Lava Fan

► Alluvial Fan

Lava Flow

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Definition

Spatially distinct solidified surface rock unit produced by lava from a single continuous episode of volcanic activity (Bates and Jackson 1987; Self et al. 1997). The term lava flow may describe both the process and the product.

Description

Lava flows are typically lobate and made up of several flow lobes (Self et al. 1997) that often coalesce with previously emplaced flows, forming lava flow fields or lava plains (► volcanic plains). Flood lavas form lava sheet flows (Keszthelyi et al. 2000). Channelized lava flows are fed by ► lava channels or lava tubes (where a roof forms over the flow). Accumulation of thick and/or high viscosity flows may result in volcanic constructs (► volcano, ► steep-sided dome (Io), and ► steep-sided dome (Venus), etc.).

Morphometry

Lava flows may reach tens to hundreds of kilometer distances on Earth (Aprodov 1982) and a hundred to a thousand kilometer on Mars. The longest flows are tube fed (Sakimoto and Baloga 1995), due to the insulating effect caused by the formation of the lid. See also section "Planetary Analogs Regional Variations" below.

Subtypes

Classification based on solidified surface texture (these terms do not characterize the molten lava):

(1) Subaerial crustal morphologies of lava flows, described from Hawaii (Dutton 1884; MacDonald 1953).
  (1.1) Pāhoehoe (smooth/ropy). Pāhoehoe crust results from low-viscosity (e.g., basaltic) flow. It displays a shiny surface, smooth at the scale of decimeters to meters, typically producing thin (1–3 m thick) flows. These flows appear typically as radar dark. Lava channels and tubes often develop. Lavas that produce pahoehoe texture are typically emplaced at low effusion rates (generally <10 m^3/s in Hawaii) and cool at a slow rate (e.g., Rowland and Walker 1990). Pāhoehoe morphology can also be produced in flood basalts emplaced with very high effusion rates (Thordarson and Self 1998), associated with the process of inflation (Hon et al. 1994).
    (1.1.1) P-type pahoehoe: pipe vesicle-bearing lobes, typically inflated (Wilmoth and Walker 1993).
    (1.1.2) S-type pahoehoe: spongy lobes with spherical vesicles, with higher concentrations toward the center; it forms with minimal inflation (Walker 1989).
  (1.2) 'A'ā (rough/rugged, often spelled plainly "aa"). 'A'ā crust results from higher (than pahoehoe) viscosity lava

flows. It is characterized by rubbly, highly irregular, autobrecciated, and rough surface, with a molten core, typically occurring in thick (3–20 m) flows. These flows show low albedo and are radar bright. Lavas that produce ‘a’ā texture are emplaced at high effusion rates (generally >20 m^3/s) and high strain rates (Peterson and Tilling 1980) and cool rapidly. Pāhoehoe surfaces may change downslope to ‘a’ā (because lavas’ viscosity may increase due to cooling and gas loss during transport), but the opposite case cannot occur. During the course of an eruption, ‘a’ā flows may change into pahoehoe flows due to a drop in effusion rate (Hon et al. 2003).

- (1.3) Transitional types between pāhoehoe and ‘a’ā, recognized recently from lava flows outside Hawaii, e.g., in Iceland, the Columbia River Basalts, the Kerguelen Plateau, etc. (Rowland and Walker 1987; Keszthelyi 2000; Keszthelyi and Thordarson 2000; Hon et al. 2003).
  - (1.3.1) Spiny pahoehoe (toothpaste). It displays longitudinal striations oriented parallel to flow direction, caused by scraping against orifice roof irregularities (Rowland and Walker 1987).
  - (1.3.2) Rubbly and slabby pahoehoe composed of broken autobrecciated pahoehoe lobes or slabs of broken pahoehoe surfaces, respectively (Keszthelyi and Thordarson 2000; Duraiswami et al. 2008).
- (1.4) Blocky. High viscosity (e.g., silicic) flows display blocky surface. They typically produce very thick (>20 m) strata. Blocky flows appear bright in radar images.

(2) Subaqueous (may be subglacial).

- (2.1) Pillow lava. Mafic lavas emplaced in liquid water. They have oval cross sections, thick glassy rinds, and paucity of vesicles (Keszthelyi et al. 2010 and references therein).
- (2.2) Submarine lobate texture (Perfit and Chadwick 1998).
- (2.3) Submarine sheet lava surface morphologies may be analogous to pāhoehoe (smooth, lineated, ropy (with lava coils)) or to ‘a’ā (jumbled and hackly) (Perfit and Chadwick 1998).

Additional Lava Flow Surface Textures

1. Ropy. Typical of pahoehoe surfaces in which the glassy pahoehoe surface has been dragged (by continued flow beneath the cooled crust) into a series of folds. The final appearance is similar to what happens when a carpet is pushed (not pulled) across a smooth surface.
2. Platy. The crust breaks in large plates. Rafted plates are commonly seen in terrestrial and in Martian flows and also documented on the Moon (Carter et al. 2012) (► platy material).
3. Ridged. (► Pressure ridge). Martian flows show a unique platy-ridged-type morphology (► platy material) (Keszthelyi et al. 2000).

Classification Based on Radar Properties

(See also ► radar feature). Radar brightness may correlate with flow rheology (Byrnes and Crown 2002; Carter et al. 2012).

1. Radar-bright flow (surface has lots of irregularities comparable to the scale of the incident radar wavelength and scatters radar waves easily back).
2. Radar-dark flow (smooth surface at wavelength scales with only little variation; radar waves are only rarely reflected directly toward the remote sensing satellite or spacecraft).

Classification Based on Flow Emplacement

(1) Lobate flows formed by medium volumetric rate.

  (1.1) Simple flows have single lobes or branch into a few main lobes and are typically characterized by ‘a’ā surface texture (Byrnes and Crown 2002; Byrnes 2002). They are not divisible into separate flow units and develop at high extrusion rates. Higher viscosity lavas are more typically simple than compound (Walker 1972). They can develop sheet-like forms. Visually simple flows may be technically compound, composed of a large sheet and several much smaller flows, or may be juxtaposed laterally rather than vertically (Self et al. 1998).

  (1.2) Compound flows are emplaced in multiple overlapping and interfingering flow lobes that typically display pahoehoe texture (Byrnes and Crown 2002; Byrnes 2002). They are visually divisible into separate flow units and develop at low extrusion rates (Walker 1972). They develop digitate forms. Stratigraphy is quite easily figured. Pahoehoe flows are generally compound (Walker 1972).

(2) Flood lavas: laterally extensive low-relief continuous sheet lava flows. Flood lavas form by high-volume flux, where lava spreads out in a sheet because its high flux inhibits the formation of a crust during emplacement (Perfit and Chadwick 1998). Sheet flows have “a continuous body of liquid lava across the entire width of the flow. In contrast, the pathways within a hummocky flow should have many dead ends (ending in tumuli) and areas in which the lava cannot flow (inflation pits)” (Self et al. 1998). “Flood lavas” are defined as “a package of sheet-like lava flows that inundates a large region, producing a smooth plain without ~100 m tall constructs” (Keszthelyi et al. 2000) (▶ large igneous province). “Flood basalt piles include both compound and simple flows, but the most extensive and far-reaching flows are simple” emplaced at high effusion rates. (Walker 1972).

(3) Submarine pillow lava flows formed by low-volume flux. Pillow lavas extrude as spherical or cylindrical tubes of lava which cool and crust over on all sides preventing the coalescence of individual lobes. Pillows build steep-sided mounds as new pillows are added to the top of the stack (e.g., Perfit and Chadwick 1998).

Formation

Lava flows are produced from the outpouring of magma which has reached the surface. Surface morphology (pāhoehoe or ‘a’ā) is controlled by viscosity and the rate of shear strain (Peterson and Tilling 1980). ▶ Inflated lava flow (pahoehoe) sheet flow forms when a chilled crust allows continued lava emplacement into the flow to raise its upper surface. It may reach thicknesses of tens of meters (Self et al. 1996). The insulating crust can maintain cooling rates of <0.1°C/km and allow travel distances up to several hundreds of kilometer (Thordarson and Self 1998). Inflated sheet flows have been observed in Hawaii, and probably the standard way of emplacing large lavas is as inflated compound pahoehoe sheet flows (Hon et al. 1994; Self et al. 1998).

Eruption Rates

The calculated emplacement rate for basaltic flows on the Earth is typically between 50 and 7,100 m^3/s (Keszthelyi and Self 1998), of the order of 10^4 m^3/s for flood lavas (Keszthelyi et al. 2006). On Io, at Pillan Patera, the estimated eruption rate was 18,000–59,000 m^3/s based on observations in 1997 (Davies et al. 2006). Similar high eruption rates (up to 10^4 m^3/s) are expected at pahoehoe and platy-ridged lavas on Mars (Davies et al. 2007). At Alba Patera on Mars, based on observed properties of lavas and model computations, the effusion rate reached the order of ~10^3 m^3/s (Cattermole 1987).

Degradation

Post-emplacement modification may produce the following features: (1) flow inflation (► tumulus; ► inflated lava flow), (2) crustal foundering after draining of the lobe interior, (3) weathering and coating of the flow surface, and (4) spallation of the surface crust (Byrnes and Crown 2002; Byrnes 2002 and references therein). Lava flows may become capping materials over inverted landforms (e.g., ► inverted channel or ► plateau degradation landforms).

Composition and Eruption Temperatures

Typical eruption temperatures are 1,700–1,900 K (komatiites), >1,500 K (various ultramafic lavas), 1,300–1,450 K (basalts), 385–393 K (sulfur polymorphs) (Lopes et al. 2004), and 814–764 K (carbonatites) (Krafft and Keller 1989).

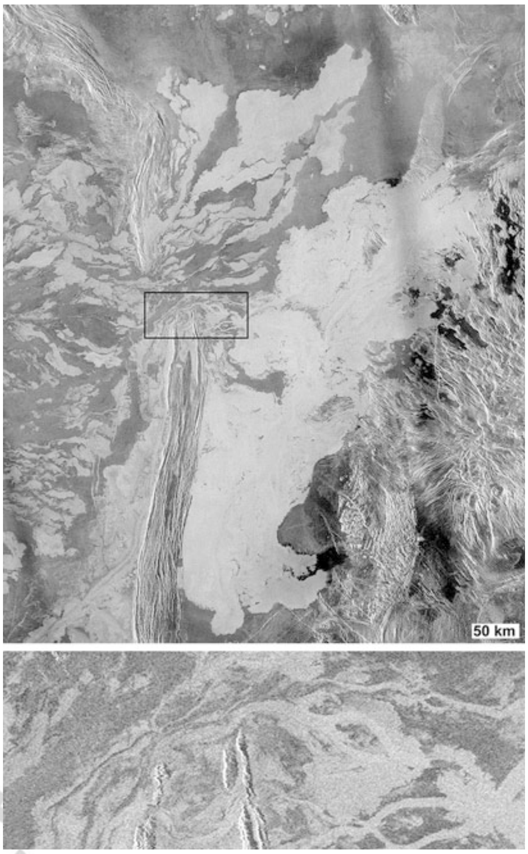
Distribution

Lava flows are common on large, differentiated rocky bodies; they occur on Earth, Venus (Fig. 1), the Moon (Fig. 6), Mars (Fig. 2), Io (Fig. 3), and possibly on Mercury and Titan. Some features on Titan are interpreted as cryolava flows (LeCorre et al. 2009).

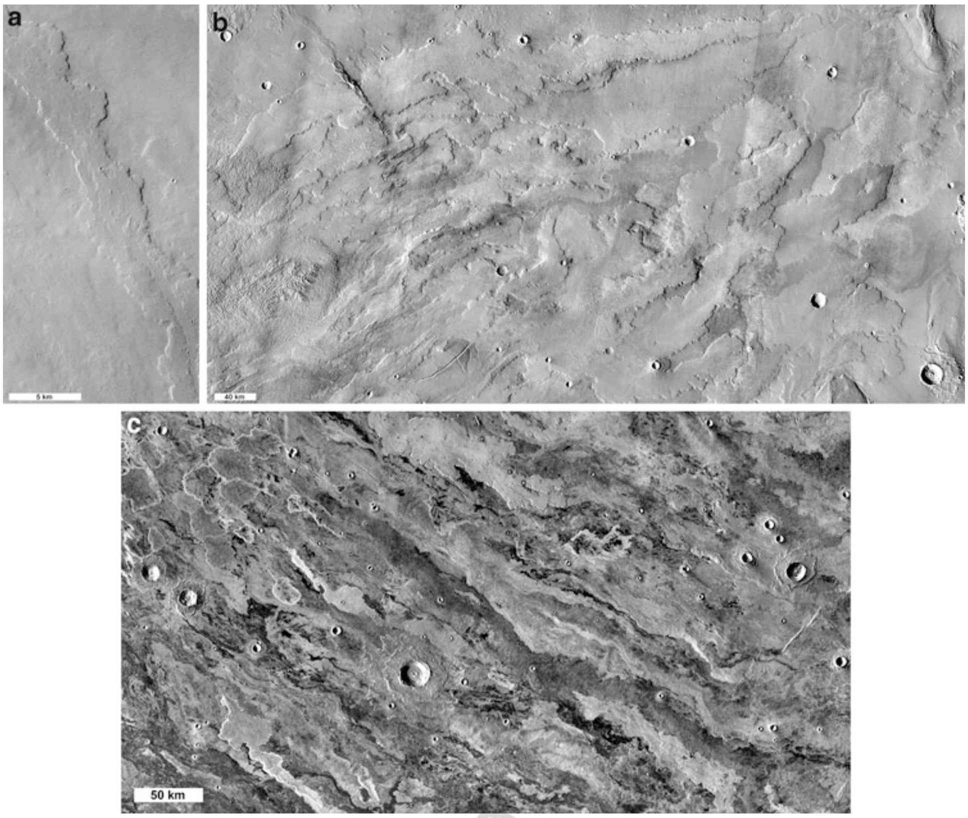
Planetary Regional Variations

Mercury: Flows forming broad channels with streamlined islands are interpreted as overland flows of voluminous, high-temperature, low-viscosity lavas (Byrne et al. 2013).

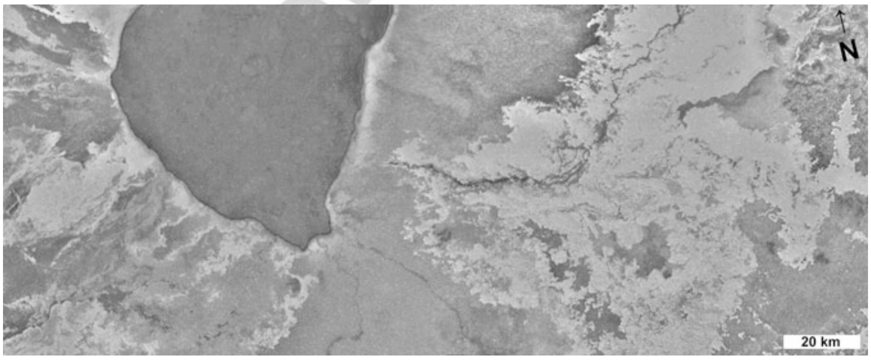
Venus: Thousand-kilometer-long channelized lava flows are common on volcanic plains, formed by low-viscosity lavas (Gregg and Greeley 1993). Flow length on Venus is typically between 140 and 300 km (Lancaster et al. 1992; Zimbelman 1998). Models suggest that the high density of the atmosphere decreases cooling time as convection transports energy more effectively in a dense atmosphere, while the thermally opaque atmosphere slows down the cooling by absorbing infrared radiation (Snyder 2002). As a result lava flows cool at a slower rate than on Earth. Large lava fields suggest high effusion rates and extensive lava flooding (Byrnes and Crown 2002); the thin individual flows often inferred to be of pahoehoe morphology (Zimbelman 2003). Identifiable lava flows



Lava Flow, Fig. 1 Venus: The radar-bright Ubastet Fluctus lava flows emanating from the vicinity of Derceto Corona (a. k. a. Ammavaru). A lava channel which is a continuation of a distributary of Kallistos Vallis, runs parallel to the Vaidilute Rupes ridge belt until lava flow lobes and branching lava channels cross it. Magellan radar, PIA00486 at 47°S, 26°E (NASA/JPL)



Lava Flow, Fig. 2 Mars: (**a**) Channeled lava flow on the flank of Ascraeus Mons on Mars (Garry et al. 2007). THEMIS V11712007 at 6°N, 250°E. (**b**) Field of overlapping lava flows east of Tharsis Tholus, near 17°N, 277°E. THEMIS Day IR mosaic (NASA/JPL/ASU). (**c**) Lobate lava flows showing different thermal inertia near 18°S 267° in Sinai Planum. THEMIS Day IR mosaic (NASA/JPL/ASU)



Lava Flow, Fig. 3 Io: Lava flows with lava channels, surrounding Emakong Patera (Keszthelyi et al. 2001; Schenk and Williams 2004). Galileo I25ISEMAKNG02 centered at 4.6°S 117.5°W. (NASA/JPL/ASU) constitute 11 % of the volcanic plains (Ernst and Desnoyers 2004 and references therein).

Size Classes for Venus Lavas

1. Large flow fields: larger than 50 000 km^2 (up to 1,6 million km^2) (► large igneous province) (Lancaster et al. 1995; Magee and Head 2001)
2. Great flow fields (“exceptionally large” or giant flows): having a maximum flow length >500 km. Example: Mylitta Fluctus flow field showing 400–1,000 km long and 30–100 km wide flow fields (Roberts et al. 1992)

Morphologic Classes for Venus Lavas

Crumpler et al. (1992) defined the following classes:

1. Amoeboid flows (radar-dark, streak-like, plain lava pattern)
2. “Fluctus” (radar-bright and dark lava flow fields, longer than several hundred kilometers in one direction from a source area) (Fig. 1)
3. “Festoon” flows (radar-bright flows that show organized patterns of internal streamlines analogous to the ridge and flow bands typical of viscous terrestrial lava flows) (► festoon)

Lancaster et al. (1995) and Byrnes (2002) grouped flows into the following types:

1. Digitate flow field (e.g., the lava fan on Derceto Plateau, Ozza Mons) is the most common morphologic type on Venus. It is composed of multiple distinct superposed flow units that are much longer than they are wide and thus represent compound flows. It indicates cooling-limited flow emplacement.
    - (1.1) Lava apron: the flow field completely surrounds the central source vent (the most common type of digitate fields).
    - (1.2) Lava fan: the flow field only partially surrounds the central source vent and forms a delta-like shape with the source region at one apex.
    - (1.3) Subparallel flow field: numerous subparallel adjacent, overlapping units emplaced from less centralized sources.
2. Sheet flow field (e.g., from Lauma Dorsa) shows a uniform radar backscatter, lack of lava channels and lobate structures, and irregular boundaries. Internal flow boundaries are barely discernible. It represents simple flows (lacks subunits). It indicates ponded, volume-limited flow emplacement.
3. Transitional flow field (e.g., Neago Fluctus) is composed of multiple, large, sheet-like, broad, lobate, elongated sheets.

Moon: The dark mare regions are sheets of basalt lava. The thickness of individual flows ranges between 30 and 60 m at the Apollo landing sites (Neukum and Horn 1976). At other locations flow fronts are between 1 and 96 m high (Gifford and El-Baz 1981), and their maximal thickness could be up to 220 m (Hiesinger et al. 2002). Some lunar flows may have been produced by higher effusion rates than that is typically observed on Earth (Murase and McBirney 1970; Hulme and Fielder 1997). Channelized lava flows typically form ► sinuous rills. Their low slope angle suggests very low-viscosity lava.

Mars: Some Martian flows show platy-ridged surface morphology (Keszthelyi et al. 2000, 2004) with ridges, plates, and smooth surfaces broken into polygons and grooves as the flows moved around obstacles. Large eruptions of low-viscosity lava was still possible late in Martian history (Plescia 1990), as evidenced by pristine-appearing lava flows in the Elysium region. At Athabasca Valles in western Elysium Planitia, volcanic flows covered ~250,000 km^2, emplaced by turbulent flow during at least several weeks (Jaeger et al. 2010). Channeled lava flows commonly reach several hundreds of kilometer distances, e.g., in the Tharsis region (Garry et al. 2007; Shockey 2004; Fig. 2). Some low-relief volcanoes (► highland patera) lack lava flow features, suggesting that they consist predominantly of pyroclastic deposits (Crown and Greeley 1993). Some outflow and other channels usually interpreted as fluvial are alternatively interpreted as formed or modified by lava flows (e.g., Leverington 2011). Lobate flows cover, e.g., Daedalia Planum and Solis/Sinai/Syria Plana (Fig. 2c).

Io: Lava flows of various colors cover 28.5 % of Io's surface (McEwen et al. 1998; Williams et al. 2011), with lengths of up to hundreds of kilometer (Fig. 3). Shield-associated flows occur on very low (<1°) slopes (Schenk et al. 2004). Besides low-silicate lavas like basalt or komatiite (Schenk et al. 2004), sulfuric lavas are probably also present (Davies 1996). High eruption temperatures inferred from spacecraft and telescope data suggest mafic or ultramafic composition (high-Mg basalts, komatiitic basalts, and komatiites) (McEwen et al. 1998; de Kleer et al. 2014).

Bright yellow flow fields are interpreted to be sulfur rich, while dark or black flows might be either silicate or sulfur flows. Since bright flows typically occur separately from dark ones, they are inferred to be derived from primary sulfur-rich effusions and not from secondary sulfurous volcanism (type example of bright flows: 45–75°N, 60–120°W). Alternatively, some bright flows may be silicate flows covered with sulfur-rich plume fallouts (Williams et al. 2011; Williams and Howell 2007). At the Prometheus region, along the frontal edge of flow lobes, bright streaks are present, probably composed of volatilized and recondensed SO_2, produced by active venting from the front edge of flow lobes (Milazzo et al. 2001).

Active emplacement is occurring on less than one third of Io's visible lava fields (as inferred from the ratio of the freshest flows) (Williams et al. 2011).

Basic eruption types on Io: (1) long-duration, flow-dominated, steady eruptions producing compound pahoehoe flows, <200 km high plumes, originating from flow fronts, (formerly Promethean); (2) Explosion-dominated, larger and violent eruptions, >200 km high plumes producing large pyroclastic deposits, rapidly emplaced lava flows from fissures (formerly Pillanian Keszthelyi et al. 2001, Williams et al. 2007); and (3) eruptions confined within paterae with or without associated plume eruptions (formerly Lokian) (Williams et al. 2007; Lopes et al. 2004) [▶ eruptive center (Io), *see plume types* in ▶ diffuse deposits (Io)].

Classification of Flow Morphologies on Io

(1) Large, broad, irregular flows: they resemble sheet flows or flood lavas (Schenk et al. 2004).
(2) Radially centered flow fields that consist of long narrow flows typically >50 km long and <10 km wide, centered on paterae (e.g., Ra Patera).

Vesta: Basalt has been identified on Vesta which has been expected to have volcanic features (Wilson and Keil 1996); however, the observed lobate features were interpreted as impact or mass movement related (Williams et al. 2013). After careful mapping with the probe Dawn, Russell et al. (2013) find that Vesta has no evident volcanic features.

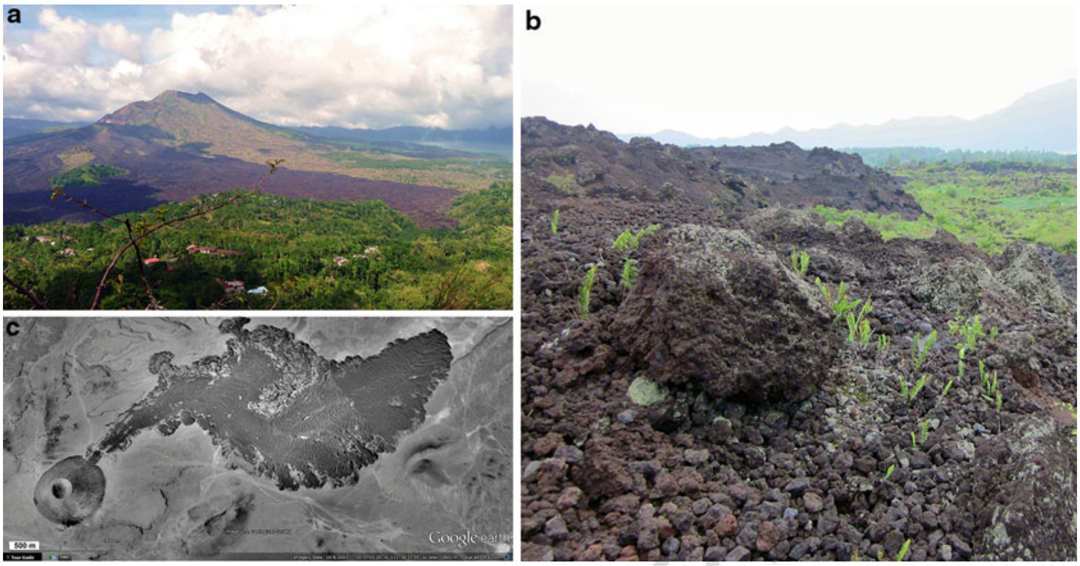
Titan: Several flow-like features were interpreted as cryovolcanic flows (Lopes et al. 2005, 2013; Le Corre et al. 2009). See details in ▶ cryovolcanic features.

Terrestrial Analog

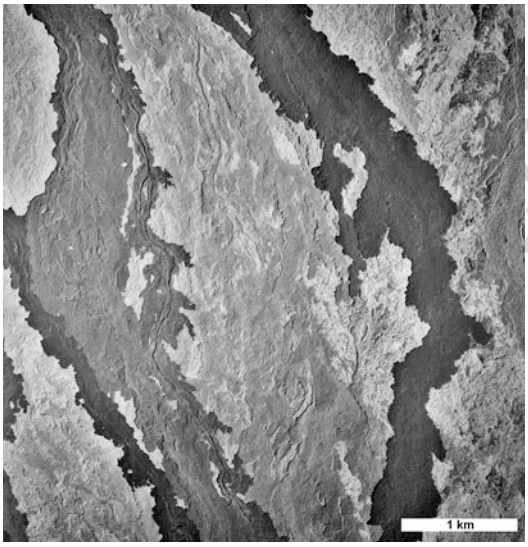
Analogs for various silicate flows are common on Earth (Fig. 4). Terrestrial flood basalts are analogs for inferred flood lavas on Mars, Io (Keszthelyi et al. 2006), and Venus (Ernst and Desnoyers 2004 and references therein) (▶ Large Igneous Province). The Laki flow field is a terrestrial analog of platy lava flows on Mars (Keszthelyi et al. 2000, 2006). Fumarolic sulfur flows on the flank of Mauna Kea is a partial analog for sulfur flows on Io (Greeley et al. 1984) (Figs. 5 and 6).

IAU Descriptor Term

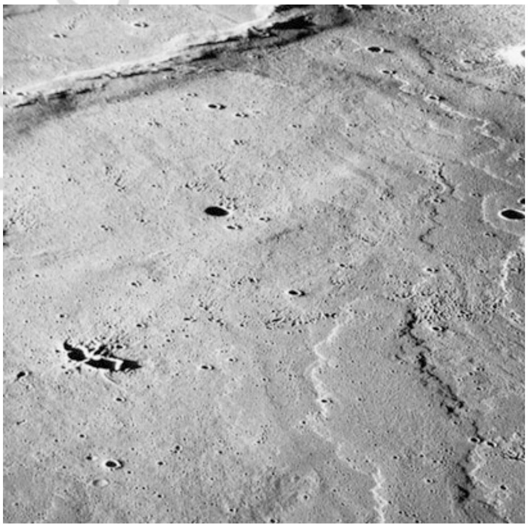
▶ Fluctus



Lava Flow, Fig. 4 Terrestrial analogs: (**a**) Lava flow produced on the flank of Batur volcano in 1998. Island Bali, Indonesia. (**b**) Close-up of aa lava flow (Photos by A. Lukashov 2012). (**c**) SP Crater and its 71,000-year-old aa lava flow, Arizona, USA (Google Earth /USGS)



Lava Flow, Fig. 5 Multiple flows from the same eruptive event on the southwest flank of Mauna Loa, typical of the flows that constitute the Hawaiian shield volcanoes (Figs. 9–11 from Carr and Greeley 1980; US Department of Agriculture, photograph EKL-J4.CC-36, 1965)



Lava Flow, Fig. 6 Lava flow in Mare Imbrium near 29.4°N 29.5°W. AS17-155-23713 (NASA/JSC)

Similar Landforms

Flow structures interpreted as possible (nonvolcanic) ► impact melt flows. On Venus: lobate flows that originate near impact crater rims (► crater outflow, Venus) (Miyamoto and Sasaki 2000); on the Moon: flow-like structures associated with craters larger than 3 km in diameter (Howard and Wilshire 1975; Bray et al. 2010).

See Also

► Eruptive Center, Io
► Impact Melt Flow
► Impact Melt Pond
► Inflated Lava Flow
► Large Igneous Province
► Lava Channel
► Lobate Plains (Venus)
► Mare (Moon)
► Volcanic Plain

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Lava Inflation Feature

► Inflated Lava Flow

Lava Lake

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Definition

Lava lakes are large volumes of exposed molten lava, usually basaltic, contained in a vent, crater, or other broad depression.

Synonyms

Lava pond; Lava pool (for inactive lava lakes); Magma sea (for Loki Patera, on Jupiter's moon Io; Matson et al. 2006)