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Flood lavas on Earth, Io and Mars

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Abstract: Flood lavas are major geological features on all the major rocky planetary bodies. They provide important insight into the dynamics and chemistry of the interior of these bodies. On the Earth, they appear to be associated with major and mass extinction events. It is therefore not surprising that there has been significant research on flood lavas in recent years. Initial models suggested eruption durations of days and volumetric fluxes of order 10^7 m^3 s^{-1} with flows moving as turbulent floods. However, our understanding of how lava flows can be emplaced under an insulating crust was revolutionized by the observations of actively inflating pahoehoe flows in Hawaii. These new ideas led to the hypothesis that flood lavas were emplaced over many years with eruption rates of the order of 10^4 m^3 s^{-1}. The field evidence indicates that flood lava flows in the Columbia River Basalts, Deccan Traps, Etendeka lavas, and the Kerguelen Plateau were emplaced as inflated pahoehoe sheet flows. This was reinforced by the observation of active lava flows of $\geqslant$100 km length on Io being formed as tube-fed flows fed by moderate eruption rates (10^2–10^3 m^3 s^{-1}). More recently it has been found that some flood lavas are also emplaced in a more rapid manner. New high-resolution images from Mars revealed 'platy–ridged' flood lava flows, named after the large rafted plates and ridges formed by compression of the flow top. A search for appropriate terrestrial analogues found an excellent example in Iceland: the 1783–1784 Laki Flow Field. The brecciated Laki flow top consists of pieces of pahoehoe, not aa clinker, leading us to call this 'rubbly pahoehoe'. Similar flows have been found in the Columbia River Basalts and the Kerguelen Plateau. We hypothesize that these flows form with a thick, insulating, but mobile crust, which is disrupted when surges in the erupted flux are too large to maintain the normal pahoehoe mode of emplacement. Flood lavas emplaced in this manner could have (intermittently) reached effusion rates of the order of 10^6 m^3 s^{-1}.

The goal of this paper is to examine the formation of flood lavas on the Earth using simple models and observations of flood lavas from Mars and Jupiter's volcanically active moon, Io. After a brief description of flood lavas on the Earth, four styles of emplacement will be discussed in some detail. These will be touched on in the order they were studied historically, with emphasis on the new observations that drove the formation of each new model.

What is a flood lava?

Flood lavas, as their name suggests, are lava flows that inundate entire regions without building large edifices (Geikie 1880; Washington 1922; Tyrrell 1937). Such extensive flows are usually mafic, most often basaltic, and rarely occur in isolation. Instead, they typically form multi-kilometre thick stacks of lavas, which are called flood basalt provinces. These flood basalt provinces are commonly divided into continental and oceanic flood basalt provinces, and are a major subset of large igneous provinces (LIPs) (Coffin & Eldholm 1994). LIPs, in turn, are a major feature on the Earth and most of the other large rocky bodies in the Solar System (Mahoney & Coffin 1997).

Figure 1 shows the distribution of the Phanerozoic LIPs. Flood basalt provinces are found on all the continents of the Earth (though the ones in Australia are Archaean and are not shown in Fig. 1). The formation of many of these provinces is argued to be associated with the arrival of a mantle plume at the base of the lithosphere and the subsequent rifting of continents (Morgan 1972; White & McKenzie 1995). Thus many LIPs are found along what are now passive margins of continents (e.g. White & McKenzie 1989; Coffin & Eldholm 1994; Mahoney & Coffin 1997).

It is important to note that many LIPs (and even flood basalt provinces) are not exclusively basaltic. In fact, in the case of the Columbia River Basalt Group, basaltic andesite is more volumetrically important than basalt (e.g. Hooper 1997). In the Etendeka–Paraná flood basalts, there are large volumes of dacites and rhyolites as well as basalt (e.g. Marsh *et al*. 2001). Similarly, there can be large volumes of explosive volcanism associated with flood basalts. Some workers estimate that 25% of the volume of the Siberian Traps is mafic pyroclastic rock (e.g. Sharma 1997).

LIPs (and flood basalts in particular) have attracted intense study for a number of reasons. They are major geological features that deserve study simply to understand the geological history of the Earth. They are a significant alternative to plate tectonics in transferring heat and mass out of the mantle. They provide essential clues to the geochemistry and dynamic history of the interior of the Earth (e.g. Coffin & Eldholm 1994). And there is a curious (and contentious) coincidence in the timing of many flood basalt eruptions and major extinctions in Earth's biota (Rampino & Stothers 1988; Haggerty 1996; Wignall 2001). Although the meaning of this coincidence is widely debated, it does suggest that flood basalt eruptions are able to have significant impact on the atmosphere and climate.

Table 1 lists some of the general characteristics typical of

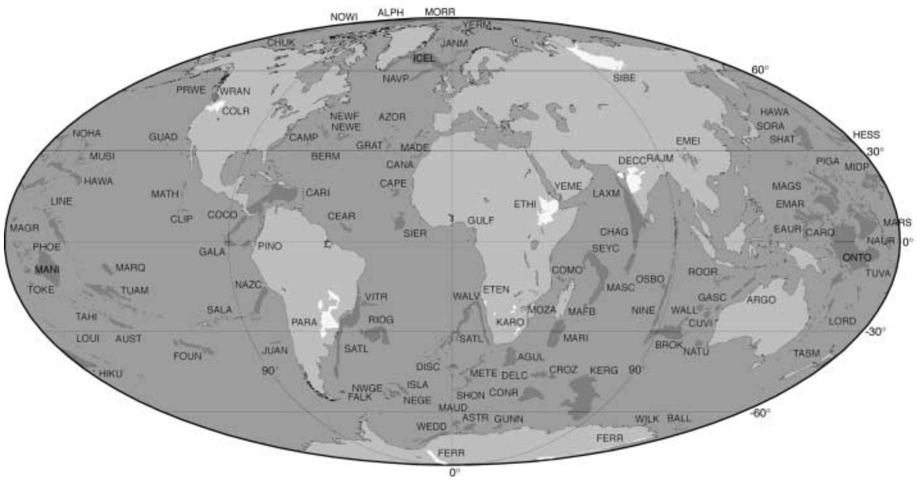

Fig. 1. Map of Recent (≤250 Ma) large igneous provinces (LIPs) on Earth. After Coffin & Eldholm (1994), who listed the full names for the abbreviations. Well-preserved continental flood basalt provinces are shown in light grey, other LIPs in dark grey. Although recent LIPs cover only a few percent of the Earth's surface, 250 Ma represents only <6% of Earth's geological history.

Table 1. *Some general characteristics of flood basalt provinces*

Characteristic	Typical or common values
Large volume eruptions	*c.* 1000 km^3
Long flows	*c.* 500 km
Shallow slopes	*c.* 0.1%, especially after initial topography inundated
Thick geochemical or stratigraphic units	*c.* 100 m
Thinner lava flows	*c.* 30 m
Geochemical or stratigraphic units are compound flow fields	2–3 flows per unit at a given location, 5–10 flows per unit
Gradual cooling	Measured cooling along the length of Columbia River Basalt flows is only 0.03–0.07 °C km^{-1}
Dominantly mafic, but wide range of compositions in most provinces	50–59% SiO_2

many flood basalt provinces. It is dangerous to imply that flood basalt provinces have a single set of characteristics, as each province (and each flow) is unique. However, the characteristics listed in Table 1 are those most often seen in terrestrial flood basalt provinces.

Some of the characteristics listed in Table 1 deserve to be expanded upon because they affect the emplacement models used in the remainder of this paper. It is important to understand that mapped geochemical or stratigraphic 'units' in flood basalt provinces can be significantly thicker than any individual lava flow laid down during flood basalt province formation. Part of the problem is that geochemically or stratigraphically recognized units may or may not correlate to the products of a single eruption. More importantly, it appears that flood basalt eruptions form compound flow fields (i.e. the eruption produces several outpourings of lava, producing multiple flows that overlap laterally and vertically; Walker 1971; Self *et al*. 1997, 1998). The thickness of the main body of liquid lava that was moving during the emplacement of flood basalts was most typically of the order of 20–30 m, not the *c.* 100 m of many mapped stratigraphic or geochemical units. Of course, there are also much smaller lobes that are scattered through the flow field, but these are usually volumetrically insignificant.

The cooling along the length of flows has been measured by using glass geothermometry on the preserved chill margins of Columbia River Basalt lava flows. Ho & Cashman (1997) measured a 20 °C drop across 500 km of the Ginkgo Flow of the Frenchman Springs Member of the Columbia River Basalt Group. Thordarson & Self (1998) measured 20 °C of cooling across 240 km of the Roza Member of the Columbia River Basalt Group. The imperceptible increase in crystallinity of other flood basalt lava flows, even after hundreds of kilometres of flow, is a strong indicator that such gradual cooling is the norm in flood basalt provinces. Based on these observations, we will use the limit of 0.1 °C km^{-1} of cooling in the lava transport system as a crude measure of the 'cooling limited length' of flood basalt lava flows.

However, it should be noted that these measured and inferred amounts of cooling only apply to the lava transport system and significant additional cooling can (must) be happening at both the vent and the flow front. The observed quench temperatures of the lava chill margins do not measure the absolute cooling from the eruption temperature. Instead, they only constrain the relative temperatures of lava that flowed different distances. Based on field measurements on active flows in Hawaii, it is reasonable to think that an additional 10–20 °C of cooling might have taken place in the flow front. Thus the 0.1 °C km^{-1} of cooling during lava transport that we allow in our models should not be confused with the total cooling that the lava was subjected to before it froze.

Basic requirements for flood basalt lava flows

The reason for the great areal extent of flood basalt lava flows has elicited debate from the beginning of the geological sciences (Geikie 1880). Initial ideas focused on the mafic nature of most flood lavas, leading to the general consensus that the great fluidity of these lavas allowed them to flow far before freezing (e.g. Washington 1922). To first order, this is an inescapable conclusion: a highly viscous flow of the same volume would produce a shorter, thicker flow than a fluid flow. However, this clearly cannot be the sole explanation because there are many examples of short basaltic lava flows.

A large erupted volume is also critical if one wishes to form a large lava flow. Although this extremely simple requirement has been repeatedly noted (e.g. Geikie 1880; Walker 1973; Pieri & Baloga 1986; Keszthelyi & Self 1998), its implications are rarely addressed in modern studies of lava flow emplacement. This is because such studies are focused on what the lava does after eruption, rather than what is happening in the magma source region. However, it must be recognized that the large volume of flood lava flows is the single characteristic that distinguishes these behemoths from the smaller basaltic lava flows seen on shield volcanoes, mid-ocean ridges, and elsewhere.

It should also be noted that topography plays a critical role in determining the areal distribution of the lava. The same volume of lava will form a squat pancake of lava on a flat slope and a long thin strip on a steep slope. Thus, long lava flows are relatively easy to form where there is substantial topography. However, the formation of a flood basalt province typically inundates the existing topography, producing a nearly level plain. The great lengths of flood basalt flows despite the shallow topography highlight the massive volumes of lava involved.

Although these basic requirements cannot be overlooked, the emphasis of most of the recent work on flood lava emplacement has been on the specifics of how the lava advanced. In the following, four modes in which flood lavas could be emplaced are examined in some detail.

Turbulent emplacement (the first model)

The first quantitative examination of the emplacement of flood lavas was carried out by Shaw & Swanson (1970). They calculated the velocity at which a typical *c*. 30 m thick flood basalt lava flow would move across the very shallow slopes of the Columbia River Plateau (assuming the entire flow was liquid). One of the most astounding conclusions from this analysis was that the lavas must have flowed in the turbulent flow regime.

The transition between laminar and turbulent flow is characterized by the non-dimensional Reynolds number (Re). For a liquid moving across an inclined plane,

$$\mathrm{Re} = \rho H \langle \mathrm{v} \rangle \eta \tag{1}$$

where the symbols (and typical values) are listed in Table 2. The flow undergoes transition from laminar to turbulent flow at a Re of *c*. 500 for sheet flow, although it does not become fully turbulent until Re reaches *c*. 10 000. The transition to turbulent flow takes place at other values of Re for other flow geometries (e.g. *c*. 2000 for pipe flow) (e.g. Bird *et al*. 1960).

For laminar flow (and a Newtonian fluid), the average flow velocity for a vertical section through the flow is given by

$$\langle \mathrm{v} \rangle = \rho g \theta H^2 / 3\eta \tag{2}$$

(e.g. Bird *et al*. 1960). It should be noted that the velocity increases as the square of the flow thickness. However, for slightly turbulent flow over a smooth surface, the average flow velocity is characterized by

$$\langle \mathrm{v} \rangle = \{ gH\theta / C_\mathrm{f} \}^{1/2} \tag{3a}$$

$$\mathrm{C_f} = (1/32)\{\log_{10}[6{\cdot}15(2\mathrm{Re} + 800)/41]^{0{\cdot}92}\}^2 \tag{3b}$$

(Goncharov 1964; Shaw & Swanson 1970). It should be noted that the velocity now increases only as the square root of the flow thickness. Usually turbulent flow is completely insensitive to the viscosity of the fluid. However, in the region of $500 < \mathrm{Re} < 10\,000$, the flow velocity is weakly dependent on the viscosity of the fluid.

For nominal values of 500 Pa s for lava viscosity and *c*. 2000 kg m^{-3} for bulk lava density (including bubbles), equation (3a) predicts average flow velocities of the order of 7 m s^{-1} (Fig. 2). This translates to a Re of 875, which shows that the flow is weakly turbulent and that equation (3a) is the appropriate one to use. As an aside, if one improperly uses equation (2), the flow velocity would be overestimated at 12 m s^{-1}. Figure 2 shows a plot of flow velocity v. flow thickness.

From these flow velocities, Shaw & Swanson (1970) inferred that a typical 300 km long flow in the Columbia River Basalt Group could be emplaced in *c*. 12 h. However, including the time

Table 2. *Symbols, definitions, and typical values used in modelling flood lavas*

Symbol	Definition	Typical value
Re	Reynolds number	Defined in equation (1)
ρ	Density	2080 kg m^{-3} (includes bubbles)
H	Flow thickness	30 m
⟨v⟩	Average flow velocity	Defined in equation (2)
η	Bulk viscosity	500 Pa s
g	Gravitational acceleration	9.8 m s^{-2} (Earth), 3.7 m s^{-2} (Mars), 1.8 m s^{-2} (Io)
θ	Slope	0.1%
C_f	Friction factor	Defined in equation (3b)
C_p^*	Heat capacity (including latent heat of crystallization)	2775 J kg^{-1} K^{-1}
Q_{rad}	Heat loss by thermal radiation	Defined in equation (4b)
Q_{atm}	Heat loss by wind	Defined in equation (4c)
Q_{entr}	Cooling by mixing of cold crust into the flow interior	Defined in equation (4d)
Q_{visc}	Heating by viscous dissipation	Defined in equations (4e), (5d) and (6e)
Q_{cond}	Heat loss by conduction through upper crust	Defined in equations (5b) and (6d)
Q_{sky}	Heat loss from skylights	Defined in equation (6c)
T	Temperature (of lava)	1100 °C initial temperature
T_a	Ambient temperature	30 °C (Earth), −70 °C (Mars), −173 °C (Io)
ϵ	Emissivity	0.95
σ	Stephan Boltzmann constant	5.67 × 10^{-8} J m^{-2} K^{-4} s^{-1}
f	Crack fraction	Variable (see Table 3)
h	Atmospheric heat transfer coefficient	70 W m^{-2} K^{-1}
T_c	Average temperature of crust	Variable (see Table 3)
H_c	Upper crust thickness	Variable (see Table 3)
τ	Crust mixing time scale	Variable (see Table 3)
r	Radius of the lava tube	Variable (2–50 m modelled)
k	Thermal conductivity	*c*. 1 W m^{-2} K^{-1}

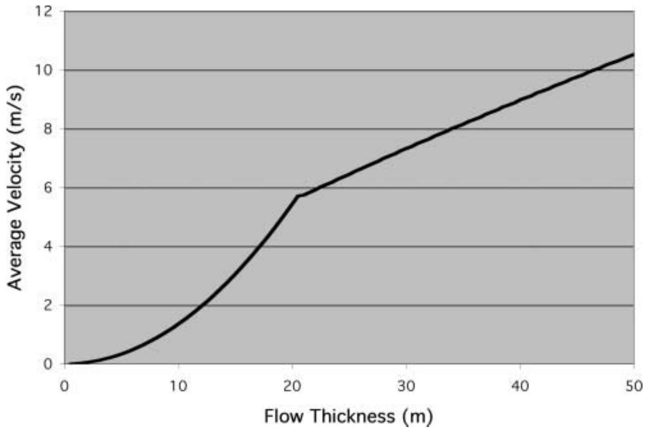

Fig. 2. Flow velocity as a function of flow thickness. Calculated using equations (2) and (3a) and values in Table 2. The change in the relationship between velocity and thickness as the flow changes from laminar to turbulent at a flow thickness of *c*. 20 m should be noted. If it were entirely liquid, a typical 30 m thick flood basalt flow would be moving at just over 7 m s^{-1}.

for an eruption to start up and ramp down, they felt that a typical eruption duration would be a few days. The volumetric effusion rate needed to allow 1000 km^3 of lava to be erupted in 12 h to 3 days is between 2.3×10^7 and 4×10^6 m^3 s^{-1}. Thus was created the idea that continental flood basalt flows were emplaced in a matter of days with extremely high effusion rates.

But does this model stand up to additional scrutiny? An obvious question is whether or not these turbulent floods would be able to transport lava with the minimal cooling that has been observed. After all, turbulent flow is one of the most thermally inefficient ways to move a hot fluid (e.g. Bird *et al*. 1960). To estimate the cooling in a turbulent flood lava, Keszthelyi & Self (1998) constructed a simple thermal budget for a sheet of turbulent lava. This model equates the cooling of the core of the flow to the sum of the heat loss via thermal radiation, atmospheric convection, mixing of cold crust into the hot core of the flow, and heating via viscous dissipation. The heart of the model is a modified version of the Crisp & Baloga (1994) thermal model for the 1984 Mauna Loa flows. The Mauna Loa flows included very active, open-channel aa flows with a crust that was highly disrupted and rapidly mixed back into the flow. Although they were laminar, these flows are the closest analogue to a turbulent lava flow for which we have detailed quantitative observations while the flow was active. The model can be summarized by the following sets of equations:

$$(H\rho C_p^*)(\partial T/\partial x)(\partial x/\partial t) = Q_{rad} + Q_{atm} + Q_{entr} + Q_{visc} \quad (4a)$$

$$Q_{rad} = \varepsilon\sigma f(T^4 - T_a^4) \quad (4b)$$

$$Q_{atm} = hf(T - T_a) \quad (4c)$$

$$Q_{entr} = \rho C_p^* H_c(T - T_c)/\tau \quad (4d)$$

$$Q_{visc} = \rho g H \langle v \rangle \theta \quad (4e)$$

where equation (4a) is the overall thermal budget for the flow, Q_{rad} is the radiative heat loss from the core of the flow, Q_{atm} is the atmospheric convective heat loss from the core, Q_{entr} is the cooling from mixing cooled crust back into the flow, and Q_{visc} is the heat added by viscous dissipation. Table 2 lists the definitions and input values for many of the model parameters. The parameters related to the dynamics of the crust (i.e. H_c, T_c, f, τ) are especially difficult to ascertain, as there are no published observations of an active turbulent lava flow. The extreme end members are (1) a crust so turbulent that no crust is able to exist and (2) a crust like the thin crust seen on the most active 1984 Mauna Loa lava flows. The parameters corresponding to these crusts (and others) are listed in Table 3.

Figure 3 shows the results of the model. To achieve the cooling rates observed in the Columbia River Basalts (Ho & Cashman 1997; Thordarson & Self 1998), the flow thickness needs to be 30–100 m. Thus, this model predicts that flood basalts could be emplaced as *c*. 30 m thick turbulent flows, if they had aa-like crusts. As these flows would be only marginally turbulent, this is not unreasonable. Therefore, we conclude that the Shaw & Swanson (1970) model for the emplacement of flood lavas is theoretically viable, from both a fluid dynamics and a thermal budget standpoint.

However, when one examines the actual flows in the Columbia River Basalts (and other terrestrial flood basalt provinces), there is a lack of field evidence indicating turbulent emplacement. Numerous models of turbulent emplacement predict that there should be significant thermal and mechanical erosion at the base of these kinds of lava flows (Hulme 1973; Huppert *et al*. 1984; Jarvis 1995; Fagents & Greeley 2001). An extensive examination of the Columbia River Basalt lava flows found no clear evidence of thermal erosion (Greeley *et al*. 1998). Furthermore, there are many examples of outcrops showing that the lava flows did not disturb even unconsolidated river gravels during emplacement

Table 3. *Parameters describing different model crusts*

Name	H_c (m)	T_c (°C)	f (%)	τ
No crust	n.a.	n.a.	100	n.a.
Thin 1984 Mauna Loa crust	0.02	700	10	300 s
Thick 1984 Mauna Loa crust	1	400	1	1 day
Rubbly pahoehoe crust (Laki 1783)	5	600	0.1	10 days

n.a., not applicable.

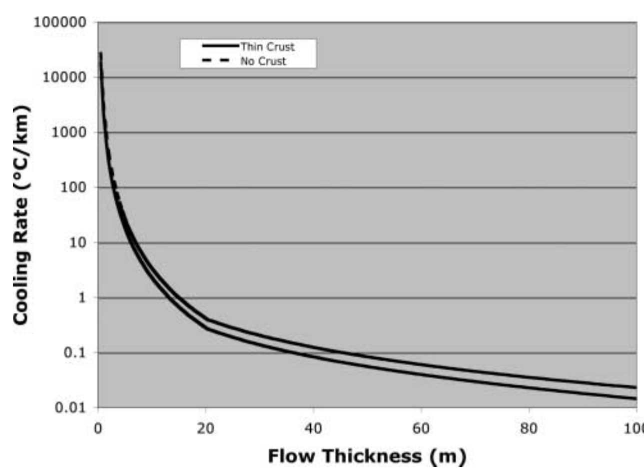

Fig. 3. Model cooling rate as a function of flow thickness. Other inputs as in Table 2. To bring the cooling rate under the observed value of 0.02–0.1 °C km^{-1}, the flow thickness would need to be 30–100 m. Thus the turbulent mode of emplacement for flood basalt lavas cannot be ruled out, based on thermal modelling alone.

Fig. 4. River gravels undisturbed by the emplacement of Columbia River Basalt flood lavas. The fact that this flow did not disturb, much less erode and entrain, these river gravels is a strong indicator that the flow was not turbulent. The photograph was taken on the south bank of the Snake River, near Lower Monumental Dam, Walla Walla County, WA. Penknife for scale.

(Fig. 4). Finally, the flow tops do not show disrupted crusts like the 1984 Mauna Loa aa flows. Instead, the lavas are dominated by smooth pahoehoe surfaces (Self *et al*. 1996, 1997; Thordarson & Self 1998). Therefore, we conclude that, even though it is theoretically plausible, we have not found evidence for any turbulently emplaced flood basalt flows in the Columbia River Basalt or elsewhere.

Inflated sheet flows (lessons from Hawaii)

If not turbulent floods, then what mechanism can explain the extreme thermal efficiency of flood lavas? A direct reading of the field evidence suggests that these lavas were emplaced as pahoehoe flows. However, in Hawaii, pahoehoe flows were associated with low effusion rates (Macdonald 1953; Peterson & Tilling 1980; Rowland & Walker 1990) and generally unimpressive outpourings of lava. However, the formation of the Kupaianaha flow field on Kilauea Volcano in 1986–1991 provided volcanologists with a first-hand lesson in the ability of pahoehoe flows to inexorably inundate large areas, including the town of Kalapana (Mattox *et al*. 1993; Hon *et al*. 1994).

The key to the growth of pahoehoe flow fields was the formation of broad ‘sheet flows’ with thick insulating crusts (Hon *et al*. 1994). The continued flux of lava underneath the growing chill crust was able to lift (i.e. inflate) the crust, producing a distinct surface morphology of tumuli, inflation plateaux, and inflation pits. The morphological similarity of these Hawaiian inflated pahoehoe sheet flows to their larger flood basalt kin led to the suggestion that they were formed in a similar manner (Hon *et al*. 1994; Self *et al*. 1996). However, there were immediate questions about how one could scale the *c*. 1 km^3 flows in Hawaii to the *c*. 1000 km^3 flows in the flood basalt provinces (Ho & Cashman 1997; Reidel 1998; Anderson *et al*. 1999).

A simplified version of the turbulent lava flow thermal model can be used to investigate whether or not a pahoehoe sheet flow could be sufficiently thermally insulating to produce a flood basalt lava flow (Keszthelyi & Self 1998). As the crust on an inflated pahoehoe sheet flow is not disrupted and mixed back into the core of the flow, the heat loss from the interior of the flow is controlled by conduction through the crust. Also, unlike the case of the turbulent flow down an inclined plane, the lava moves between two essentially stationary surfaces. The resulting thermal model was described mathematically as

$$(H\rho C_{\rm p}^{*})(\partial T/\partial x)(\partial x/\partial t) = Q_{\rm cond} + Q_{\rm visc} \qquad (5a)$$

$$Q_{\rm cond} = k(T - T_{\rm a})/H_{\rm c} \qquad (5b)$$

$$H_{\rm c} = 0.0013\,t^{1/2} \qquad (5c)$$

$$Q_{\rm visc} = \rho g H \langle {\rm v} \rangle \theta \qquad (5d)$$

$$\langle {\rm v} \rangle = \rho g \theta H^2/3\eta \qquad (5e)$$

by Keszthelyi & Self (1998). The expression for the growth of the upper crust (equation (5c)) comes from the empirical observations of Hon *et al*. (1994) but is confirmed to be applicable to other basaltic lava flows with less than a 25% error (Self *et al*. 1998).

Before this model can be applied to inflating sheet flows, it is useful to include an expression for the thickening of the entire flow via inflation. Field observations from inflated pahoehoe flows of many different sizes in Hawaii, Iceland, and the Columbia River Basalt (Thordarson 1995; Self *et al*. 1998; Thordarson & Self 1998) can be used to create some crude empirical relationships between the thickness of the upper crust and the rest of the flow. These observations show that the thickness of the dense core of the flow is usually about the same as the thickness of the upper vesicular crust. Also, for flows that are active for more than a few hours, the lower vesicular crust has a remarkably constant thickness of 0.2–0.5 m, with 0.3 m being the most common. For the sake of equations (5a) and (5e), it is the thickness of the liquid core of the flow that matters. Based on the empirical observations, this is equated to the thickness of the upper crust.

Figure 5 shows the results of this modelling. The 20–30 m thick flows of the Columbia River Basalt require that the sheets have been active for over a year. After only 6 months, the sheet is sufficiently insulating to match the observed cooling rates, so

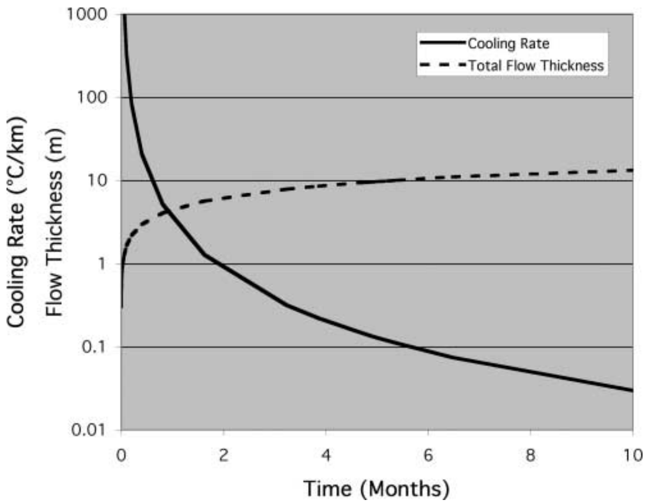

Fig. 5. Results from insulated pahoehoe sheet flow model. The total flow thickness includes the upper crust, lava core, and lower crust. Pahoehoe sheet flows become sufficiently insulating to explain the observations from the Columbia River Basalt only after they have been active for about 6 months and have achieved a total flow thickness of about 10 m.

there are no issues with long-lived inflated pahoehoe sheet flows attaining the thermal efficiency of flood basalt lava flows.

It is interesting to note that the flow velocities within these sheets are predicted to be of the order of 0.1–0.3 m s^{-1}. This allows lava to move 100–300 km from the vent in *c.* 10 days. Also, assuming that the sheet is of the order of 10 km wide, the volumetric flux would be *c.* 5000 m^3 s^{-1}. At this rate, it would take about 6 years to erupt the 1000 km^3 of a typical flood basalt unit. Thus, although each batch of lava takes only about 10 days to move from the vent to the flow front, the eruption must last several years. The field evidence for this is in the compound nature of most flood basalt units: they are composed of many sheets that are arranged in a complex, overlapping pattern (Self *et al*. 1996, 1997; Thordarson & Self 1998).

Given the combination of field evidence and modelling results, there is little doubt that many (if not most) Columbia River Basalt lava flows were emplaced as inflated pahoehoe sheet flows. Examination of lava flows in the Deccan Traps, Etendeka lavas, and Kerguelen Plateau also shows a predominance of inflated pahoehoe flows (e.g. Walker 1971; Self *et al*. 1998; Keszthelyi *et al*. 1999; Jerram 2002; Keszthelyi 2002). Thus, emplacement as inflated pahoehoe sheet flows is thought to be the most common (but not exclusive) mode in which terrestrial flood lavas are emplaced (Self *et al*. 1998).

Tube-fed flood lavas (lessons from Jupiter's moon, Io)

Earth is not the only body in the Solar System where we can study flood lavas. In fact, Io, Jupiter's volcanically active moon, is the only place where we can examine flood lavas in the act of formation. The *Voyager* spacecraft flybys provided a snapshot of the volcanic activity on Io in 1979, but this was not sufficient to examine the emplacement processes (e.g. Smith *et al*. 1979). However, the *Galileo* spacecraft orbited Jupiter from December 1995 to September 2003, providing long-term monitoring of Io (McEwen *et al*. 1998*a*, 2000; Keszthelyi *et al*. 2001; Turtle *et al*. 2001, 2004).

Changes in lava flow morphology were tracked at a number of volcanic centres (Geissler *et al*. 2004). Given the fact that Io appears to output more lava than the Earth, it was somewhat surprising that the volcanic centres seen by *Voyager* were mostly still recognizable in the *Galileo* observations some 20 years later (McEwen *et al*. 1998*a*). One of the key new results from the *Galileo* mission was the determination that most of the volcanism on Io is silicate, probably with a mafic to ultramafic composition (McEwen *et al*. 1998*a*, *b*). The largest active lava flow is the 300 km long Amirani Flow Field. Repeat observations in 1999 and 2000 showed that new lava was being formed at a rate of 50 m^2 s^{-1} (Keszthelyi *et al*. 2001) (Fig. 6). At the 100 km long Prometheus Flow Field, the area coverage rate was only 5 m^2 s^{-1} (McEwen *et al*. 2000) (Fig. 7). Although the *Galileo* imaging was not able to place strong limits on the thickness of these particular flows, in other locations Ionian lavas appear to be about 10 m thick (Williams *et al*. 2001). It is therefore inferred that 100–300 km long flows on Io are being fed by eruption rates of only 50–500 m^3 s^{-1}.

Thermal imaging of these flow fields showed that hot areas occurred only in isolated patches, with the intervening lava having a cold crust (Lopes-Gautier *et al*. 2000). This indicates that the lava flowed within these flow fields under a thick, insulating crust. Hot lava is exposed only where the liquid lava breaks out from the confines of the insulating transport system. This could be consistent with inflated pahoehoe sheet flows. However, the low inferred eruption rates would lead to rapid freezing of the lava, if the liquid lava was dispersed across a wide sheet flow. Application of the inflated pahoehoe sheet flow model under Ionian conditions, with the assumption that the active sheets are *c.* 10 km wide, would predict that the cooling rate should be 2–60 °C km^{-1} for effusion rates of 500–50 m^3 s^{-1}. It seems highly unlikely that the Ionian lavas could undergo >600 °C of cooling as they move 100–300 km between the vent and the flow front, so wide sheet flows do not seem viable.

Instead, it appears that these long Ionian lava flows are fed by relatively narrow lava tubes. This hypothesis is supported by the narrow line of breakouts and sulphurous alteration seen on the 100 km long Culann Flow Field (Fig. 8). The Keszthelyi (1995) thermal budget for lava tubes can be used to verify that lava tubes could indeed transport lava hundreds of kilometres on Io even at relatively low effusion rates. The Keszthelyi (1995) model can be summarized with the following equations:

$$(H\rho C_p^*)(\partial T/\partial x)(\partial x/\partial t) = Q_{sky} + Q_{conv} + Q_{cond} + Q_{visc} \quad (6a)$$

$$\partial x/\partial t = \langle v \rangle = \rho g \theta r^2/8\eta \quad (6b)$$

$$Q_{sky} = \varepsilon \sigma f(T^4 - T_a^4) \quad (6c)$$

$$Q_{cond} = 2\pi(T - T_c)k/\cosh^{-1}(2H_o/D + 1) \quad (6d)$$

$$Q_{visc} = \rho g \pi r^2 \langle v \rangle \theta \quad (6e)$$

where all the terms are described in Table 2. This ignores the cooling by atmospheric convection and rain that is included in the Keszthelyi (1995) model because Io's 'atmosphere' is actually a vacuum with only a few isolated molecules. Figure 9 shows the model results. Additional assumptions used in generating the plots are: (1) the tube roof thickness is 10% of the tube diameter (roughly fits terrestrial field observations); (2) the lava is broadly basaltic (as opposed to ultramafic); (3) the slope is

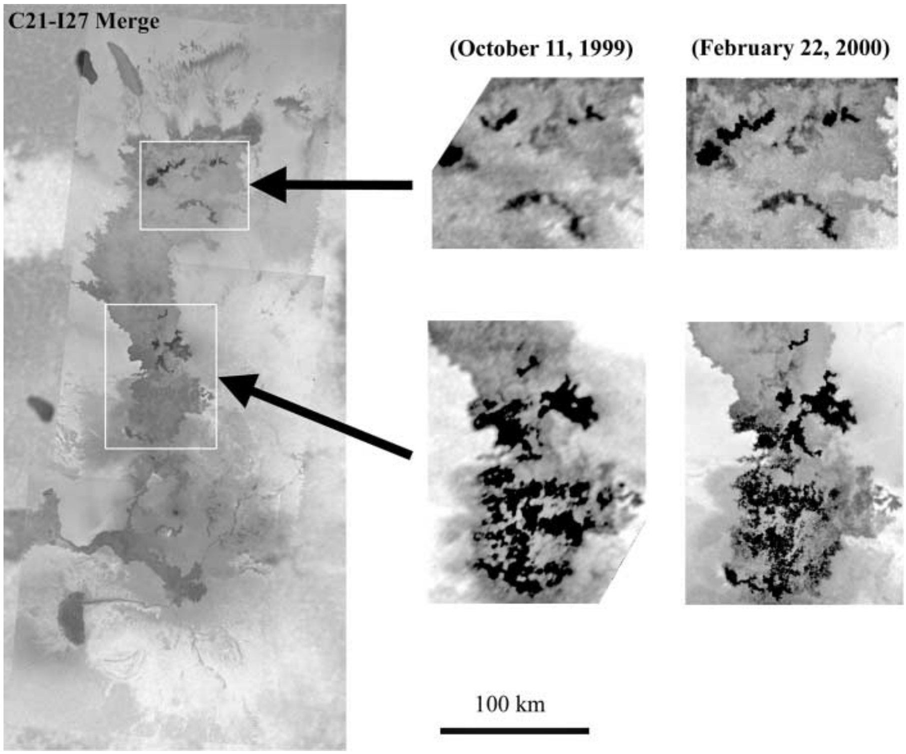

Fig. 6. Repeat observations of the Amirani Flow Field, Io. Images taken by the Solid State Imager (SSI) on the *Galileo* spacecraft. The panel on the left is a composite of images taken in June 1999 and February 2000 and has a resolution of 210 m per pixel. The October 1999 observation has a resolution of 500 m per pixel. North is to the top. A comparison of the dark lavas in the observations shows that 620 km^2 of new lava was erupted over the 134 days between the observations (Keszthelyi *et al*. 2001).

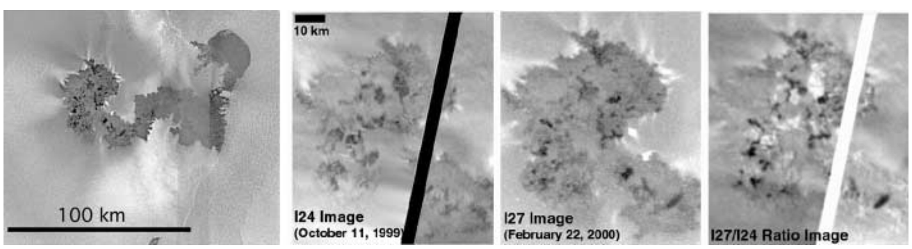

Fig. 7. SSI observed changes at Prometheus, Io. The overview image on the left is a composite of images taken in February 2000 and June 1999. The October 1999 and February 2000 observations have a resolution of 180 m per pixel. North is to the top. The rightmost panel is a ratio image. Dark areas in this image are new dark lavas; bright areas are dark lavas that have faded as a result of deposition of bright volatiles onto the cooled lava. About 60 km^2 of new lava was erupted over the 134 days between the observations and a similar area had cooled off (McEwen *et al*. 2000).

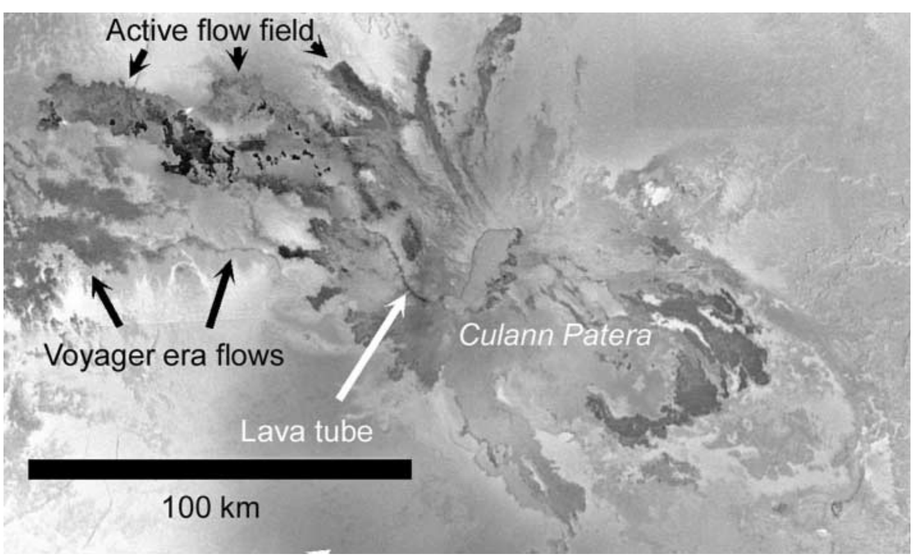

Fig. 8. Image of lava tubes at Culann, Io. This picture was constructed from images taken through the red, green, and violet filters of the *Galileo* SSI camera in November 1999 and has a resolution of 200 m per pixel. North is to the top. The colour version of the image is available at http://photojournal.jpl.nasa.gov/catalog/PIA02535. A dark red, curving line extending NW from Culann Patera seems to mark a crusted-over lava tube feeding the dark (and hot) silicate flows to the NW. The red deposits are interpreted to be sulphur deposits condensing from gases escaping from the lava as it moves through the tube. Also, the location of the flows seen by the *Voyager* spacecraft should be noted; this shows that a compound flow field has been growing here since 1979.

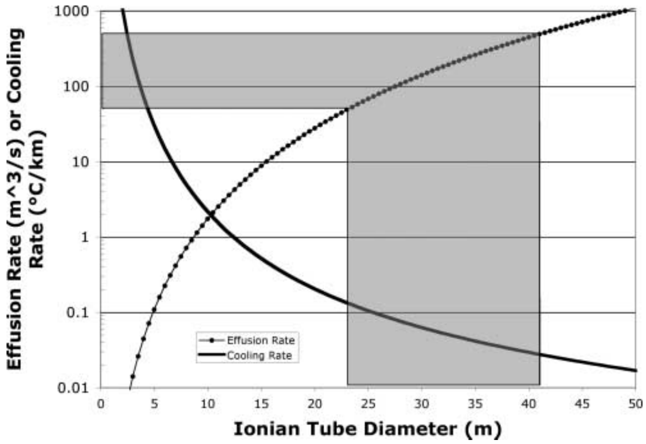

Fig. 9. Thermal efficiency of Ionian lava tubes. Given the observed effusion rates of the order of 50–500 $m^3\ s^{-1}$, the lava in the tubes is estimated to be cooling about 0.1–0.03 °C km^{-1}. This implies about 10 °C of cooling in the tubes between the vent and the flow fronts. The flows would also need to be a few tens of metres thick. At the flow fronts, Ionian flows are estimated to be only *c*. 10 m thick, but the established lava tubes could easily be in slightly thicker parts of the flow.

0.1% (this is poorly constrained on Io, but must be very shallow).

These model results show that the long lava flows on Io could indeed be fed by lava tubes. However, it is not clear that this has any applicability to terrestrial flood lavas. Despite much searching, there have not been any definitive identifications of lava tubes in flood basalt provinces. Upon further examination, the possible lava tube in the Columbia River Basalts mentioned by Self *et al*. (1996) was found not to be a lava tube. It appears that ancient terrestrial flood lavas were not emplaced at the low effusion rates of many of the long Ionian lava flows that are forming today.

Rubbly pahoehoe (lessons from Mars)

Mars has the largest volcanoes in the Solar System, including the 27 km tall Olympus Mons (e.g. Greeley & Spudis 1981). It is also home to massive flood lavas of many ages (Greeley & Schneid 1991). Perhaps most intriguing is the evidence for very young flood lavas. The Cerberus plains of Mars, a $>1 \times 10^6$ km^2 region near the equator, have age estimates from crater counting of *c*. 3–200 Ma (Plescia 1990; Lanagan 2004). The youngest ages apply to relatively small areas that are devoid of any craters larger than *c*. 100 m in diameter and the oldest ages are derived from looking at the largest craters, most of which are embayed by more recent lavas (Plescia 1990; Hartmann & Berman 2000; Lanagan 2004). Although there is significant debate about how to interpret the regions with no visible craters, there is no reason to doubt that there have been flood lava eruptions on Mars in the last 100 Ma. Some of these flows appear to have extended >1500 km (Lanagan 2004).

How were these flood lavas emplaced? The shallow slopes and lower gravity of Mars mean that the Martian flood lavas would be thicker and slower moving than their terrestrial equivalents. This should favour the formation of inflated pahoehoe flows on Mars, as compared with the Earth (Keszthelyi *et al*. 2000). However, there have been very few images from Mars showing tumuli, inflation plateaux, or inflation pits (Keszthelyi *et al*. 2000; Lanagan 2004). Instead, the Martian flood lavas are dominated by a 'platy–ridged' surface morphology (Keszthelyi *et al*. 2000).

Figure 10 shows some examples of platy–ridged flow morphology. The surface appears to be broken into 1–10 km scale plates that have translated with respect to each other. Pressure ridges form where the plates collide. Occasionally, grooves are cut into the surface of the flow as the plates slide over underlying topographic obstacles. Where the plates have been completely crushed, the entire surface can be composed of a series of parallel, arcuate ridges. There are a few examples of flows where this ridged surface has then been broken into plates (Keszthelyi *et al*. 2000).

This complex array of surface morphologies can be best explained by an emplacement model where lava flows under a thick disrupted crust that moves intermittently. Surges in the effusion rate are one way to produce such motion (Keszthelyi *et al*. 2000). However, without more information on the nature of the disrupted crust, and how it moves, it is difficult to model these flows. In fact, the only firm conclusion that could be made from initial modelling efforts was to show that the 10–30 m thick Martian flood lavas must have had a rheology broadly similar to basalts, as opposed to andesites or komatiites (Keszthelyi *et al*. 2000).

For a better understanding of these platy–ridged lavas, flows in Iceland with similar morphologies were examined. The most useful example is the southwestern portion of the Laki Flow Field. The Laki eruption is the largest basaltic eruption for which good written records are available (Steingrímsson 1998). The eruption progressed through a series of episodes over 8 months in 1783 and 1784 (Thorarinsson 1968; Thordarson & Self 1993). The southwestern portion was emplaced during some of the highest effusion rates, estimated at *c*. 8000 $m^3\ s^{-1}$ (Thordarson & Self 1993). This portion of the flow field has ridges, plates, and grooves morphologically indistinguishable from the Martian examples (Fig. 11).

Detailed field observations from the platy–ridged portion of the Laki Flow Field (Keszthelyi *et al*. 2004) show that the smooth inter-plate and intra-groove areas are mostly pahoehoe surfaces similar to that found on lava ponds. This is what would be expected to form if lava gently welled up to fill slowly created gaps in the upper crust. What was more puzzling was the detailed morphology of the breccia in the ridges (Fig. 12). The breccia is not composed of classic aa with gnarled, spinose clasts. Instead, the clasts are dominantly broken pieces of pahoehoe. In some cases the clasts are simple slabs of pahoehoe that have been pushed up against each other, as in pressure ridges along the edges of lava ponds. Where the brecciation seems to have been more extensive, the clasts are composed of 1–100 cm scale fragments of pahoehoe lobes. In some cases, there are entire intact lobes in the breccia. More commonly, there are fragments of lobes, with some clasts engulfing and chilling against other clasts. This indicates an extended period of brecciation where some pahoehoe lobes cooled and broke then new hot lobes were intruded into the breccia, only to cool and break themselves.

This kind of breccia has been noted in flood basalt provinces. Self *et al*. (1997, 1998) mentioned the presence of flows with 'rubbly' tops in the Columbia River Basalts. Keszthelyi (2002) provided some more detailed descriptions of examples seen in drill core from the Kerguelen Plateau. Because these breccias are composed of broken pieces of pahoehoe, the phrase 'rubbly pahoehoe' was used to describe them. With the Laki observations, it is now clear that platy–ridged lava flows are rubbly pahoehoe flows. Thus the Martian flood lavas do have their morphological

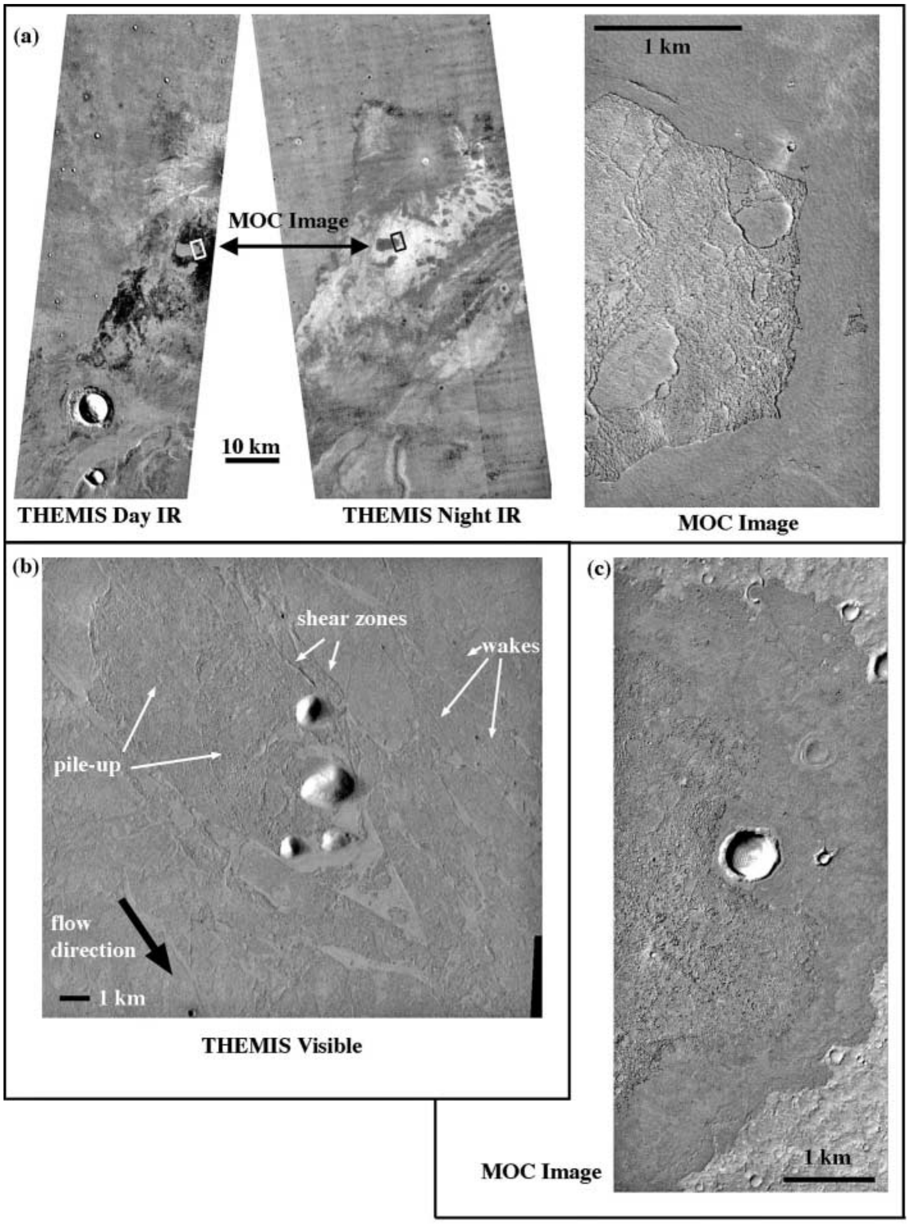

Fig. 10. Some examples of platy–ridged lava morphology from the Cerberus plains of Mars. (**a**) Portions of THEMIS IR observations I01118002 (day), I00875002 (night) and I01237007 (night) and MOC image E11-03799. THEMIS IR images show surface temperatures at *c*. 04.00 h and 16.00 h local time. It should be noted that much of the flat lava is relatively cool in the day and warm at night, indicating a high thermal inertia and therefore significant dense rock in the upper few centimetres. However, the ridged section, in this case, has relatively low thermal inertia. This could be due to trapping of large amounts of dust, which would also explain why the area seems bright in the MOC image taken in visible wavelengths. North is to the top in the THEMIS images. Resolution of THEMIS images is 100 m per pixel; that of MOC image is 3.63 m per pixel. (**b**) Portion of THEMIS visible image V06012001. Lava shows shear structures and wakes in the lava as well as the pile-up of debris on the flow top as a result of topographic obstacles. The flow direction and some properties of the translating upper crust can be determined from this observation. Image resolution is 18 m per pixel; north is to the top. The sun is close to the horizon on the west (left) accentuating the topography. (**c**) Portion of MOC image M01-00111. Image shows lava flow transition from pahoehoe along margins to platy–ridged interior, similar to flows in Iceland. Flow margin is no more than a few tens of metres thick. Image resolution is 5.9 m per pixel; north is approximately up.

counterparts on the Earth. However, the terrestrial examples are generally visible only in cross-section, making it difficult to relate to the Martian flows that are only seen in plan view.

From the field observations from terrestrial lava flows, and the written eyewitness accounts of the Laki flow, the properties of the brecciated crust can be estimated (Keszthelyi *et al*. 2004). The crust is about 5 m thick, on average, and is unlikely to allow more than a miniscule fraction of the fluid lava to be exposed at the surface. The crust is also fairly stable, with very slow mixing between the crust and the fluid interior. However, given the evidence for continued intrusions of liquid lava within the breccia, the average crust temperature should be relatively high. The best-estimate values are shown in Table 3. The values for the crust from the slow-moving portions of the 1984 Mauna Loa flow (as reported by Crisp & Baloga (1994)) are shown for comparison.

The same set of equations used to examine turbulent emplacement (equations (2) to (4a-e)) can be used to investigate the thermal efficiency of rubbly pahoehoe flows. Figure 13 shows the model results. The rubbly pahoehoe flow in the Columbia River Basalt could achieve the observed 0.03–0.07 °C km^{-1} of cooling with flow thicknesses of only 15–20 m. At these flow thicknesses, the average flow velocity should be about 4–6 m s^{-1}. If we estimate that the rubbly pahoehoe flows are *c*. 10 km wide, it would suggest a flux of $(0.6–1.2) \times 10^6$ m^3 s^{-1}. These fluxes would theoretically allow a flood basalt flow to be erupted in a matter of weeks. However, as the formation of rubbly pahoehoe is likely to be associated with surges in the effusive flux, it is unlikely that the entire flood lava unit would have been emplaced quite so quickly. Several months is a more likely total eruption duration. It is also interesting to note that this model helps explain the very long Martian platy–ridged flows. The *c*. 20–

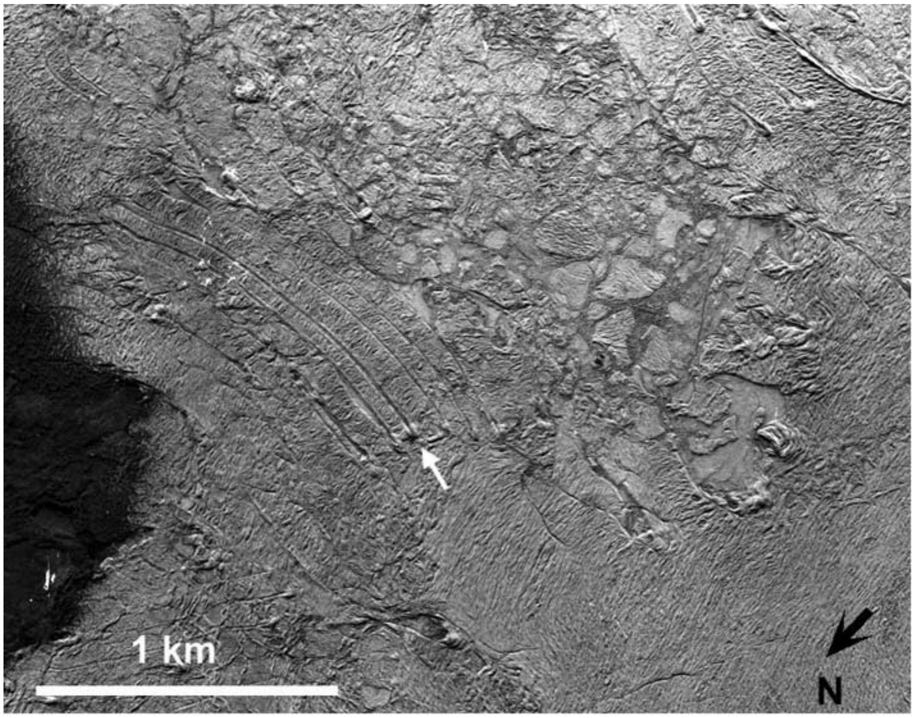

Fig. 11. Aerial photograph of the surface of the Laki Flow Field, Iceland. These lavas were emplaced in a surge of activity on 21 June 1783. The plates, ridges and grooves, similar to the platy–ridged flood lavas on Mars, should be noted. Grooves (white arrow) are >1 km long and follow the flow lines of the advancing lava.

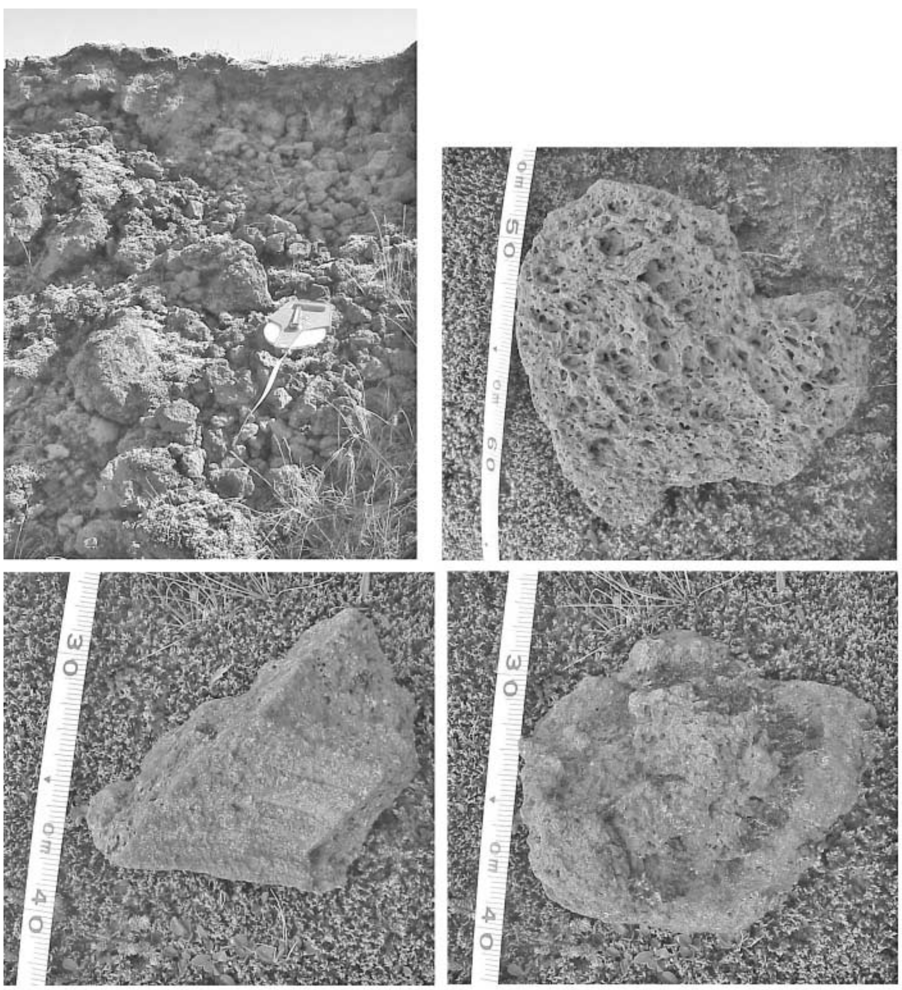

Fig. 12. Close-up of rubbly pahoehoe breccia at Laki. Breccia from an outcrop provided by the Kúdafljót River. Total thickness of breccia is 4–5 m; the breccia is clast supported and generally not agglutinated or welded at this location. It should be noted that some of the clasts are composed of vesicular lava with the rounded vesicles characteristic of pahoehoe, rather than the angular vesicles of aa (Macdonald 1953). Many clasts appear to have had their edges rounded, probably by mechanical abrasion by motion within the breccia. Other clasts have groove-like marks formed by scraping against slabs in the breccia. These marks are interpreted to have formed when another clast scraped against this clast while this (bottom) side of the slab was still hot and plastic. There are also clasts that have wrapped around and welded to other clasts. The folded, outer, clast is chilled against the inner clast. Clasts such as this one provide the best evidence that the flow top breccia included a mix of hot and cold pieces of lava.

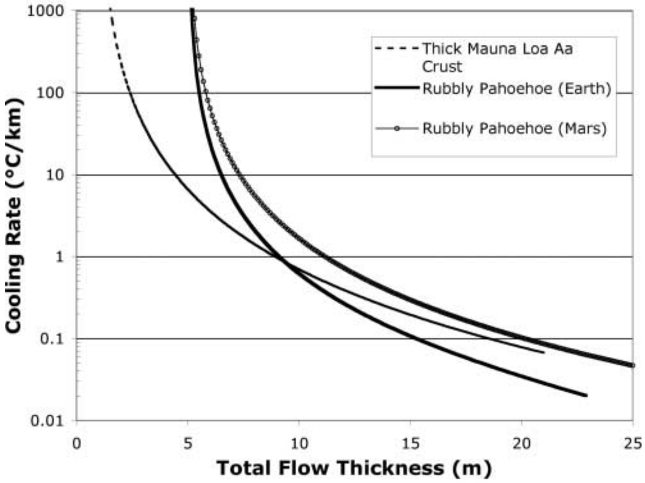

Fig. 13. Rubbly pahoehoe model output. A flow moving over the same slope as a flood basalt flow, but having a crust like the thickest crust on the 1984 Mauna Loa eruption is shown for comparison. Aa crust parameters are from Crisp & Baloga (1994). Rubbly pahoehoe crust parameters are listed in Table 3. It should be noted that for typical flood basalt flow thicknesses, the rubbly pahoehoe flow is much more thermally efficient than even an aa flow with a thick crust. At a given flow thickness, flows would be somewhat less thermally efficient on Mars because the lower gravity leads to slower flow velocities. There is no difficulty in explaining the slow cooling observed in the Columbia River Basalt with this mode of emplacement.

30 m thick flows would cool only 50–150 °C even after 1500 km of transport.

Conclusions

An examination of flood lavas across different bodies in the Solar System shows that there is remarkable diversity in their styles of emplacement. On Io, there is direct evidence of flows 100–300 km long forming at effusion rates of only 50–500 $m^3\ s^{-1}$ through lava tubes. On Earth, emplacement in inflating pahoehoe sheet flows with eruption rates of *c.* 5000 $m^3\ s^{-1}$ appears to be the most common. However, flood lavas on Mars seem to be primarily emplaced as rubbly pahoehoe flows with a platy–ridged surface morphology. The peak eruption rates for these types of flows is likely to be close to $10^6\ m^3\ s^{-1}$. Examples of such relatively rapidly emplaced flood lava flows are now also recognized on the Earth. The root causes for this diversity are still unclear, but are likely to be dominated by differences in the way the magma achieves eruption.

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