Titan, although this evidence is currently limited (Robshaw et al., 2008). Floods of geological materials that undergo only solid–liquid transitions (e.g. rocks melting to produce flood lavas) are outside the scope of this work.

Some of the materials and conditions on these three bodies are listed in Table 1. These different materials and conditions cause each body to have its own mechanisms for generating floods. This paper compares and contrasts flooding on these three bodies by reviewing the flood morphologies and the flood generation mechanisms by discharge for each body.

2. Palaeoflooding on Earth

2.1. Glaciation

The largest palaeofloods on Earth, with discharges of the order of 10^6–10^7 m^3 s^{-1}, are associated with glaciation (Baker 1996, O'Connor and Costa 2004). The primary mechanism that produced these 'megafloods' (cf. Baker, 2009) was the sudden release of water from glacial lakes. Proglacial lakes result from damming by the glacier of pre-existing river valleys. These glacial lakes and their outbursts occurred frequently during the Quaternary glaciations as a result of the disruption of pre-existing fluvial drainage (Starkel, 1995). Ice-marginal lakes result from impoundment of the glacial meltwater against the glacier margin, commonly by moraine debris. Ice-marginal (or moraine basin) lakes usually store less water than proglacial lakes, and so generally produce relatively smaller discharges (O'Connor and Beebee, 2009). The most extensive known examples of glacial lake outburst flooding are located in the northern mid-latitudes, where continental ice sheets disrupted pre-existing fluvial flow (e.g., Grosswald, 1998). The most voluminous examples (in terms of discharge) have been found in areas of significant relief where deep valleys supported tall ice dams that impounded large lakes. The largest ice-dam failure floods on Earth include: the Kuray and other floods in the Altai Mountains, Siberia, during the Late Pleistocene (Baker et al., 1993; Rudoy, 1998; Carling et al., 2002; Herget, 2005); the Missoula floods that carved the Channeled Scabland in Washington, USA (Baker, 2009, and references therein); and early Holocene floods down the Tsangpo River gorge in southeastern Tibet (Montgomery et al., 2004). The largest ice-marginal or moraine dam failure floods include the Lake Agassiz overflow floods in North America (Teller et al. 2002; Kehew et al., 2009, and references therein). It has been argued that freshwater outbursts to the Atlantic from Lake Agassiz may have been an important driver of the environmental changes that led to the Younger Dryas event and other periods of cooling in the Northern Hemisphere during the last deglaciation (Teller et al. 2002).

Table 1
Key parameters of relevance for flood generation on Earth, Mars, and Titan.

Parameter	Earth	Mars	Titan
Surface gravity (m/s^2)	9.81	3.71	1.35
Surface temperature (K)	287	210	94
Surface pressure (bar)	1.01	0.007	1.44
Fluvial liquid, density (kg/m^3), viscosity (Pa s)	Water, 1000, 1×10^{-3} Pa s	Water, 1000, 1×10^{-3} Pa s	CH_4/N_2, 450, 2×10^{-4} Pa s
Fluvial sediment, density (kg/m^3)	Quartz, 2650	Basalt, 2900	Water ice, 992 Organics, 1500
Atmospheric composition	~79% N_2, 20% O_2	~95% CO_2, 2.7% N_2	~95%N_2, ~5%CH_4
Surface area (km^2)	510×10^6 km^2	145×10^6 km^2	83×10^6 km^2

Titan fluid density and viscosity values from Lorenz et al. (2003); organic density from Khare et al. (1994), but lower values are possible.

2.2. Volcanism

In addition to directly producing palaeofloods on Earth, glaciation contributes to flood production indirectly in conjunction with near-surface volcanism or enhanced geothermal heat flow (Björnsson, 2009). Some of the largest floods associated with volcanism result from direct melting of overlying snow and ice by eruption or geothermal heat flow. Persistent sub-glacial hydrothermal systems may result from the interaction of the resultant glacial meltwater with shallow magmatic intrusions. Continued increase of the sub-glacial lake volume eventually breaks the hydraulic seal of the overlying glacier, and the meltwater is catastrophically released. This process takes place today in Iceland, as in the 1996 sub-glacial eruption and resultant jökulhlaup from the Grímsvötn cauldron beneath the Vatnajökull glacier (Fig. 1) (Guðmundsson et al., 1997) and the 1918 jökulhlaup from beneath the Kötlujökull glacier (Tómasson, 1996). Early Holocene jökulhlaups with discharges of the order of 10^5 m^3 s^{-1} drained northward from the Kverkfjöll glacier (Carrivick, 2009 and references therein), carving the Jökulsá á Fjöllum flood channel (Waitt, 2002).

Volcanism also causes flooding by other means than direct melting. Caldera-lake breaching can produce discharges of similar magnitude to ice-dam breaches, as in the case of a late Holocene flood from the Aniakchak volcano, Alaska (Waythomas et al., 1996). More commonly, breaching of water-filled calderas produces floods one to two orders of magnitude lower. The near instantaneous failure of a large ignimbrite dam at Lake Taupo, New Zealand, for example, produced a caldera flood of the order of 10^5 m^3 s^{-1} (Manville et al., 1999). Other examples of large floods from breached volcaniclastic dams include floods from Tarawera caldera, New Zealand (Manville et al., 2007) and the Holocene flood from Mount Mazama, USA (Conaway, 1999, in O'Connor and Beebee, 2009). Large floods resulted from Pleistocene lava dams on the Colorado River, USA (Fenton et al., 2006), and pyroclastic flows, lahar deposits, and landslides triggered by eruptions have likewise caused flooding.

2.3. Tectonic basin overflow

Volcanic calderas are one of three types of geological basins that produce flooding, the other two being moraine basins (reviewed in the section on glacial flooding above) and tectonic basins. Floods from tectonic basins can be volumetrically the largest of the three basin-breach type floods because they can impound the most water (see O'Connor and Costa, 2004 and O'Connor and Beebee, 2009, from which the following discussion is taken).