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Submarine lineated sheet flows: a unique lava morphology formed on subsiding lava ponds

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Abstract Lineated sheet flows are flat-lying, glassy lava flows characterized by a regular surface pattern of parallel grooves or furrows aligned with the flow direction. They are unique to the submarine environment. We propose that the lineations are developed within the collapsed interiors of partially ponded lobate sheet flows that initially inflate and then drain out during emplacement. During lava drainout, the original lobate crust founders and a new crust begins to grow on the subsiding lava surface. Lineated flow texture is created where molten lava emerges laterally from beneath a growing crust. The lineations are formed by raking of the emerging lava surface by irregularities on the bottom edge of the crust and are preserved owing to rapid chilling by seawater. Therefore, lineated sheet flows are the product of a specific sequence of events over a short period of time during the course of a deep submarine eruption.

Key words Lineated sheet flow · Submarine lava morphology · Sea-floor eruptions · Mid-ocean-ridge volcanism

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Introduction

Lava that is erupted underwater develops a different suite of surface textures than it does when erupted on land. This is because water convectively transmits heat away from the lava surface at a much faster rate than does air; therefore, the surfaces of submarine lava flows cool and crust over more quickly. This rapidly thickening crust mechanically constrains the way in which the lava is able to flow and advance and greatly influences the final surface morphology.

Analog laboratory experiments involving the extrusion of molten wax into cold sucrose solution under controlled conditions have shown that the rate of extrusion and flow viscosity are the most important influences on submarine lava morphology (Griffiths and Fink 1992; Gregg and Fink 1995). In these laboratory simulations, a predictable sequence of flow morphologies was produced (pillows–rifts–folds–levees) as the extrusion rate increased and/or the cooling rate decreased, mimicking the range of lava flow morphologies (pillowed–lobate–lineated–ropy–jumbled) observed on the sea floor (Fox et al. 1988; Gregg and Fink 1995; Perfit and Chadwick 1998). Viscosity was varied slightly in these experiments by varying the extrusion temperature (Gregg and Fink 1995). This adequately accounted for the small variations in eruption viscosity observed at mid-ocean ridges, based on geochemical analyses (Weaver and Langmuir 1990; Perfit et al. 1994) which show that the viscosity is relatively uniform within a given segment (Reynolds et al. 1992; Smith et al. 1994). Thus, extrusion rate has the greatest influence on submarine lava morphology.

The key differences among various submarine flow morphologies are the dimensions of individual parcels of lava delivered to the flow front, their inter-connectivity, and the rate of crust formation relative to the rate at which lava moves away from the vent during emplacement (Gregg and Fink 1995; Perfit and Chadwick 1998). At one end of the spectrum, pillow lava extrudes slowly as individual spherical or cylindrical tubes of lava, typically 1–2 m^3 each, and rapidly cool and crust over on all sides, generally preventing coalescence with neighboring pillows (Moore 1975). At the other end of the spectrum are sheet flows, which form when lava spreads out rapidly as a continuous sheet. Intermediate conditions generate lobate flows emplaced by budding one lobe at a time from a flow front. However, lobate flows advance rapidly enough so that the individual lobes can quickly coalesce, forming a continuous liquid core beneath a lobate or hummocky surface crust, much like tube-fed pahoehoe or pahoehoe sheet flows on land (Swanson 1973; Hon et al. 1994; Kauahikaua et al. 1998).

The final morphology of a submarine lava flow is also determined by its specific emplacement history. For example, the well-studied "young sheet flow" (YSF) at the northern Cleft segment on the Juan de Fuca Ridge (Fig. 1) is interpreted to be the product of a single brief fissure eruption, but it displays multiple surface morphologies including lobate, lineated, ropy, and jumbled varieties (Embley et al. 1991; Embley and Chadwick 1994). Gregg and Chadwick (1996) presented a model for the emplacement history of the YSF involving: (a) the initial advance of lava as a thin (20–30 cm) lobate sheet flow; (b) lateral confinement and partial ponding of lava by the cooled flow margins as well as pre-existing topographic barriers; (c) upward inflation of the flow (to a maximum thickness of ~5 m) as fluid lava continued to be injected into the molten flow interior beneath a solid upper crust, similar to inflated pahoehoe flows observed on Kilauea Volcano, Hawai'i (Hon et al. 1994; Kauahikaua et al. 1998); (d) the development and upward growth of lava pillars during this inflation process; and (e) subsidence of the molten flow interior by drainout and/or drainback, leading to collapse of the thin, mostly unsupported upper crust. As the molten flow interior was again exposed to seawater, new crust grew on the subsiding lava surface and repeatedly adhered to, and broke off from, confining walls and lava pillars (Ballard et al. 1979; Francheteau et al. 1979; Gregg and Chadwick 1996). Thus, the lobate flow morphology in the original upper crust was preserved only at the uncollapsed margins of the YSF or on the tops of lava pillars (Figs. 1c, d, 2a, b). These are the only remnants of the lava morphology associated with the initial advance of lava away from the vent (directly related to extrusion rate). All the other flow textures are found within the collapsed areas and are morphologies produced during the later stages of lava emplacement.

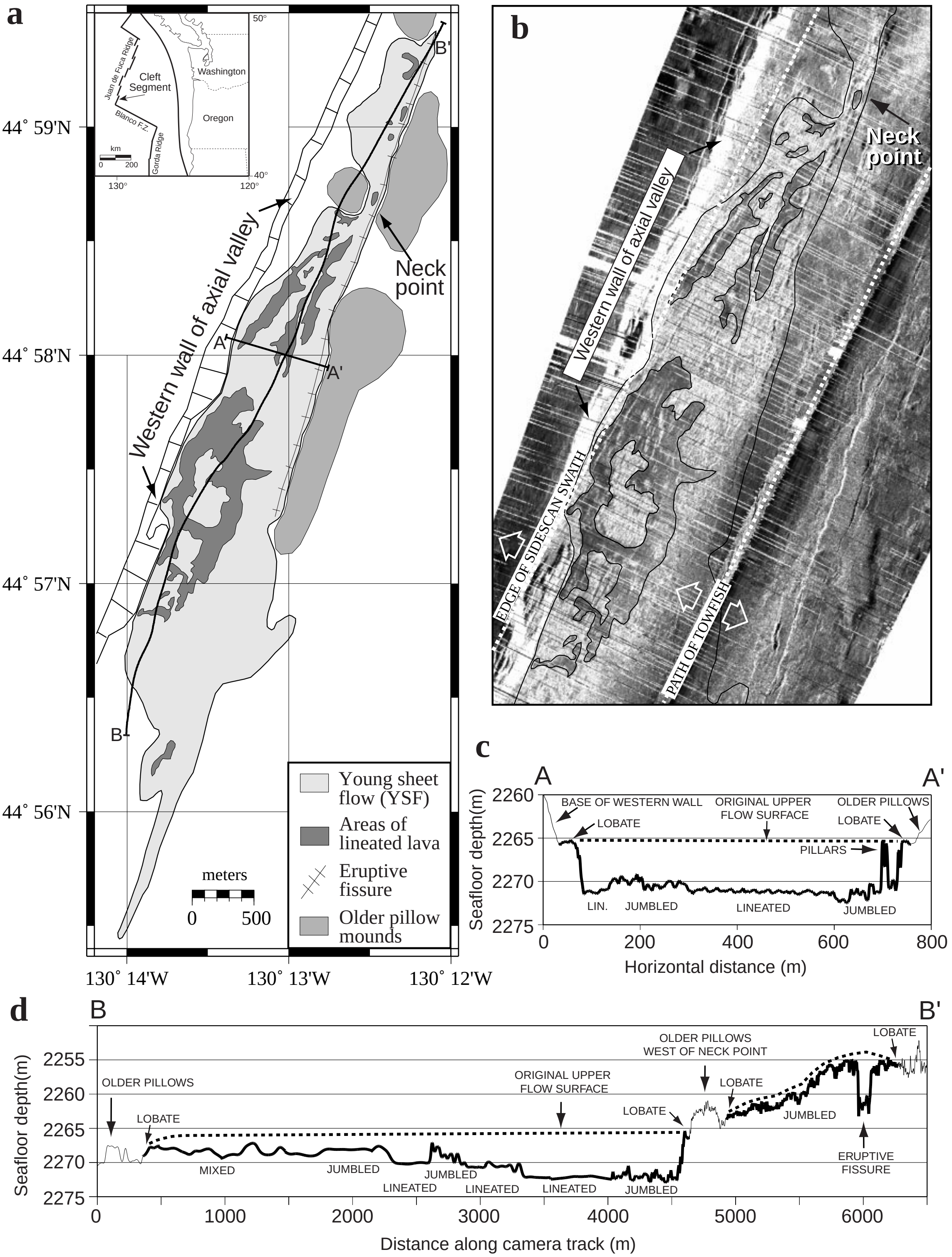
The YSF at Cleft has broad areas of lineated sheet flows within the floor of its collapsed interior (Figs. 1, 2), amounting to 16% of the total flow area (6.8×10^5 m^2 out of 4.2×10^6 m^2 total). The lineated parts of the YSF appear as areas of low reflectivity on SeaMARC I (International Submarine Technology, Everett, Washington) sidescan sonar images (the dark, outlined patches in Fig 1), because their flat surfaces do not reflect much acoustic energy back toward the sidescan towfish, in comparison with rougher jumbled or pillowed lava. In the past, lineated sheet flows have usually been lumped together with other sheet flows, particularly ropy sheet flows, which share many of the features of subaerial ropy pahoehoe. Lava ropes are clearly produced by compression and buckling of the flow surface (Fink and Fletcher 1978), but available evidence suggests that the long, straight ridges and furrows on lineated sheet flows are not produced in this manner. Lineated sheet flows are common features on intermediate and fast-spreading mid-ocean ridges, as well as in the summit calderas of some seamounts, yet the formation of their distinctive morphology has never been explained. In this paper we first describe lineated sheet flows using the Cleft YSF as an example and show that they have no direct subaerial analog. We then develop a model for the formation of lineated lava surfaces in the deep submarine environment and examine the possible implications.

Fig. 1a Map of the Young Sheet Flow (*YSF*) at the northern Cleft segment, Juan de Fuca Ridge (*inset*). The YSF (*light stipple*) erupted primarily from its shallower northern end. Lava flowed southward through a topographic constriction (the neck point) and spread between the western boundary fault and preexisting pillow mounds to the east (*medium stipple*). Areas of lineated lava morphology, based on sidescan sonar imagery, are shown (*dark stipple*). **b** SeaMARC I sidescan sonar imagery of the central YSF (*light shades* indicate high reflectivity, *dark shades* indicate low reflectivity or acoustic shadow). The mosaic is made up of two overlapping swaths; the path of towfish and edge of the upper swath are shown by *dashed white lines*; *white arrows* indicate the direction of insonification from the towfish. The YSF is outlined for clarity. *Dark patches within the YSF* (also outlined) are areas of lineated sheet flow, which have low reflectivity because they are very flat. Depth cross sections **c** across and **d** along the YSF show the distribution of lava morphologies (microbathymetry from Alvin dive 2431 and camera tow 88-03, respectively). Locations of cross sections shown by endpoints *A–A'* and *B–B'* in **a**. In both cross sections, extent of YSF lavas is shown by a *thicker line.* Primary, uncollapsed lobate lava crusts are preserved only near the margins of the YSF, whereas lineated lava flows are found only within the collapsed, drained-out interior of the flow

Submarine lineated sheet flows

The surface morphology of lineated sheet flows is characterized by corrugations that are generally long (up to tens of meters), continuous, and parallel to one another (Fig. 2c, d). Individual lineations are grooves or furrows on the upper flow surface between smooth, glassy, convex-upward bands of lava several centimeters to several meters wide. The height of the convex-upward bands above the bottom of the furrows is typically <5 cm. Sediment commonly accumulates in the furrows, because bottom currents keep the intervening smooth bands relatively sediment free, accentuating the lineations in photographs (Fig. 2).

The narrowest bands resemble rolls or folds, but where they are widest they generally have a billowy or



gently undulating surface (Fig. 2e, f). The distance between adjacent lineations may be different, but the distance between specific pairs of furrows (the width of each intervening band) remains nearly constant along their lengths. The lineations on submarine sheet flows have been interpreted as oriented parallel to the direction that the lava flowed (Embley and Chadwick 1994). At Cleft, for example, lava erupted from fissures along the northern end of the YSF subsequently flowed south–southwestward (Fig. 1), and the lineations within the interior of the YSF are dominantly oriented parallel to this direction (Embley and Chadwick 1994). On a finer scale, clear evidence for alignment of lineations parallel to the flow direction comes from parts of the

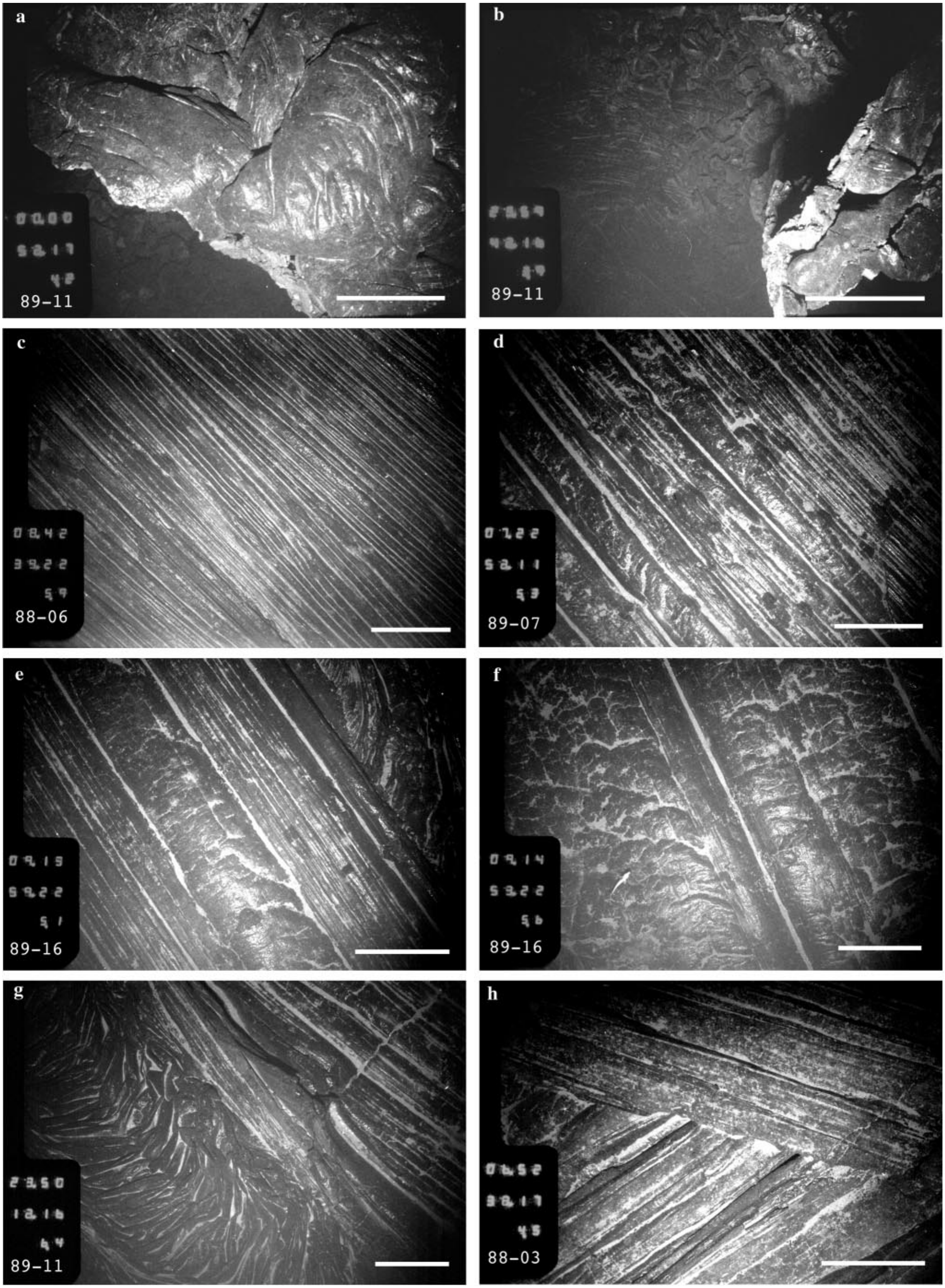

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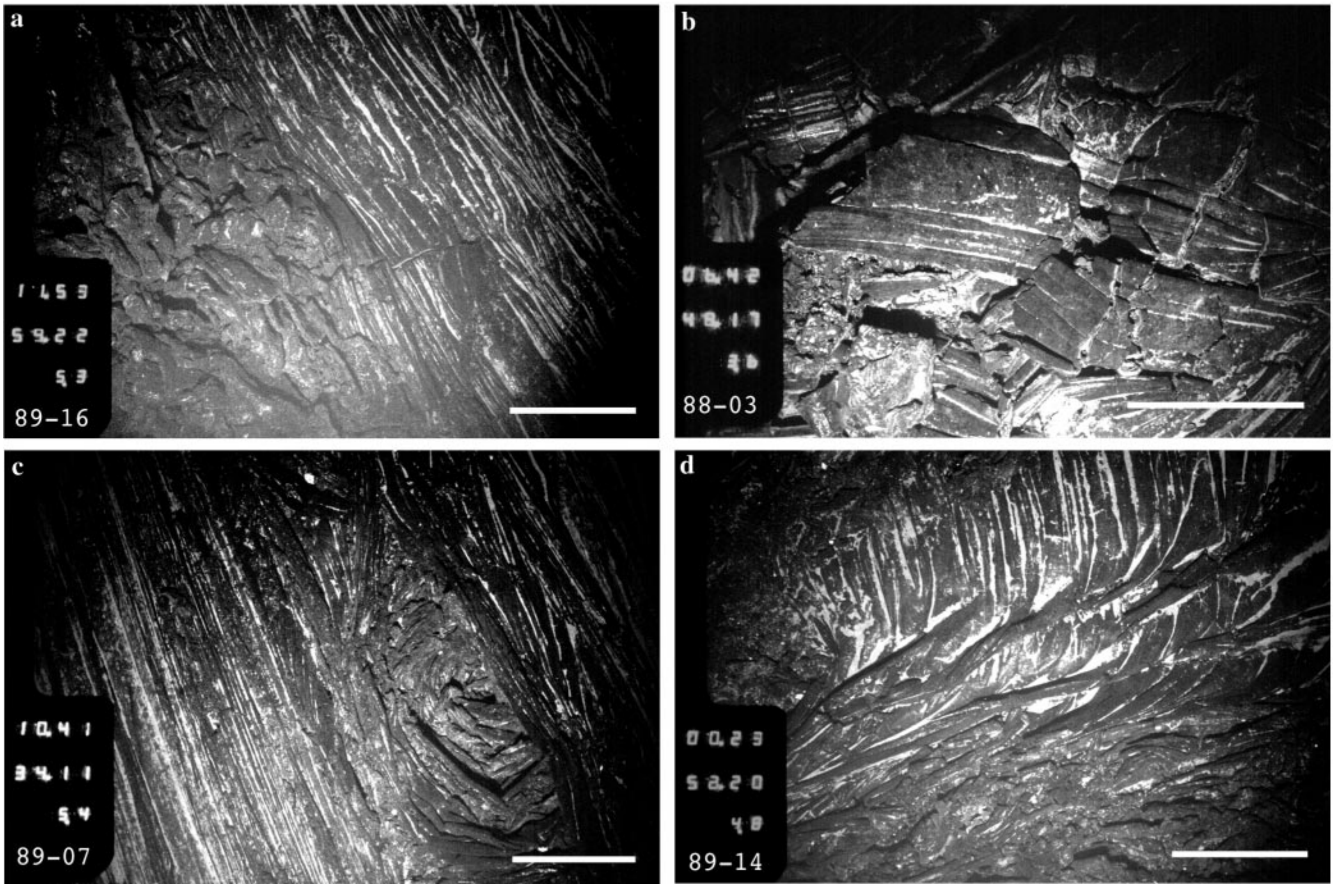
Fig. 2a–h Camera tow photographs of the YSF showing lobate and lineated flow surfaces. In each photograph the *two-digit numbers* in the lower left are hour, minute, second, day of the month, altitude in meters, year, and tow number. *White bars* in lower right are 1 m long. **a** Partially collapsed and drained-out primary lobate flow surface near the margin of YSF. The thin lobate crust is only ~5 cm thick and hollow underneath. Talus visible on the floor of the collapse in the lower left is approximately 5 m below the upper crust. **b** Lobate flow morphology preserved on the top of a lava pillar at the edge of a collapse area with talus and lineated lavas in the floor of the collapse. **c–h** The character and variety of lineated sheet flow surfaces: **c** closely spaced lineations; **d** lineations with variable spacing; **e** lineations with wider bands showing billowy texture; **f** area of mostly billowy texture with faint lineations; **g** ropy folds within a narrow channel clearly show that the adjacent lineations are oriented parallel to the flow direction (toward lower right); **h** example of cross-cutting lineation directions

YSF that are mixtures of both lineated and ropy flow textures. The ropy morphology provides unambiguous evidence for flow direction (from the axis of surface folds), and where both textures exist, the furrows on lineated lava are consistently aligned parallel with the flow direction deduced from surface folds (Fig. 2g). This also shows that the lineations themselves are not surface folds but must form in some other way. On the other hand, lineations can also be oriented in many different directions within a small area, with curving patterns and cross-cutting relationships (Fig. 2h), so a more complete understanding of their formation is required to explain these observations.

The areas of lineated lava within the YSF are irregular but range up to 100–200 m wide and 500–1000 m long (Fig. 1). The direction of the lineations is most consistent in the center of these areas, becoming more variable near the edges. At the margins of lineated areas the lava morphology abruptly changes to jumbled sheet flow (Fig. 3a). These margins are evidently zones where the lineated flow surface became highly disrupted due to shear across a velocity gradient (Fig. 3a, b). Jumbled sheet morphology is similar in appearance to subaerial a’a flows but is produced purely by the mechanical disruption (both plastic and brittle) of the crust on mobile sheet flows. In some locations within lineated areas, spiral lava coils (Peck 1966; Lonsdale 1977) are observed, evidence of the plastic deformation

Fig. 3a–d Camera tow photographs of the YSF showing relationships at the edges of lineated areas. *Numbers in the lower left* of each photo as in Fig. 2. *White bars* are 1 m long. **a** Lineated lava grading into jumbled sheet flow morphology (*lower left*) at the margin of a lineated area. **b** Jumbled sheet flow made of disrupted plates of lineated crust in a shear zone. **c** Lava coil formed within a lineated area from shear of plastic crust between two mobile crustal plates. **d** Downstream edge of a lineated flow area where lineated texture grades into ropy and jumbled flow due to compression and shear



of surface crust within shear zones between adjacent mobile slabs of lineated crust (Fig. 3c). On sidescan sonar images of the YSF, isolated lines of high reflectivity within the low-reflectivity (lineated) areas (Fig. 1b) are narrow, flow-parallel shear zones of jumbled lava, as seen on camera tow photographs. The downstream edges of lineated areas grade into a mixture of morphologies, including ropy folds and jumbled textures, probably resulting from steep gradients in flow velocity and shear stresses on the mobile solidifying lava crust (Fig. 3d).

Lineated sheet flows are typically extremely flat with little or no surface slope or relief (Fig. 2) and are consistently found in the interior of collapsed lava flows. Thus, they represent the last preserved upper crust on a partially ponded and subsiding molten flow interior, often referred to as submarine "lava lakes" or "lava ponds" (Ballard et al. 1979; Francheteau et al. 1979; Hekinian et al. 1983; Ballard et al. 1984; McConachy et al. 1986). To understand the formation of submarine lineated sheet flows, we first examine how lineations form on subaerial lava flows.

Lineations on subaerial lava flows

Lineated sheet flows have been observed only in the deep-submarine environment, but some insight can be gained by examining processes that produce flow-parallel lineations on land. Since lineated flows are commonly ponded and associated with submarine lava lakes, one obvious comparison is to subaerial lava lakes. The solid crust on subaerial lava lakes is mechanically coupled to the mobile lava beneath and becomes segmented into plates that are bounded by rifts, sinks, and transforms, analogous to the basic elements of global plate tectonics (Duffield 1972). In the divergent zones where new crust is generated, the plates are imprinted with striations perpendicular to the rift (Fig. 4a) by "differential stretching and scratching of the solidifying viscous lava" and by the elongation of vesicles, giving the crust a homogeneous texture (Duffield 1972). These striations form parallel to the direction of flow, but they are much finer, shorter, and less continuous, and do not exhibit the variation in spacing that is found on submarine lineated flows. In addition, the surface of submarine lineated flows is smooth and glassy, not rough from the disruption of volcanic glass and vesicles, and therefore must be produced by a different mechanism.

Subaerial toothpaste lava has both similarities and differences to submarine lineated flows (Fig. 4b). This subaerial lava type, described as transitional between pahoehoe and a'a, forms when lava has a viscosity higher than that of pahoehoe and a flow rate slower than that of a'a (Rowland and Walker 1987). Toothpaste lava may form primary lava lobes or be extruded from rootless openings (also called boccas or orifices). Toothpaste lava is similar to submarine lineated flows in that it is characterized by: (a) surface grooves and ridges that are oriented parallel to the direction of flow, maintain the same separation from each other along their length, and are variable in spacing; (b) the flows are commonly emplaced on low (<1°) slopes; and (c) shear zones near the edges of a flow unit may produce lava coils by the rotation and tearing of surface crust in a lateral velocity gradient (Rowland and Walker 1987). Unlike submarine lineated flows, however, toothpaste lava: (a) has a surface crust that is rough and spinose on a centimeter scale; (b) displays transverse undulations caused by pulsing or surging flow out of the orifice; (c) has a dull (not glassy) surface rind due to an abundance of microlites; and (d) is emplaced at very low flow rates (2–10 m/h; Rowland and Walker 1987). In contrast, submarine lineated flows are probably emplaced at moderate effusion rates (Gregg and Fink 1995).

The progressive crusting of pahoehoe lava channels, a process involved in the formation of some lava tubes (Greeley 1971; Peterson and Swanson 1974; Peterson et al. 1994), may also generate flow-parallel lineations on subaerial lavas. In this case, lineations form when ribbons of viscous lava adhere to the walls of established channels and progressively build a roof from both levees inward until eventually the two halves meet along the center line of the channel, often with a narrow train of ropy coils at the center, curved in the direction of flow (Fig. 4c). Although this process forms lineations parallel to the flow direction, they are not as continuous along strike or as variable in their spacing across strike, nor do they form flat surfaces over broad areas as on submarine lineated sheet flows. These differences suggest that roofed channels are not analogs to submarine-lineated flows.

Another process on land that creates lineations parallel to the flow direction is the formation of migrating shear zones on the surface of channelized lava flows. In any channelized lava flow (a'a or pahoehoe), shear zones lie between the stationary channel levees and the moving lava in the channel interior. As the volume of lava flowing through the channel decreases (e.g., due to decreased supply at the vent), the shear zones migrate inward to the center of the channel. The result is a series of flow-parallel shear zones on the solidified channel surface; however, the spacing of the resulting lineations is commonly >1 m, a much larger scale than the lineations observed on the sea floor.

The last subaerial process that we believe sheds some light on the formation of submarine-lineated flows has been observed recently near the active Pu'u O'o vent on Kilauea Volcano, Hawaii (J. Kauahikaua, pers. commun.). This process involves the detachment of shelly pahoehoe crusts from the underlying molten flow interior on relatively steep slopes. Shelly pahoehoe forms in near-vent settings when gas-charged lava wells up and overflows a vent (Wentworth and Macdonald 1953; Swanson 1973). Because exsolving gases can be trapped under the surface crust, the crust can become partially or completely detached from the un-

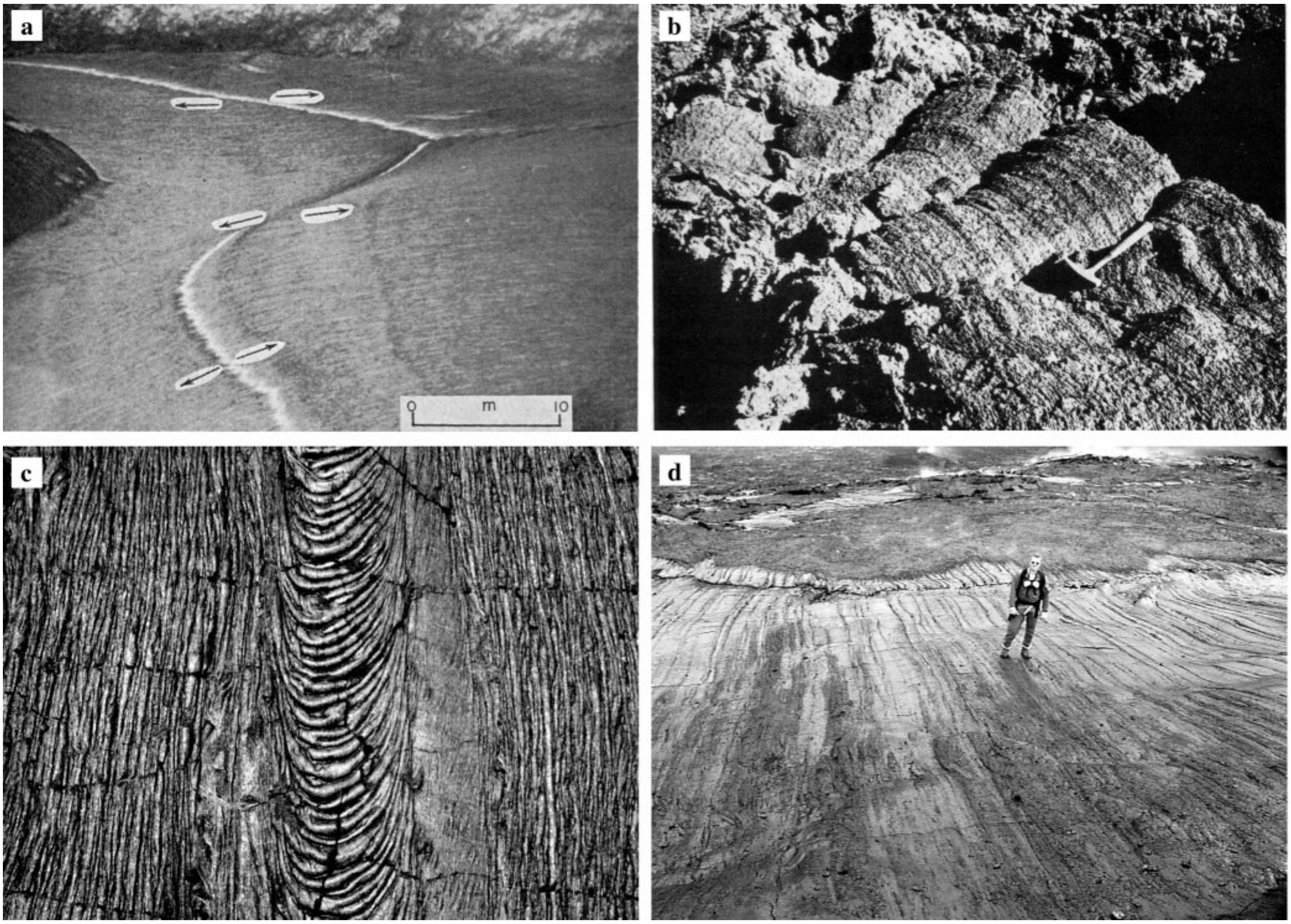


Fig. 4a–d Processes forming lineations on lava flows on land (all examples from Kilauea volcano, Hawai'i. **a** Oblique photo of crust forming on a lava lake, with fine lineations oriented perpendicular to spreading axes (from Duffield 1972). **b** A small tongue of toothpaste lava that flowed from lower right to upper left (from Rowland and Walker 1987). **c** Lineations formed by lava adhering to the sides of a pahoehoe channel as it roofed over. The last crust to solidify at the center of the channel formed ropy folds showing the flow direction was top to bottom (field of view is 1 m across). **d** Lineations formed when a shelly pahoehoe crust slid downhill (away from camera) over the still molten flow interior during gas-charged overflows from Pu'u O'o vent. (Courtesy of J. Kauahikaua)

derlying flow, and can fold, buckle, and slide over it, particularly in what Swanson (1973) called the "sheet-flood variety" of shelly pahoehoe. This occurred commonly in the latter half of 1997 at Pu'u O'o whenever shelly pahoehoe overflowed or drained back within its funnel-shaped crater (J. Kauahikaua, pers. commun.). On the slope of the spillway (~10°), the shelly pahoehoe crust often mechanically decoupled from the underlying flow and independently slid tens of meters down the slope. As it slid, the crust scraped the underlying viscous lava and left grooves in its relatively smooth surface that were preserved (Fig. 4d). These grooves are broader and more subdued in profile than the lineations on submarine flows, but they are continuous and maintain their spacing along their observed length (up to 50 m).

Each of these subaerial processes produces features similar to, but also inconsistent with, the characteristics of submarine lineated sheet flows. We conclude that none of these potential subaerial analogs is an exact match to submarine lineated flows, although some of the mechanisms that produce lineations on subaerial lava flows may operate on the sea floor within a different context.

A model for the development of submarine lineated texture

The most remarkable characteristic of submarine lineated flows is the pattern of parallel furrows with variable spacing. This pattern is key to understanding how the lineations form. On land, lava textures of similar character (toothpaste lava and detached shelly pahoehoe crusts) form by processes that involve the raking of solid crust over a molten lava surface. We believe this same process can explain the lineations on submarine flows.

We interpret that, on the sea floor, this process most likely occurs in the context of a partially ponded, lobate sheet flow that has previously spread laterally and inflated upward (Gregg and Chadwick 1996) and then subsides due to lava drainout and/or drainback. We consider a sheet flow to be "partially ponded" if it is confined on most sides, either by pre-existing topography or by the chilled margins of the flow itself, but has an outlet allowing lava drainout. The effect of partial ponding is that the upper lava surface is nearly horizontal during the drainout stage. This setting is somewhat similar to a "perched lava pond," a feature on land that forms when a lava flow is temporarily ponded and elevated behind its own levees (Holcomb et al. 1974; Carr and Greeley 1980; King 1982; Tilling et al. 1987).

Once lava subsidence begins due to drainout, the upper (original) lobate lava crust collapses where it is no longer in physical contact with, and therefore supported by, the underlying molten lava (Figs. 2a, b, 5). This original crust apparently breaks up, founders, and is assimilated within the underlying molten lava, because broken fragments of this crust are not observed within collapsed areas (except around pillars and roof remnants, where they have clearly fallen after the flow solidified). Once the original lobate crust fails, the upper surface of the subsiding molten flow interior is suddenly exposed to cold seawater and begins to cool and grow a new crust. The morphology of the new crust reflects the conditions of the ponded, drainout stage of the eruption rather than the emplacement stage that generated the primary lobate crust. At first, the new crust is thin and plastic, and it adheres to walls and lava pillars near the flow margins. Within minutes, the crust cools and thickens until it becomes rigid and brittle (Gregg and Chadwick 1996). As lava subsidence continues at a steady rate, we interpret that the new crust

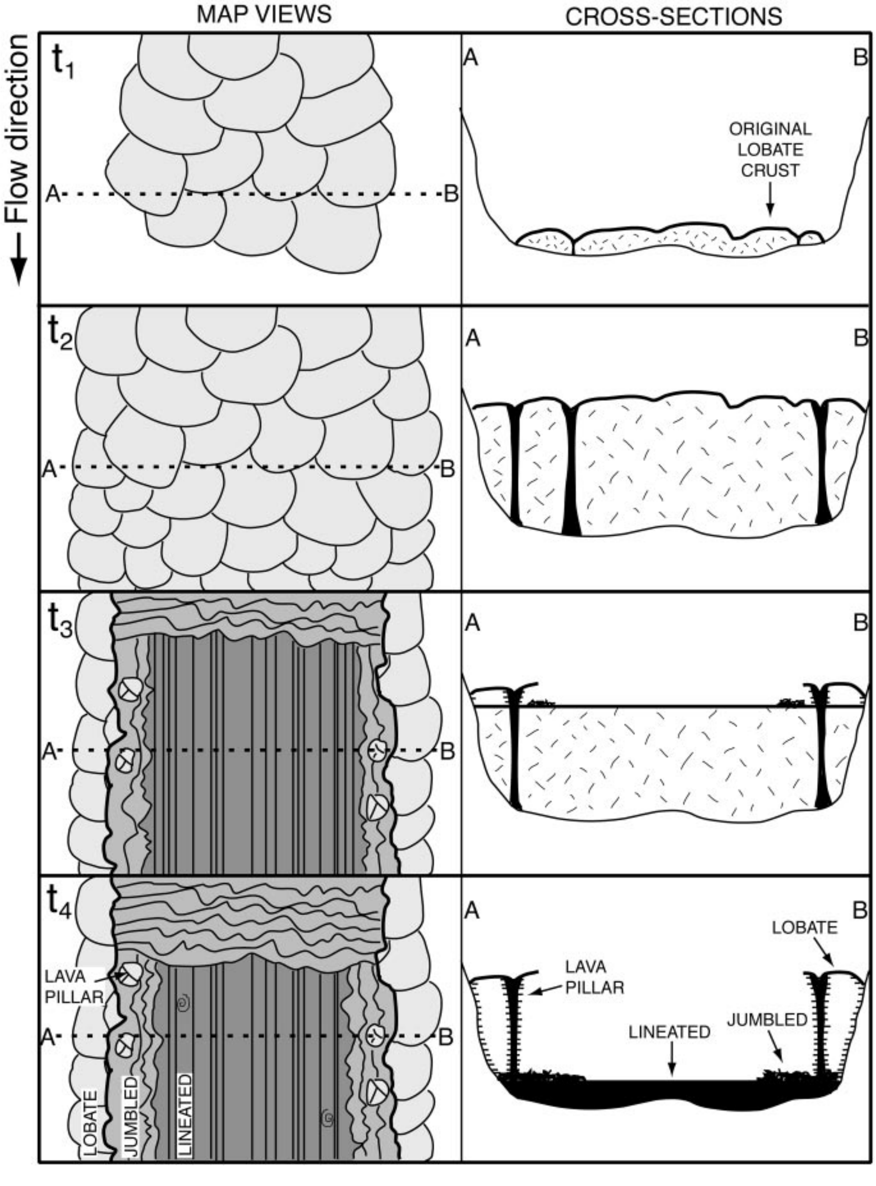


Fig. 5 Model depicting formation of submarine lineated sheet flows. Map views on the left; cross sections (*A*–*B*) on the right. *Cross hatch pattern* in cross sections represents molten lava beneath a solid crust. At time = t_1, lava initially spreads out as a thin lobate flow (*light stipple* in map view). At time = t_2, topographic barriers (and/or crusted flow fronts) have restricted the lateral advancement of the lava, but continued input from the eruptive vent causes the flow to inflate, uplifting the solid upper crust and allowing lava pillars to form near the margins (Gregg and Chadwick 1996). At time = t_3, a waning eruption rate and/or continued flow-area enlargement causes the level of molten lava within the flow to start falling. The original upper crust collapses where it is unsupported. A new jumbled crust (*medium stipple*) begins to form on the upstream part of the flow. Molten lava is raked as it emerges from beneath this new growing crust, which forms lineations parallel to the flow direction (*dark stipple*). Jumbled lava forms along shear zones at the margins of lineated areas. At time = t_4, the molten lava has completely drained away, leaving the final configuration with lineated lava in the floor of a collapsed lobate flow

remains in contact with the lowering lava surface on most of the flow but is forced to fracture locally where it is rigidly attached to upright walls and pillars (Fig. 5). This fracturing occurs over and over during lava subsidence as the subsiding crust repeatedly attaches, thickens, becomes brittle, and breaks away from walls and pillars, leaving the evenly spaced stacks of selvages (crust remnants) commonly observed on these structures within collapse areas (Francheteau et al. 1979; Gregg and Chadwick 1996). In contrast, away from walls and pillars, only a single crust subsides along with the underlying lava. On some lava pillars, the subsiding crust slowly scrapes the viscous sides of the pillar instead of periodically attaching and breaking free, which forms vertical grooves instead of horizontal selvages (Francheteau et al. 1979). Eventually the rate of lava subsidence decreases due to a cessation in the outward spreading of the flow (for drainout), and/or the lava level approaches the lowest elevation of the vent (for drainback).

We interpret that lineations form locally on the new lava crust while it is forming on this subsiding lava surface. Specifically, we envision that the lineations are created by the raking of molten lava by a solid overlying crust, and that this occurs as a molten flow interior emerges laterally from beneath an earlier crust within a partially ponded flow that is draining (Fig. 5). This scenario requires that, during lava subsidence, the upstream part of the flow has a solid crust and the downstream part does not. It is not clear exactly how such a condition is established in all cases, but we can envision several possibilities. For example, drainout or drainback may preferentially cause foundering of downstream crust due to strong gradients in velocity and subsidence between upstream and downstream locations. Alternatively, the new crust on the subsiding lava may form progressively from upstream to downstream within a flow. Another possibility is that lineations may be generated at a point where there is a physical constriction in the flow of lava. A narrow point in the flow may help initiate new crust formation, because it would be easier for crust to form and adhere to the flow margins there. Regardless of how it develops, this condition would be somewhat analogous to a partially roofed-over lava tube where lava emerges downstream from beneath a crust (Peterson et al. 1994) or to the situation in which toothpaste lava extrudes from an orifice (Rowland and Walker 1987).

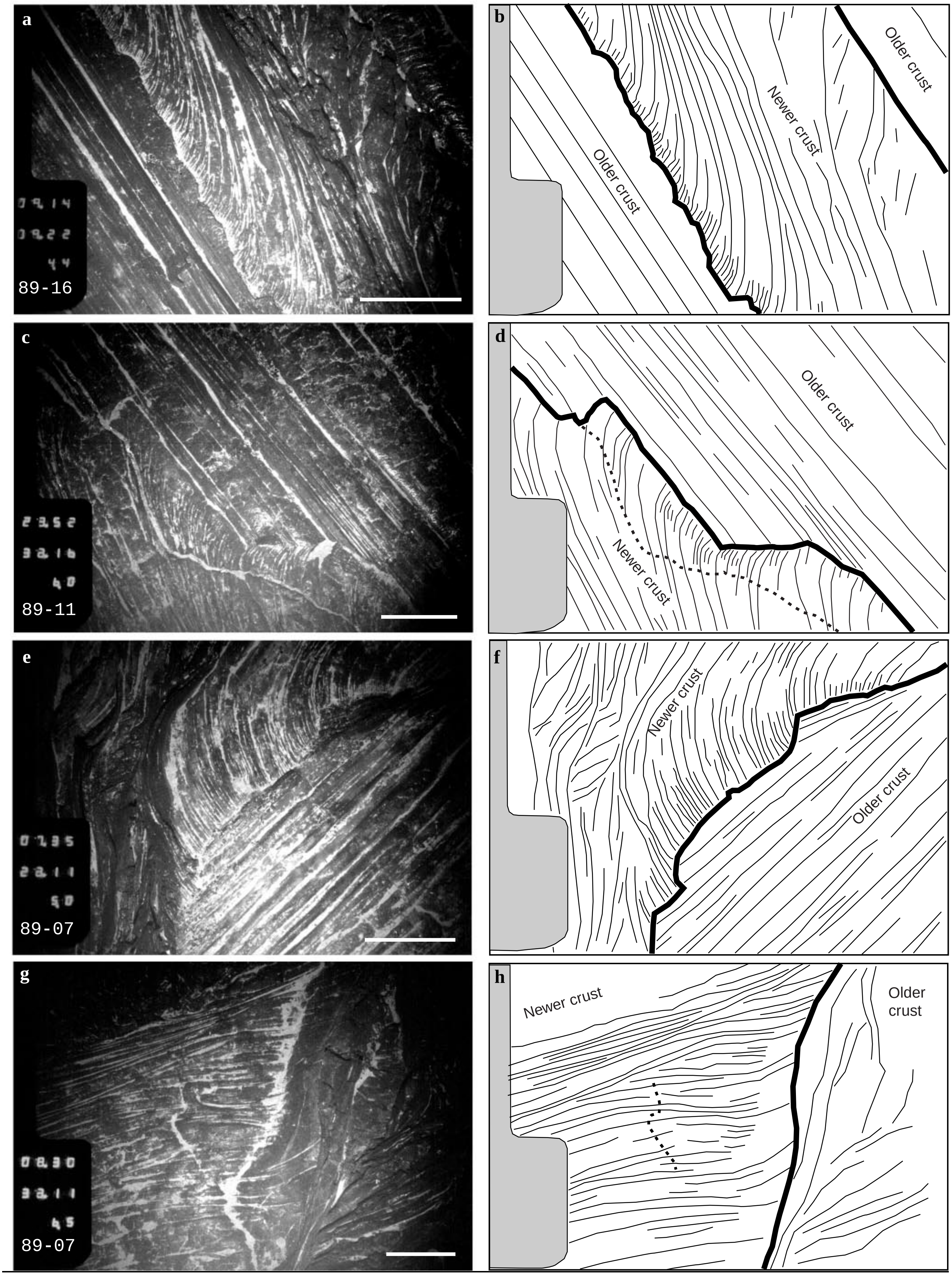
The downstream edge of this upstream crust inevitably has irregularities on it that rake the surface of the molten lava. The lava that emerges from beneath the crust is rapidly cooled by seawater and the indentations from the overlying crust are frozen into the extruding lava surface, forming lineations. The spacing of the lineations is primarily a function of the spacing between any cuspate irregularities on the bottom of the crust. Where the lava is not raked by a cusp, it wells up slightly as it emerges from the crust (due to the pressure exerted on it by the overlying crust and the inherent hydrostatic pressure of the lava), making the intervening bands between furrows convex upward. The greater the distance between furrows, the more the lava surface between them appears billowy in texture. This billowy texture may be the product of small eddies within these zones of upwelling.

Evidence for the interpretation that lineations are formed by raking of crust over lava can be found in photographs of the YSF at Cleft. Locally, the lineated crust cracked and spread apart slightly, apparently during the last stages of flow movement (Fig. 6a–f). Within these small pull-aparts, subsequent lineations are oriented oblique to the lineations on the older crust and perpendicular to the crack boundary, and therefore parallel to the spreading direction that opened the crack. This is clear evidence that the lineations form due to the raking of crust over the underlying molten lava surface. These successive, small-scale pull-aparts with lineations parallel to the spreading direction are also observed on toothpaste lava (Rowland and Walker 1987). Unlike toothpaste lava, however, little or no vertical offset develops between older and newer crust on submarine lineated flows (Fig. 6). Cross-cutting lineations are thus due to more than one generation of crustal raking. In places, the lineations within these late-stage spreading cracks follow an S-shaped pattern, suggesting that a velocity gradient existed across the crack between the two spreading plates (Fig. 6a–d). In other places, curved lineations suggest that crustal plates rotated or changed direction as they moved apart (Fig. 6e–f). The upstream edge of larger lineated areas is marked by lineations emerging from beneath an edge of older crust (Fig. 6g–h).

Discussion

Flow velocity and rate of crust growth must be critical variables in the preservation of lineations on submarine sheet flow surfaces (Fink and Griffiths 1990; Gregg and Fink 1995). If the velocity is too low, a lava morphology other than sheet flow would form instead, such as lobate or pillow lava; if the velocity is too high, the lava surface will have enough time to relax and erase any lineations before the crust solidifies. Photographs in which the lineations are faint and almost overprinted

Fig. 6a–h Camera-tow photographs of the YSF and accompanying interpretive sketches, showing evidence that lineations are formed where molten lava flows out from under the edge of older crust. *Numbers in lower left* of each photo as in Fig. 2. *White bars* are 1 m long. **a, c, e** More than one generation of lineation is present, and older crust has cracked and spread apart to form newer crust (along *bold lines* in **b, d, f**). In each case the younger lineations formed parallel to the apparent direction of crustal spreading. Curving lineations suggest that they formed within a velocity gradient (**a–d**) or where crustal plates were rotating (**e–f**). Lineations at the upstream edge of major lineated areas emerge from beneath an older crust (**g–h**). *Dotted lines* in **d** and **h** are fractures that formed after the lineations were created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Older crust
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Newer crust
Older crust

with billowy texture (Fig. 2f) may have formed near this upper velocity threshold. Laboratory simulations in which molten wax was extruded at a constant rate and temperature beneath cold sucrose solution (Gregg and Fink 1995) identified a specific flow type called "rifted," which was correlated with submarine lineated flows and formed at a particular combination of effusion rate and cooling rate. In this regime, solid plates of wax were separated by zones of liquid wax along which spreading occurred, and flow-parallel crustal stringers were observed to form within this spreading zone. The formation of lineated sheet morphology depends on both viscosity and effusion rate, but if we estimate that a typical mid-ocean ridge basalt is erupted with a viscosity of 10^2–10^4 Pa s, then submarine lineated sheet flows can be associated with volumetric effusion rates of 10–10^2 m^3/s (Gregg and Fink 1995).

This dependence on effusion rate may also explain why the lava flows that preserve lineations on the sea floor and on land are so different in character. On land, lineations are preserved on toothpaste lava, which is more viscous and is extruded at a very slow rate (so the less efficient cooling in air has time to freeze the lineations before they can be smoothed out by the gravity-driven relaxation of the viscous lava). At faster extrusion rates on land the lineations are not preserved. In the submarine environment, however, the lava can be extruded at a higher rate and have the lineations frozen in the flow surface, because seawater rapidly quenches the surface of molten basalt to glass (Griffiths and Fink 1992; Gregg and Chadwick 1996). On the other hand, lava that is extruded at a slower rate underwater forms pillows (which have striations, but not a sheet morphology).

Application to the Cleft YSF

How does this model apply to the YSF at the Cleft segment? Specifically, how can the pattern of lineated areas mapped on the YSF be explained in terms of a later crust forming on the upstream part of the flow during the drainout stage? The YSF can be divided into northern and southern parts connected by a narrow channel within a bathymetric constriction (which we call the "neck point"). All the major lineated areas are south of the neck point, although minor areas of lineations are north of it (Fig. 1). Some of the lineated areas appear to emanate from the neck point (Fig. 1), suggesting that it may have played a key role in the generation of lineated flow surfaces within the YSF. The eruptive fissure for the YSF extended both north and south of the neck point, but Embley and Chadwick (1994) interpreted that most of the YSF lava was erupted from north of the neck point. Because the depth of the sea floor is ~10 m shallower north of the neck point than south (Fig. 1), this implies that throughout the emplacement of the YSF, lava was erupted at its northern end, flowed southward through the neck point, then spread again and continued south.

Once the YSF had spread, inflated, and begun to drain, we envision that the growth of the new lineated crust occurred as follows: Collapse of the initial lobate crust on the flow began in the northern part of the YSF, probably due to waning eruption rate, and progressed from north to south. After collapse started on the northern part of the flow, rafts of new crust formed and moved downstream on the subsiding lava surface. Leading into the narrow neck point, the lava flow converged and rafts of crust coalesced just upstream of the channel constriction, similar to the way some subaerial lava channels are roofed over (Peterson et al. 1994). Camera tows show that the neck point is filled with lineated lava between jumbled levees, consistent with the idea that crust accumulated north of the constriction and formed lineated flow surfaces on the lava flowing out from beneath it. The neck point itself probably roofed over soon thereafter, creating an arrangement in which lineated lava surfaces could be formed and rafted southward over the southern part of the YSF as roof collapse and additional crust resurfacing progressed from north to south. The width of the YSF increases south of the neck point, and to cover this larger area the crust may have undergone further cracking and spreading (perhaps as depicted in Fig. 6), or the solid crust generating the lineations may have continued to grow and extend southward from the neck point until it covered the full width of the flow. On the other hand, the pattern of the lineated areas in the sidescan imagery suggests that the lineated areas south of the neck point were somewhat channelized between shear zones of jumbled lava (Fig. 1b). In any case, we interpret the large lineated areas on the southern part of the YSF to have formed where molten lava emerged from beneath solid crust just south of the neck point and continued downstream with the flowing, subsiding lava until drainout ended and the crust became frozen in its current configuration.

We have used the YSF at the Cleft segment as our primary example, but these relationships have been observed in many other sites along the Juan de Fuca Ridge (R. Embley and W. Chadwick, unpublished data). In fact, lineated lava flows consistently lie within the drained-out interiors of ponded lobate sheet flows wherever they are observed on the Juan de Fuca Ridge. The neck point may have played a key role in the development of lineations on the YSF, but we believe that the Cleft YSF is not unique and that the model presented here applies to submarine lineated sheet flows in general. The various stages of lineated lava formation (flow spreading, inflation, collapse, draining) probably take place within a very short amount of time (hours), which seems to be characteristic of sheet-flow forming eruptions on the mid-ocean ridge (Gregg et al. 1996). For example, the lobate crust on the uncollapsed margins of the YSF, which grew during the initial advancement of lava away from the vent and subsequent flow inflation, is typically ~5 cm thick, implying that it was in contact with the molten lava for only ~1 h before subsidence began (see Fig. 2 of Gregg and Chadwick 1996). The processes of roof collapse and new crust growth during drainout most likely also proceed relatively quickly.

Although we have observed less than 1% of the global mid-ocean ridge system at sufficiently high resolution to identify lineated flows (Perfit and Chadwick 1998), some trends are apparent. Lineated sheet flows seem most common on intermediate-rate spreading centers, such as the Juan de Fuca Ridge, and are less common at fast and slow spreading centers. On slow spreading ridges, where most eruptions form pillowed lavas, the limiting factor is probably eruption rate (Perfit and Chadwick 1998). On the fast-spreading East Pacific Rise, lobate sheet flows with collapse areas and lava pillars are very common, but in many places new lava flows are erupted and confined within a narrow (40–200 m) axial summit trough (Fornari et al. 1998). This geometry forces lava to pond directly over the eruptive vent and limits its ability to spread laterally. When drainback occurs in this setting, the lava either drains straight back down the vent or out through pre-existing holes and caverns in the walls of the summit trough (Fornari et al. 1998). Perhaps volcano-tectonic conditions at intermediate-rate spreading centers are such that the combination of lava viscosity, effusion rate upon eruption, and pre-existing bathymetry are conducive to producing lineated sheet flows. However, lineated lava flows in our model do not represent the conditions during initial lava flow emplacement but instead are the product of lava drainback and/or drainout within lobate sheet flows. Thus, the preponderance of lineated flows at the Juan de Fuca Ridge suggests that the conditions there favor the formation of broad, partially ponded lava flows that are subsequently able to flow laterally as they drain. Perhaps the broad axial valleys at intermediate spreading centers provide the most suitable topography for the formation of laterally extensive sheet flows like the YSF at the northern Cleft segment.

Conclusion

Lineated sheet flows are unique to the submarine environment; some subaerial flows also exhibit flow-parallel lineations, but no subaerial analog is exact. Photogeologic evidence strongly suggests that submarine lineated flows form within the collapsed interiors of partially ponded lobate sheet flows during drainout or drainback. During this process large portions of the primary lobate crust founder and are assimilated into the subsiding, still-molten interior of the flow. While a new crust grows on the draining lava, it repeatedly adheres to, and breaks off from, the surrounding upright walls and lava pillars while it subsides, forming the stacks of regularly spaced selvages commonly observed on these features. Collapse and growth of new crust does not occur on the entire area of the flow at the same time. Instead, lineated flow surfaces form where molten lava emerges laterally from beneath an edge of earlier crust, and irregularities on the underside of that crust rake across the molten lava. Because seawater rapidly quenches the surface of freshly exposed basalt to glass, these lineations are quickly preserved on the flow surface. The continuity of the lineations can be subsequently destroyed within zones of high strain, which deform and break up the flow surface, producing jumbled flow morphology. Lineated sheet flows, therefore, are indicative of a specific history of events during the emplacement of a submarine lava flow.

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References

Ballard RD, Holcomb RT, van Andel TH (1979) The Galapagos Rift at 86°W. 3. Sheet flows, collapse pits, and lava lakes of the rift valley. J Geophys Res 84:5407–5422

Ballard RD, Hekinian R, Francheteau J (1984) Geological setting of hydrothermal activity at 12°50'N on the East Pacific Rise: a submersible study. Earth Planet Sci Lett 69:176–186

Carr MH, Greeley R (1980) Volcanic features of Hawaii: a basis of comparison with Mars. SP-403. NASA, Washington, DC, 211 pp

Duffield WA (1972) A naturally occurring model of global plate tectonics. J Geophys Res 77:2543–2555

Embley RW, Chadwick WW Jr (1994) Volcanic and hydrothermal processes associated with a recent phase of seafloor spreading at the northern Cleft segment: Juan de Fuca Ridge. J Geophys Res 99:4741–4760

Embley RW, Chadwick WW Jr, Perfit MR, Baker ET (1991) Geology of the northern Cleft segment, Juan de Fuca Ridge: recent lava flows, sea-floor spreading, and the formation of megaplumes. Geology 19:771–775

Fink JH, Fletcher RC (1978) Ropy pahoehoe: surface folding of a viscous fluid. J Volcanol Geotherm Res 4:151–170

Fink JH, Griffiths RW (1990) Radial spreading of viscous-gravity currents with solidifying crust. J Fluid Mech 221:485–509

Fornari DJ, Haymon RM, Perfit MR, Gregg TKP, Edwards MH (1998) Axial summit trough of the East Pacific Rise 9°N to 10°N: geological characteristics and evolution of the axial zone on fast-spreading mid-ocean ridges. J Geophys Res 103:9827–9855

Fox CG, Murphy KM, Embley RW (1988) Automated display and statistical analysis of interpreted deep-sea bottom photographs. Mar Geol 78:199–216

Francheteau J, Juteau T, Rangan C (1979) Basaltic pillars in collapsed lava-pools on the deep ocean-floor. Nature 281:209–211

Greeley R (1971) Observations of actively forming lava tubes and associated structures, Hawaii. Mod Geol 2:207–223

Gregg TKP, Chadwick WW Jr (1996) Submarine lava-flow inflation: a model for the formation of lava pillars. Geology 24:981–984

Gregg TKP, Fink JH (1995) Quantification of submarine lava-flow morphology through analog experiments. Geology 23:73–76

Gregg TKP, Fornari DJ, Perfit MR, Haymon RM, Fink JH (1996) Rapid emplacement of a mid-ocean ridge lava flow on the East Pacific Rise at 9° 46'–51'N. Earth Planet Sci Lett 144:E1–E7

Griffiths RW, Fink JH (1992) Solidification and morphology of submarine lavas: a dependence on extrusion rate. J Geophys Res 97:19729–19737

Hekinian R, Francheteau J, Renard V, Ballard RD, Choukroune P, Cheminee JL, Albarede F, Minster JF, Charlou JL, Marty JC, Boulegue J (1983) Intense hydrothermal activity at the axis of the East Pacific Rise near 13°N: submersible witnesses the growth of sulfide chimney. Mar Geophys Res 6:1–14

Holcomb RT, Peterson DW, Tilling RI (1974) Recent landforms at Kilauea volcano. In: Greeley R (ed) Geologic guide to the island of Hawaii: a field guide for comparative planetary geology. NASA CR-152416, pp 49–86

Hon K, Kauahikaua J, Denlinger R, MacKay K (1994) Emplacement and inflation of pahoehoe sheet flows: observations and measurements of active lava flows on Kilauea volcano, Hawaii. Geol Soc Am Bull 106:351–370

Kauahikaua JP, Cashman KV, Mattox TN, Heliker CC, Hon KA, Mangan MT, Thornber CR (1998) Observations on basaltic lava streams in tubes from Kilauea volcano, island of Hawaii. J Geophys Res 103:27303–27323

King JS (1982) Selected volcanic features of the south-central Snake River Plain, Idaho. In: Bonnichsen B, Breckenridge RM (eds) Cenozoic geology of Idaho. Idaho Bur Mines Geol Bull 26:439–451

Lonsdale P (1977) Abyssal pahoehoe with lava coils at the Galapagos Rift. Geology 5:147–152

McConachy TF, Ballard RD, Mottl MJ, Herzen RP von (1986) Geologic form and setting of a hydrothermal vent field at 10°56′N, East Pacific Rise: a detailed study using *Angus* and *Alvin*. Geology 14:295–298

Moore JG (1975) Mechanism of formation of pillow lava. Am Sci 63:269–277

Peck DL (1966) Lava coils of some recent historic flows, Hawaii. US Geol Surv Prof Pap 550B:148–151

Perfit MR, Chadwick WW Jr (1998) Magmatism at mid-ocean ridges: constraints from volcanological and geochemical investigations. Geophys Monogr 106:59–116

Perfit MR, Fornari DJ, Smith MC, Bender JF, Langmuir CH, Haymon RM (1994) Small-scale spatial and temporal variations in mid-ocean ridge crest magmatic processes. Geology 22:375–379

Peterson DW, Swanson DA (1974) Observed formation of lava tubes during 1970–1971 at Kilauea Volcano, Hawaii. Studies in speleology 2:209–222

Peterson DW, Holcomb RT, Tilling RI, Christiansen RL (1994) Development of lava tubes in the light of observations at Mauna Ulu, Kilauea Volcano, Hawaii. Bull Volcanol 56:343–360

Reynolds JA, Langmuir CH, Bender JF, Kastens KA, Ryan WBF (1992) Spatial and temporal variability in the geochemistry of basalts from the East Pacific Rise. Nature 359:493–499

Rowland SK, Walker GPL (1987) Toothpaste lava: characteristics and origin of a lava structural type transitional between pahoehoe and a‘a. Bull Volcanol 49:631–641

Smith MC, Perfit MR, Jonasson IR (1994) Petrology and geochemistry of basalts from the southern Juan de Fuca Ridge: controls on the spatial and temporal evolution of mid-ocean ridge basalt. J Geophys Res 99:4787–4812

Swanson DA (1973) Pahoehoe flows from the 1969–1971 Mauna Ulu eruption, Kilauea volcano, Hawaii. Geol Soc Am Bull 84:615–626

Tilling RI, Christiansen RI, Duffield WA, Endo ET, Holcomb RT, Koyanagi RY, Peterson DW, Unger JD (1987) The 1972–1974 Mauna Ulu eruption, Kilauea volcano: an example of quasi-steady-state magma transfer. US Geol Surv Prof Pap 1350:405–469

Weaver JS, Langmuir CH (1990) Calculation of phase equilibrium in mineral-melt systems. Comput Geosci 16:1–19

Wentworth CK, Macdonald GA (1953) Structures and forms of basaltic rocks in Hawaii. US Geol Surv Bull 994:1–95