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Quantitative constraints on the growth of submarine lava pillars from a monitoring instrument that was caught in a lava flow

William W. Chadwick Jr.

Oregon State University/NOAA, Hatfield Marine Science Center, Newport, Oregon, USA

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[1] Lava pillars are hollow, vertical chimneys of solid basaltic lava that are common features within the collapsed interiors of submarine sheet flows on intermediate and fast spreading mid-ocean ridges. They are morphologically similar to lava trees that form on land when lava overruns forested areas, but the sides of lava pillars are covered with distinctive, evenly spaced, thin, horizontal lava crusts, referred to hereafter as "lava shelves." Lava stalactites up to 5 cm long on the undersides of these shelves are evidence that cavities filled with a hot vapor phase existed temporarily beneath each crust. During the submarine eruption of Axial Volcano in 1998 on the Juan de Fuca Ridge a monitoring instrument, called VSM2, became embedded in the upper crust of a lava flow that produced 3- to 5-m-high lava pillars. A pressure sensor in the instrument showed that the 1998 lobate sheet flow inflated 3.5 m and then drained out again in only 2.5 hours. These data provide the first quantitative constraints on the timescale of lava pillar formation and the rates of submarine lava flow inflation and drainback. They also allow comparisons to lava flow inflation rates observed on land, to theoretical models of crust formation on submarine lava, and to previous models of pillar formation. A new model is presented for the rhythmic formation of alternating lava crusts and vapor cavities to explain how stacks of lava shelves are formed on the sides of lava pillars during continuous lava drainback. Each vapor cavity is created between a stranded crust and the subsiding lava surface. A hot vapor phase forms within each cavity as seawater is syringed through tiny cracks in the stranded crust above. Eventually, the subsiding lava causes the crust above to fail, quenching the hot cavity and forming the next lava crust. During the 1998 eruption at Axial Volcano, this process repeated itself about every 2 min during the 81-min-long drainback phase of the eruption, based on the thickness and spacing of the lava shelves. The VSM2 data show that lava pillars are formed during short-lived eruptions in which inflation and drainback follow each other in rapid succession and that pillars record physical evidence that can be used to interpret the dynamics of seafloor eruptions. *INDEX TERMS:* 3035 Marine Geology and Geophysics: Midocean ridge processes; 3045 Marine Geology and Geophysics: Seafloor morphology and bottom photography; 3094 Marine Geology and Geophysics: Instruments and techniques; 8419 Volcanology: Eruption monitoring (7280); 8429 Volcanology: Lava rheology and morphology; *KEYWORDS:* submarine volcanic eruption, lava flow inflation, sheet flow, lava pillars

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1. Introduction

[2] Lava pillars are unique to submarine lava flows and are common features along intermediate to fast spreading parts of the global mid-ocean ridge system. Lava pillars are tall, narrow pipes of solidified lava that extend between the lower and upper crusts of a lava flow [*Ballard et al.*, 1979; *Francheteau et al.*, 1979]. Lava pillars are only observed in the collapsed interiors of ponded sheet flows, and are never found in pillow lavas. They are similar to lava trees and tree molds found on land [*Moore and Richter*, 1962; *Ballard et al.*, 1979], except that their hollow interiors are cooled by seawater rising from beneath the lava flow, instead of by standing trees. Although recent conceptual models and detailed sampling have advanced our understanding of lava pillars [*Gregg and Chadwick*, 1996; *Gregg et al.*, 1996a; *Chadwick et al.*, 1999; *Gregg et al.*, 2000], the details of how they form has remained under debate because the process had never been observed.

[3] In January 1998, a volcanic eruption occurred at Axial Seamount [*Dziak and Fox*, 1999; *Embley et al.*, 1999], an active hot spot volcano on the Juan de Fuca Ridge in the NE Pacific (Figure 1). The eruption produced a sheet flow with lava pillars as tall as 5 m. The 1998 lava flow overran a seafloor monitoring instrument, called

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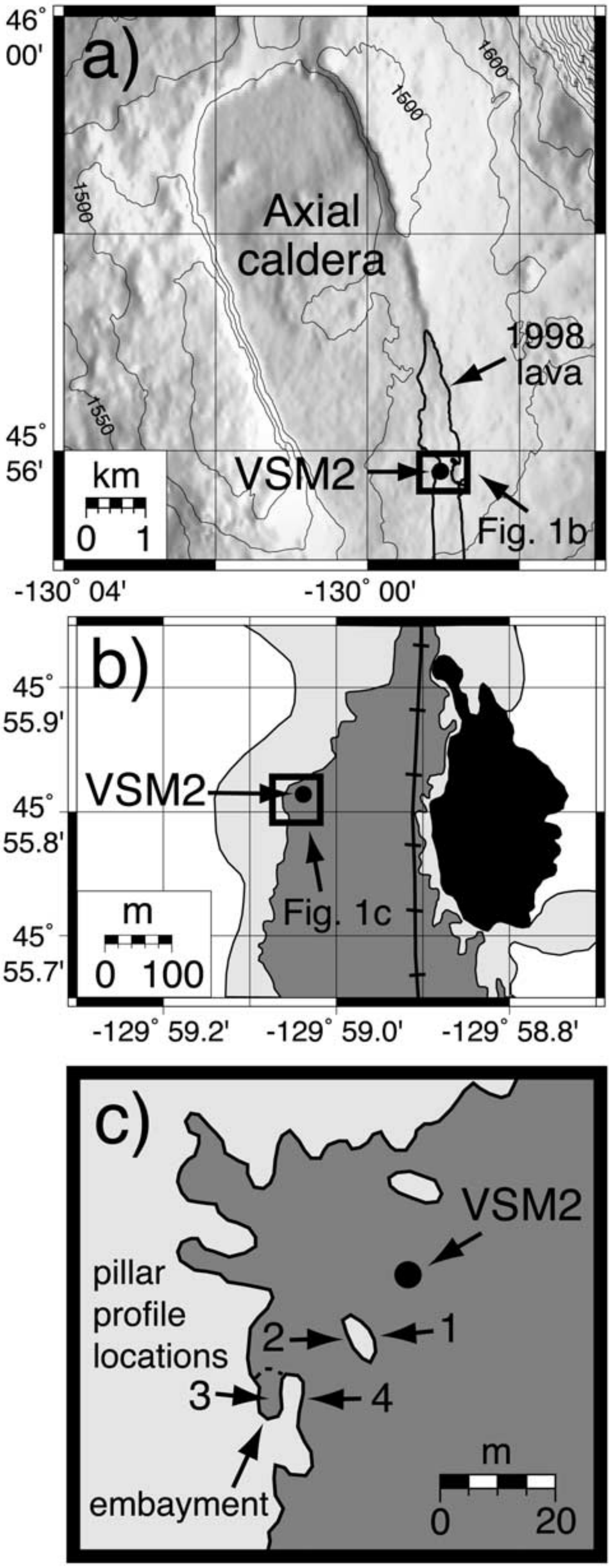
VSM2 (also known as a "rumbleometer"), that had been deployed at the site 4 months earlier [*Fox et al.*, 2001]. Amazingly, the instrument survived and was not buried by lava, because it became embedded in the upper crust of the lava flow, and was later extracted and recovered. VSM2 included a bottom pressure recorder (BPR) which precisely measured the vertical motion of the instrument (and thus a time history of lava flow height) during the eruption. These BPR data show that at the VSM2 site the sheet flow was initially thin (<0.5 m), then rapidly inflated upward over 3 m and then drained out (Figure 2), all within the span of only 2.5 hours [*Fox et al.*, 2001]. These unique data provide the first direct observations and quantitative constraints on the growth of lava pillars during a deep-sea volcanic eruption, and can be used to interpret the eruptive conditions that formed them. The instrumental data also confirm that the structures and textures on lava pillars can reveal information about eruption dynamics on the seafloor.



2. Recent Models of How Lava Pillars Form

[4] "Lobate" morphology on submarine lava flows has generally been treated as a distinct intermediate form between pillow lavas and sheet flows [*Fox et al.*, 1988; *Perfit and Chadwick*, 1998]. However, throughout this paper I use the term "lobate sheet flow", because in my view lobate flows are fundamentally sheet flows. That is, they are just one of the various sheet morphologies (ropy, lineated, jumbled, etc.), although at the moderate end of the extrusion rate spectrum [*Gregg and Fink*, 1995]. The morphology of lobate sheet flows reflects the fact that they advance one lobe at a time, but rapidly enough that the lobes coalesce into an interconnected sheet of liquid lava between a solid upper and lower crust. Lobate sheet flows frequently undergo inflation, drainback, and local collapse of the original upper crust and other lava morphologies can form within those areas of collapse.

[5] Recent models suggest that the formation of lava pillars is intimately related to the inflation of lobate sheet flows, and implies particular eruption conditions and a specific series of events [*Gregg and Chadwick*, 1996; *Chadwick et al.*, 1999]. Lava flow inflation is now recognized as an important process during the emplacement of pahoehoe sheet flows at many scales [*Walker*, 1991; *Chitwood*, 1994; *Hon et al.*, 1994; *Self et al.*, 1998]. Lava pillars form within lobate sheet flows that are

Figure 1. (opposite) (a) Map of the caldera at Axial volcano, showing location of the VSM2 instrument and the outline of the 1998 lava flow. Outline of Figure 1b is indicated. (b) Geologic map showing the location of VSM2 within the 1998 lava flow, based on high-resolution bathymetry and bottom observations. Light grey and dark grey areas represent uncollapsed and collapsed parts of the 1998 flow, respectively. Areas shown in white and black are older surrounding sheet flows and older highstanding pillow lavas, respectively. Cross-hatched line running north-south is the 1998 eruptive fissure. Location of Figure 1c is shown. (c) Detailed geologic map of the immediate area around VMS2, showing the locations where pillar profile measurements were made (Figures 3 and 4) and the location of the embayment discussed in the text. Dashed line indicates probable northern boundary of the embayment when it was fully enclosed, before collapse. Other lava pillars exist along the edge of the collapse area but have not been mapped in detail and are not shown for clarity.

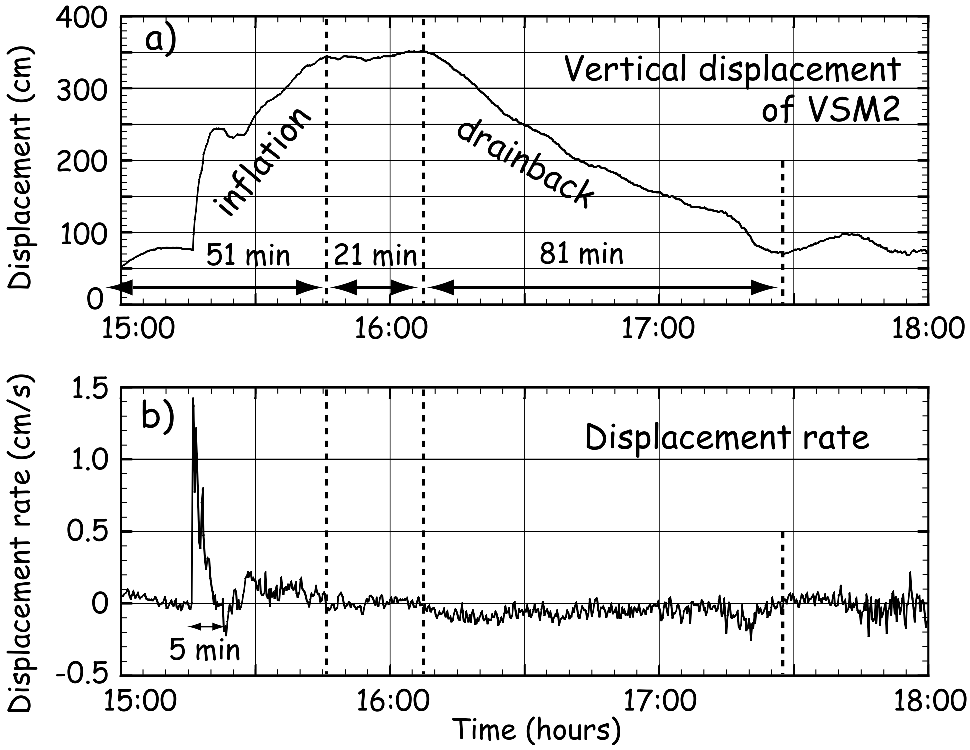


Figure 2. (a) Data from the VSM2 instrument that was embedded in the upper crust of the 1998 lava flow showing vertical displacement of the instrument versus time during the eruption on 25 January (from pressure measured every 15 s). Note that the inflation phase began at 1455 UT, and the first 5 min (and 7 cm) of uplift is not shown. The instrument was uplifted ~3 m during the inflation phase and then set back down during the drainback phase. Zero displacement is arbitrary, but is chosen so that the displacement approximates the thickness of the lava flow with time, because the legs of the instrument were 0.5 m long. (b) Rate of vertical displacement of VSM2 during the eruption, calculated from Figure 2a.

emplaced on relatively flat terrain or within closed depressions. The model of *Gregg and Chadwick* [1996] envisions that lobate flows initially spread out as thin sheets (~20–30 cm thick), and the sites where lava pillars will grow begin as small gaps between adjacent lobes of lava. These gaps are quickly frozen in place because they are locations where seawater that is heated beneath the flow can escape upward [*Gregg and Chadwick*, 1996]. Alternatively, some lava pillars may form above preexisting hydrothermal vents or along preexisting fractures [*Gregg et al.*, 1996a, 2000; *Engels et al.*, 2003].

[6] The idea that pillar locations are frozen in place while the flow is still thin is supported by observations of inflating pahoehoe sheet flows at Kilauea Volcano, Hawaii [*Hon et al.*, 1994; J. Kauahikaua, personal communication, 2002]. On land, wherever an obstacle stops the advance of a sheet flow long enough to cause the flow front to freeze, a pit will subsequently form there when the flow later inflates around the obstacle. These pits are small versions of the larger "lava rise pits" and "plateau pits" described previously in inflated lava flows [*Walker*, 1991; *Chitwood*, 1994]. The pit remains even after the lava has inflated to a thickness greater than the height of the obstacle. In other words, once the flow front freezes around the obstacle, the presence of the obstacle itself is no longer important: it is the frozen crust around the obstacle that prevents lava from filling in the pit. During inflation this barrier of frozen crust is extended upward. At Kilauea Volcano, examples of such obstacles have included rock walls, garbage cans, and even individual rocks as small as few 10's of cm across [*Hon et al.*, 1994; J. Kauahikaua, personal communication, 2002]. On the seafloor, seawater that rises up between lava lobes from beneath the flow creates local thermal obstacles to flow advance that are analogous to the physical obstacles discussed above. The idea that gaps between lava lobes serve as the nucleation sites for lava pillars is also supported by the fact that the tops of lava pillars are often funnel-shaped remnants of interlobe junctions [*Ballard et al.*, 1979; *Francheteau et al.*, 1979; *Gregg and Chadwick*, 1996].

[7] On the seafloor, lava flow inflation begins after the lateral advance of the sheet flow is retarded or stopped, either by thickening crust at the flow boundaries or by topographic barriers [*Gregg and Chadwick*, 1996]. During inflation, the upper solidified crust of the flow is uplifted while molten lava continues to be injected into the flow interior from the eruptive vent. When the eruption wanes and inflation ends, drainback quickly follows. During drainback, the molten lava in the interior of the flow subsides as it either drains back into the vent or drains away downslope (both referred to as "drainback" hereafter). As this happens,

the original upper crust of the lava flow collapses where it is left unsupported in the middle of the flow and this suddenly exposes cold seawater to the subsiding molten lava, which immediately begins to form a new crust. The crust on the subsiding lava repeatedly adheres to and breaks off from any vertical surfaces within the flow such as lava pillars or walls [*Francheteau et al.*, 1979]. The outer surface of lava pillars are thus covered with evenly spaced horizontal "shelves", "ledges", or "selvages" (referred to as "lava shelves" hereafter), which are stacks of thin lava crusts (1–2 cm) that were left behind like bathtub rings during the drainback phase (Figure 3). In summary, lava pillars are seawater conduits between the upper and lower crusts of submarine lobate sheet flows. They grow upward during the inflation phase, and lava crusts are added to their sides during the drainback phase. They are exposed where the original upper crust has collapsed to reveal the drained out interior of a sheet flow.

3. Quantification of Lava Inflation and Drainback Rates During the 1998 Eruption

[8] This hypothesized sequence of events was largely confirmed by the BPR data recorded by VSM2 during the 1998 eruption at Axial Volcano [*Fox et al.*, 2001], but the BPR data also provide rate information for this process for the first time. The BPR instrument measures ambient pressure on the seafloor every 15 s with a Paroscientific digiquartz pressure sensor [*Watts and Kontoyiannis*, 1990]. The pressure data can be converted to depth, the effects of the tides removed, and the data can then be displayed as relative vertical displacement. The details of the data processing methods are described by *Fox* [1990, 1999]. Because the VSM2 instrument was embedded in the upper crust of the lava flow as it inflated and drained, the BPR data quantify the rate of vertical displacement of the upper lava crust during the eruption.

[9] The BPR data from VSM2 (Figure 2) show that initially the lava flow was thin enough to flow under the instrument (which had 0.5-m-long legs). The exact time that the eruption began is not known, but presumably it was only minutes before VSM2 began to be uplifted (at 1455 UT on 25 January 1998). Once the flow started thickening, the instrument was uplifted 30 cm during the first 21 min. Rapid inflation of the lava flow then took place in two main stages that were separated by a brief pause. The first stage was the most rapid and uplifted the instrument 168 cm in only 5 min, an average rate of 32 cm/min (but an instantaneous rate as high as 73 cm/min). Then inflation paused for the next 4 min while the flow subsided 13 cm. When inflation resumed, the flow surface uplifted another 113 cm over then next 21 min, an average rate of 5.5 cm/min, about 6 times lower than the previous rate. The flow then remained near this fully inflated thickness, uplifting only another 7 cm over the next 21 min, before drainback began abruptly. Once the drainback phase began, the upper surface of the lava subsided 281 cm in the next 81 min, at a fairly uniform rate of 3.5 cm/min (Figure 2). This rate is an order of magnitude slower than the average rate of inflation during the initial, fastest stage. The entire inflation and drainback cycle lasted only 153 min [*Fox et al.*, 2001]. At the end of the eruption only 1 m of new lava remained under the instrument (it ended 0.5 m higher than it started, plus the 0.5 m height of the legs).

4. Comparison of Rates, Measured Pillar Profiles, and Implications

[10] On land, fluid basaltic lava flows have been observed to begin as thin sheets (<0.5 m) and then rapidly increase in thickness, in environments both proximal to and distant from the eruptive vent. In the proximal environment, this occurs when lava discharges out of an eruptive fissure at a faster rate than it can move away (J. Kauahikaua, personal communication, 2002). In the distal environment, lava flows increase in thickness by slow inflation, as high internal pressure within a flow gradually raises the solid upper crust [*Hon et al.*, 1994; *Kauahikaua et al.*, 1998]. Below, the term "inflation" is used to refer to both of these processes, to emphasize the similarity that an upper crust is uplifted over a thickening flow (even though it is acknowledged that the mechanisms of thickening are different, and that this term is generally not applied in near-vent settings). The main difference between inflation in proximal vs. distal settings is that the rate of inflation is much higher close to the vent. This is because proximal inflation is observed during the initial high effusion rate stage of fissure eruptions, whereas distal inflation tends to occur during long-lived, low effusion rate eruptions that build stable lava tube systems. Also, as distance from the vent increases, the lava supply reaching any given part of a flow may decrease due to downstream branching of the feeder system. Inflated flows in the distal environment on land commonly lift heavy objects such as cars in their upper crust [*Hon et al.*, 1994].

[11] Inflation in the submarine environment may fall somewhere in between the proximal/distal extremes observed on land. On the one hand, lobate sheet flows form from moderately high discharge rates in the proximal environment [*Gregg and Fink*, 1995]. On the other hand, they have many morphologic similarities with distally inflated flows (including a very flat upper surface and the ability to lift heavy objects in their upper crust, like VSM2), probably because of the higher rate of crust growth underwater [*Gregg and Fornari*, 1998].

4.1. Inflation Rates in the Proximal Environment

[12] On land, in the proximal environment (within 0.1–1 km of the vent), lava flows with a surface crust can rapidly vary in thickness while being directly fed from the eruptive fissure. When such a flow inundates a forested area, lava trees form if the flow inflates and drains out relatively quickly (within hours). For example, at Kilauea Volcano, Hawaii, during the September 1961 eruption, lava trees up to 4 m tall formed in under 3 hours [*Moore and Richter*, 1962], and during the October 1968 eruption lava trees up to 8 m tall formed in under 2 hours [*Jackson et al.*, 1975]. These observations provide a minimum estimate of 2–7 cm/min for the rate of proximal flow inflation during these eruptions. This rate is a minimum because the published time intervals include both inflation and drainback phases and the reported heights of the lava trees do not include the thickness of the flow in which they stand (the bottom of each lava tree is at the base of the flow).

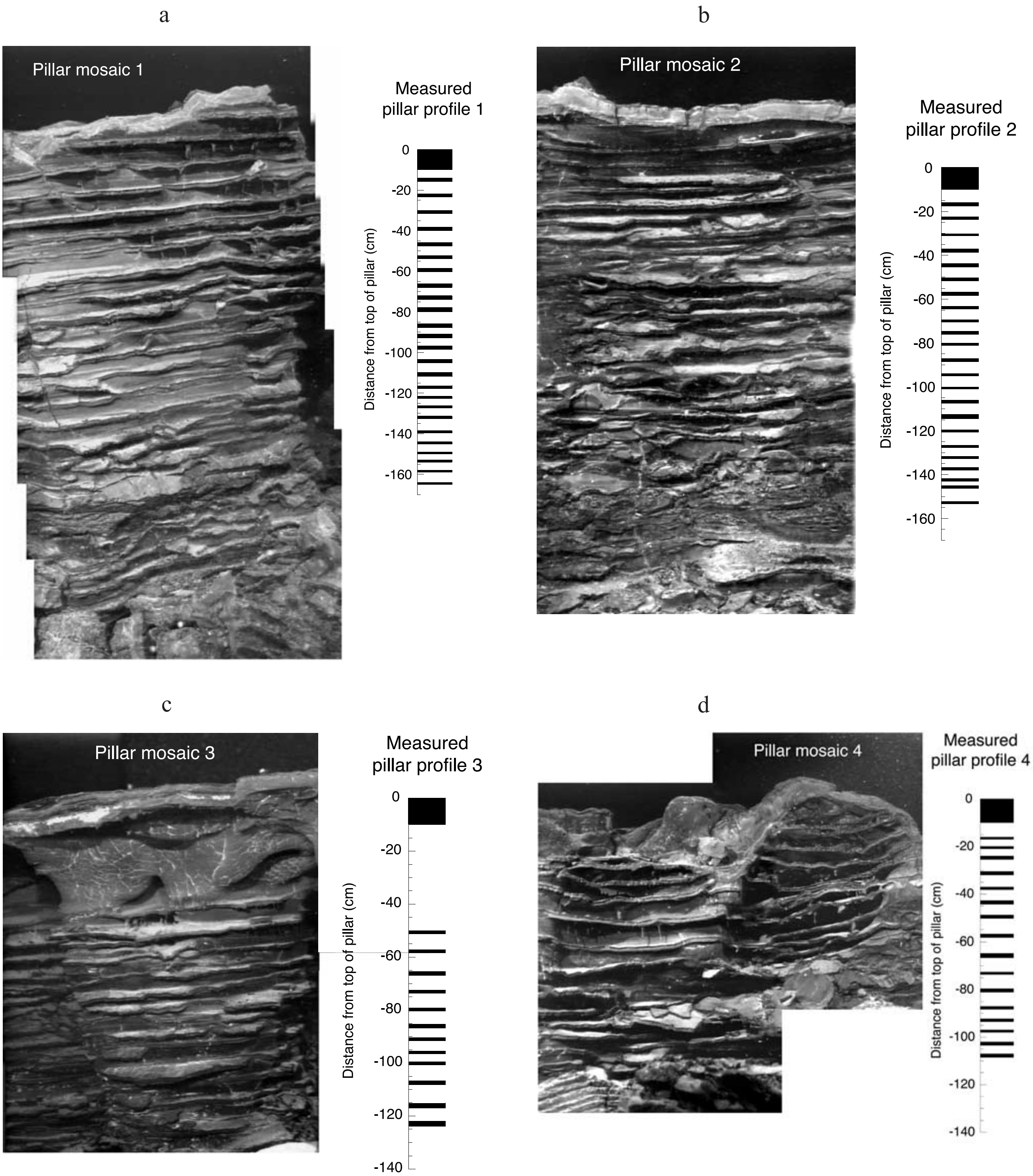


Figure 3. Mosaics of the sides of lava pillars near VSM2 created from video frame grabs collected during a remotely operated vehicle dive (ROPOS dive R630). Lasers spaced at 10 cm apart were used for scale. Each mosaic was used to make measurements of the thickness and spacing of the lava shelves. Measured pillar profiles are shown to the right of each mosaic (black bars represent lava crusts, horizontal length is arbitrary, and vertical scale is not the same as in mosaic). Location of each profile is shown in Figure 1d. (a and b) Profiles 1 and 2 were made on opposite sides of an elongate pillar wall (3 m long, 1 m wide, and 2.5 m tall) made of several coalesced pillars. (c and d) Profiles 3 and 4 were made inside and outside the isolated embayment, respectively, which is discussed in the text (section 7.2). Note the lack of lava shelves in the upper part of profile 3, whereas closely spaced lava shelves formed within that same interval in profile 4.

[13] Lava pillars and lava trees both form in the proximal environment and their rates of formation appear to be similar as well. The rate of proximal inflation on land during lava tree formation (estimated above) is within an order of magnitude of the rate of inflation documented by the VSM2 instrument during lava pillar formation at Axial Volcano in 1998 (5–32 cm/min).

4.2. Inflation Rates in the Distal Environment

[14] In contrast, on land at distances greater than 0.1–1 km from eruptive vents, lava flow inflation takes place where tube systems feed flow lobes on very gentle slopes. Compared to the proximal environment, these distal flows inflate at rates that are lower by 1–2 orders of magnitude, they inflate over longer periods of time (days to months), and they generally solidify in-place without significant lava drainback. Inflation rates documented in the distal environment at Kilauea Volcano, Hawaii, typically peak early (0.3–0.8 cm/min) and decline by over an order of magnitude after the first 10 hours (0.01–0.05 cm/min) [*Hon et al.*, 1994; *Kauahikaua et al.*, 1998]. At these slower rates of inflation the walls of inflation pits are characterized by horizontal V-shaped spreading cracks that extend into the flow away from the pit (J. Kauahikaua, personal communication, 2002). These are analogous to the larger-scale ‘‘liftup caves’’ or ‘‘accordion structure’’ described elsewhere [*Chitwood*, 1994].

[15] The character of inflation pits associated with slow inflation on land is quite different from the narrow glass-lined pipes inside lava pillars, which seem to require higher inflation rates. Therefore lava pillars probably do not form in the distal flow environment on the seafloor, because the distal inflation rates on land (cited above) are much lower than those observed by VSM2. Consequently the inflation rates estimated by *Gregg and Chadwick* [1996] for lava pillar formation (based on distal inflation rates on land) are also probably too low. Instead, other larger-scale inflation features that have been described on the seafloor, such as tumuli and pressure plateaus, most likely form from slower rates of inflation in the distal environment [*Appelgate and Embley*, 1992; *Chadwick et al.*, 2001].

[16] This comparison of inflation rates raises the question: how fast can a submarine lava flow inflate without destroying the lava pillars that are forming within it? We can imagine, for example, that if the rate of inflation were too fast, then lava would be able to flow into the hollow pillar pipes and close them off. *Gregg and Chadwick* [1996] argued that the rate of inflation needs to be less than the rate of crust growth in order for pillars to grow and survive. However, this reasoning now seems flawed because while these two rates are certainly key, they do not act in the same direction. The rate of inflation describes how fast the pillar pipe is lengthening in the vertical direction, whereas the relevant rate of crust growth is in the horizontal direction, perpendicular to the vertical walls of the pillar pipe. Thus their relation to each other is not necessarily one to one. In fact, the maximum rate of inflation measured by VSM2 (1.2 cm/s) is greater than the initial rate of crust growth (~2 mm/s) by about an order of magnitude [*Gregg and Fornari*, 1998]. Of course, another important prerequisite for pillar survival is that there is sufficient flow of seawater up the pillar pipe to cool its interior, thicken crust, and prevent remelting [*Gregg and Chadwick*, 1996; *Gregg et al.*, 1996a, 2000].

[17] The process of pillar lengthening probably occurs in a similar way to how pillow lava lobes grow [*Moore*, 1975; *Gregg et al.*, 2000]. That is, pillars probably grow by periodic cracking and spreading of the crust, except in the case of pillars the crust is the wall of a hollow pipe that is extending and is cooled from the inside, rather than a lava-filled tube that is cooled from the outside. Therefore within a lengthening lava pillar new lava is only exposed within a narrow zone at a spreading crack (probably located near the top of the pillar, beneath the upper crust), and the critical factor for pillar survival is how fast lava spreads away on either side of the crack (at half the inflation rate) in relation to how long it takes for the crust to cool and grow thick enough to prevent lava from flowing into the hollow pipe.

[18] This issue relates to the results from analog experiments which show submarine lava morphology depends on a single parameter relating the rate of crust formation to the rate of lateral spreading [*Griffiths and Fink*, 1992; *Gregg and Fink*, 1995]. From the VSM2 data we know that the maximum permissible rate of inflation for pillar survival is greater than the maximum instantaneous inflation rate measured during this eruption (1.2 cm/s). Theoretical models show that the surface of lava at $\sim$1200°C that is exposed to cold seawater will cool to its solidus temperature in $\sim 10^{-3}$ s, and the thickness of this crust will grow to 1 mm after only 0.2 s [*Griffiths and Fink*, 1992; *Gregg and Fornari*, 1998]. Given the rapid rate of cooling in the submarine environment, I speculate that the rate of inflation could be perhaps an order of magnitude higher than observed during the 1998 eruption at Axial without destroying lava pillars.

4.3. Drainback Rates, Measured Pillar Profiles, and Lava Shelf Formation

[19] Previous authors have assumed that the presence of lava shelves on the sides of lava pillars implied a continually fluctuating rate of lava subsidence during drainback, and specifically that each lava shelf represented a temporary standstill of the ponded lava which alternated with a rapid lowering of the lava surface to form the gaps between shelves [*Ballard et al.*, 1979; *Francheteau et al.*, 1979; *Gregg et al.*, 2000]. However, it is difficult to imagine how such rapid changes in drainback rate could happen so regularly and repeatedly, or why almost all sheet flow eruptions would experience them. Indeed, the VSM2 data clearly show for the first time that lava shelves can form on the sides of lava pillars when lava drains out at a continuous and constant rate, and in fact I believe this is almost always the case. Below, in section 6, I develop a new model for how lava shelves and gaps are created by a rhythmic process during lava drainback at a constant rate. However, first I examine pillars near VSM2 in light of the data it recorded.

[20] The known rate that lava subsided during the drainback phase of the 1998 eruption at Axial Volcano can be compared with the measured thickness and spacing of individual lava shelves on the sides of lava pillars located near the VSM2 instrument. Since the BPR data reveals the height of the upper lava surface with time as it subsided, we can determine the amount of time that it took to form each

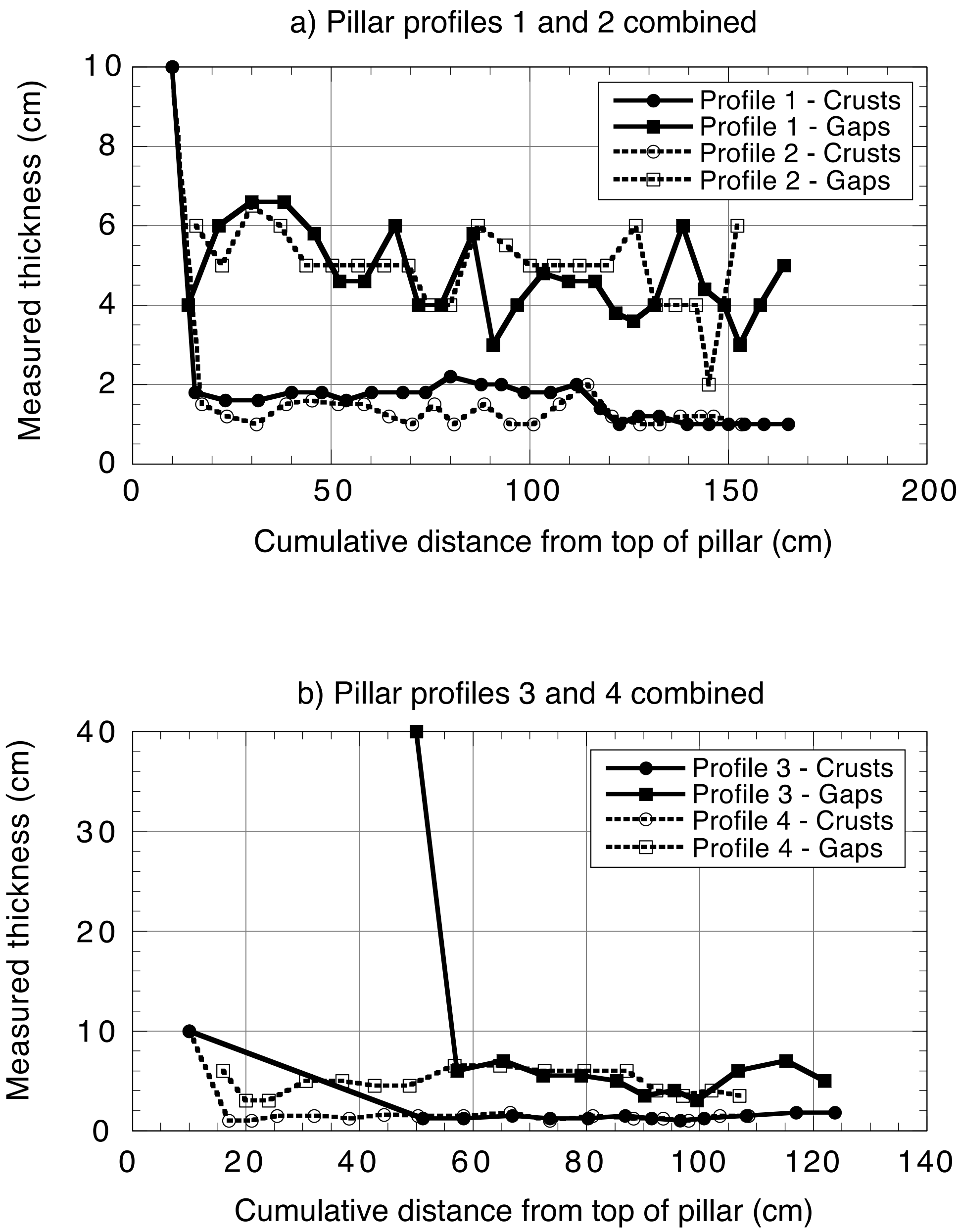


Figure 4. Data from the pillar profile measurements (Figure 3). Plots of lava shelf thickness (circles) and width of gaps between shelves (squares) versus distance from the top of the pillars. (a) Profiles 1 (solid line and solid symbols) and 2 (dotted line and open symbols). (b) Profiles 3 (solid line and solid symbols) and 4 (dotted line and open symbols). Note different scales in the two plots due to the unusually large gap at the top of profile 3.

lava shelf crust on the sides of the pillars. This is because each crust can only grow in thickness while it is in physical contact with molten lava.

[21] To relate the BPR data with the rate of crust formation on the sides of pillars, I made detailed observations of several pillars near the VSM2 instrument, within the collapse area of the 1998 lava flow (Figure 1). Measurements of the thickness and spacing of lava shelves on the sides of the pillars were made from frame grabs of video taken by a remotely operated vehicle (Figure 3). The distance scale in the imagery was determined by a set of lasers that were mounted on the vehicle at a fixed spacing of 10 cm. Four profiles were made at two different locations on each of two pillar structures (Figures 1, 3, and 4). The measurements were made from the top of each pillar downward a distance of 1.0–1.5 m, until the thickness and spacing of the crusts could no longer be clearly distinguished in the imagery. The error of the thickness measurements is estimated to be about ±0.5 cm. The upper surface of inflated sheet flows is nearly horizontal [*Hon et al.*, 1994; *Chadwick et al.*, 1999], as would be the ponded lava surface during drainback, so the same distance downward from the upper crust of nearby pillars represents approximately the same time window during the drainback phase.

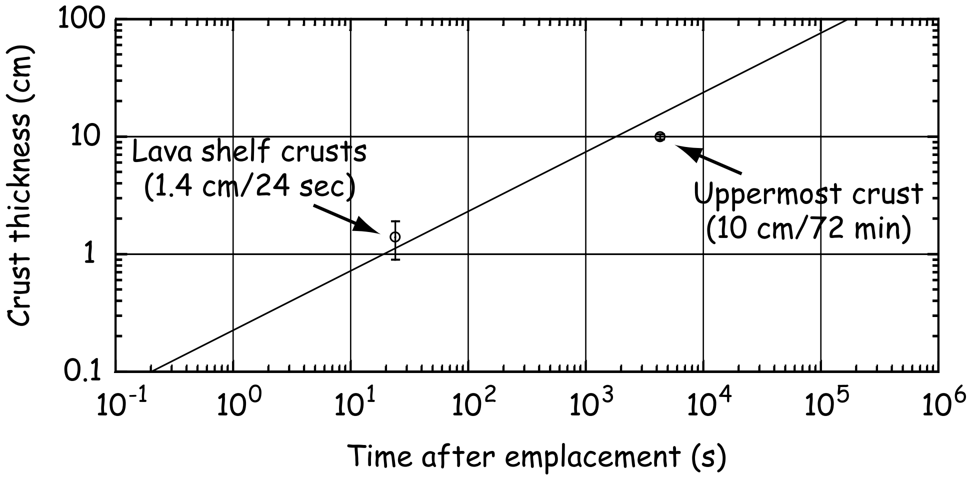


Figure 5. Comparison of lava crusts on lava pillars near VSM2 with a theoretical model for the rate of crust growth on a submarine lava flow from *Gregg and Fornari* [1998]. Error bars for crust thickness measurements (Figures 3 and 4) are ±0.5 cm. The average thickness and the growth time (from the VSM2 data) of the lava shelves on the sides of pillars agree well with the model. The thickness and growth time of the uppermost crust on the 1998 lava flow is less than expected probably because the model assumes that there is no lava input during crust growth, but in this case it is known that the flow was actively inflating.

[22] Profiles 1 and 2 (Figures 1c, 3a, and 3b) were made on opposite sides of a free-standing, elongate wall of coalesced pillars to see how consistent the measurements were on different parts of a single structure. The profile data show them to be fairly consistent within measurement error (Figure 4a). Profiles 3 and 4 (Figures 1c, 3c, and 3d) were made on opposite sides of another wall of coalesced pillars, but this one is near the edge of the collapse area and separates a partially enclosed embayment from the rest of the collapse area. Profiles 3 and 4 are strikingly different at the top (Figure 4b), which will be discussed later in section 7.2. On each of the four pillar profiles (Figures 3 and 4), the uppermost lava crust is 10 cm thick. This crust started forming when lava first reached this location after spreading out from the vent, and it stopped growing when inflation ceased and drainback began. Near the VSM2 instrument, we know that the original uppermost crust (where it is left stranded atop pillars) was in contact with molten lava for about 72 min (this is the time from the beginning of inflation until the beginning of drainback in Figure 2).

[23] All the lava shelves below the top crust are much thinner, with an average thickness of 1.4 cm (σ = 0.3 cm). The gaps between the lava shelves are on average 4.9 cm wide (σ = 1.1 cm), about 3.5 times the thickness of the lava shelves (Figure 4). These dimensions are similar to those found on pillars from the East Pacific Rise where the shelf thickness was 0.5–1.5 cm and the gaps were 6–9 cm wide [*Gregg et al.*, 2000]. At Axial, since the rate of lava subsidence during drainback is known to have been 3.5 cm/min (0.58 mm/s), this implies that each lava shelf was in contact with the subsiding lava for only 24 s, and each gap between shelves represents 85 s during which no crust was forming. In other words, there was a rhythmic cycle of crust formation and gap formation about every 2 min which repeated itself over and over again during the drainback phase.

[24] The measured thickness of these lava crusts and the known time that it took to form them can be compared with theoretical models of crust growth rates on submarine lava flows. Figure 5 shows a plot of the predicted rate of crust growth on a submarine lava flow from *Gregg and Fornari* [1998]. The 1.4-cm-thick lava shelf crusts on the sides of the pillars lie close to the predicted curve, within the estimated error of the thickness measurements. However, the 10-cm-thick upper crust on the tops of the pillars is only half as thick as would be predicted (Figure 5). This discrepancy is likely due to the fact that the theoretical model assumes the lava is stagnant while the crust is growing, whereas in this case, we know that lava and heat were being added to the flow during inflation. Consequently, the upper crust is not as thick as would be predicted by this model. Once inflation stopped and drainback began, however, the lava flow was more or less thermally stagnant and so there is better agreement between the lava shelf crusts and the model.

5. Evidence for Formation of a Hot Vapor Phase During Pillar Formation

[25] A natural question is: what creates the gaps between the lava shelves on the sides of lava pillars, even though the rate of lava subsidence during the drainback phase was nearly constant? *Engels et al.* [2003] and *Perfit et al.* [2003] recently presented convincing evidence that vapor at magmatic temperatures can be created by lava-seawater interaction during deep-sea eruptions. Likewise, I interpret that a transient hot vapor phase forms between the formation of individual lava shelves on the sides of pillars during lava drainback. The main evidence for a vapor phase in the gaps between lava shelves is that lava drips (Figure 6) are commonly observed on the undersides of the lava shelves [*Francheteau et al.*, 1979; *Gregg et al.*, 2000; *Engels et al.*,

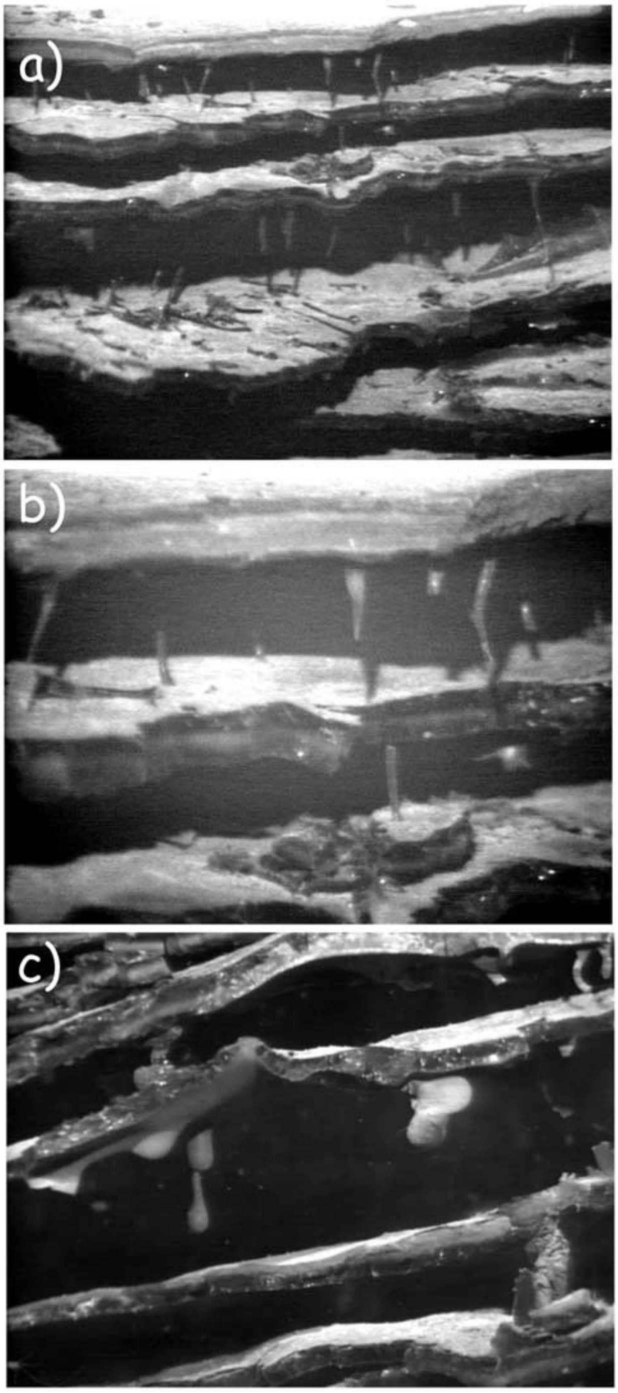


Figure 6. Video frame grabs from a remotely operated vehicle dive (ROPOS dive R630) showing lava drips or stalactites, 1–5 cm long, that formed under lava shelves on the sides of pillars near VSM2. These drips are evidence that a hot vapor phase temporarily existed within a cavity beneath each crust during lava drainback.

2003; *Perfit et al.*, 2003]. Lava drips are lava stalactites, made entirely of glass, that are attached to the bottom surface of lava shelves and extend down into the gaps. In the 1998 lava flow they are typically 2–5 mm in diameter at their base and 1–5 cm long, sometimes extending all the way between lava shelves. The lava drips are clear evidence that there had to be an "empty" space (not filled with lava) that was very hot (not filled with cold seawater) into which the residue of molten lava that had previously been in contact with the underside of a shelves was able to drip [*Engels et al.*, 2003; *Perfit et al.*, 2003]. The temperature of such cavities must be well above the solidus for basalt (>1000°C) for the lava residue to be sufficiently mobile to drip [*Engels et al.*, 2003; *Perfit et al.*, 2003]. Similarly, lava stalactites have also been observed within active lava tubes on land where temperature measurements confirm that the air-filled space above the lava streams is well above the solidus temperature for basalt [*Kauahikaua et al.*, 1998].

[26] Another piece of evidence for the presence of transient hot vapor pockets is the fact that the upper and lower surfaces of lava shelves have very different textures [*Engels et al.*, 2003; *Perfit et al.*, 2003]. The upper surfaces of lava shelves are typically black and glassy, suggesting rapid quenching of a molten lava surface by cold seawater. However, the undersides of the lava shelves and the vertical sides of lava pillars within the gaps have a very different dull, brownish surface texture, apparently due to contact with a hot vapor phase [*Engels et al.*, 2003; *Perfit et al.*, 2003]. Thus the gaps between lava shelves represent a time period when a hot vapor phase existed between the previous lava shelf crust and the subsiding lava surface.

6. A Model for Rhythmic Crust and Vapor Pocket Formation During Lava Drainback

[27] I interpret that the sequence of events during the drainback phase is as follows. Once the lava flow is fully inflated (Figure 7a), the upper crust cannot move downward where lava pillars are holding it up from below. Thus, as soon as drainback starts and molten lava begins to subside under the upper crust of the flow, small cavities are created between the crust and the lava and seawater is immediately sucked or syringed into these spaces through small cooling cracks in the crust (Figure 7b). This small volume of seawater immediately flashes to steam when it encounters the subsided lava surface and a hot vapor phase is created inside the cavities. The temperature of the vapor phase is >1000°C, hot enough to allow lava residue on the underside of the upper crust to drip into the cavity [*Engels et al.*, 2003; *Perfit et al.*, 2003]. The volume of these vapor-filled cavities gradually increases with time as the lava level continues to lower. Eventually, the lava level has subsided enough that the upper crust is no longer supported, except near lava pillars and walls, and it fails. When this happens cold seawater rushes in, the vapor phase is condensed, and all the formerly hot surfaces (including the lava drips) are quenched (Figure 7c).

[28] As soon as the upper crust fails and seawater is in contact with the molten lava again, it starts to form a new crust on its upper surface (Figure 7c). This new crust adheres to the sides of lava pillars and any other vertical surfaces. For a short time, the growing crust keeps in contact with the subsiding lava, but eventually the crust grows sufficiently thick (>1 cm) to become semirigid and since it is attached to the pillar it is eventually left behind by the subsiding lava. The stranded crust on the pillar creates another small cavity below it, because away from the pillar the new upper crust remains in contact with the lowering

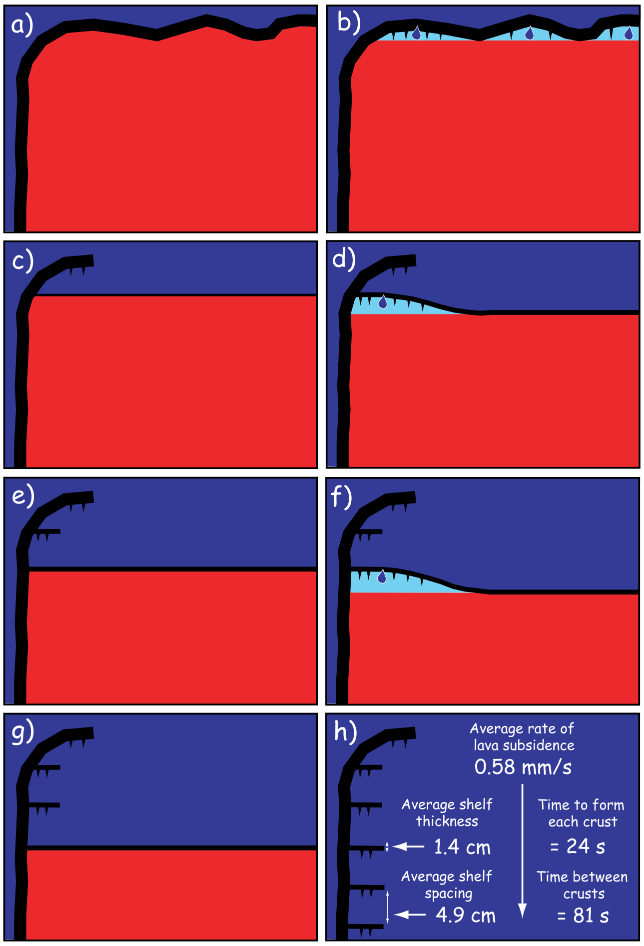


Figure 7. Model for the rhythmic formation of vapor cavities and lava shelves during lava drainback at a continuous, steady rate. See an animation of this model in the auxiliary material. The left edge of each figure is the hollow center of a lava pillar. Black is lava crust, red is molten lava, dark blue is cold seawater, and light blue is hot vaporized seawater. (a) Lava flow at the end of inflation is shown. (b) Drainback begins. Small cavities form under the upper lava crust into which seawater is immediately syringed from above. A hot vapor phase forms, allowing lava residue to drip from the upper crust. (c) The upper crust fails where unsupported from below, exposing the lava to cold seawater. A new crust starts to form on the subsiding lava which attaches to the side of the pillar. (d) As drainback continues, the new lava crust becomes perched and a new vapor cavity forms, this time only adjacent to the pillar because the crust stays on the lava surface away from the pillar. (e) The perched crust fails creating a lava shelf with quenched lava drips. (f and g) The process repeats until drainback ends. (h) The average thickness and spacing of lava shelves are shown with the time it took to form them, based on the rate of drainback measured by VSM2 during the 1998 eruption.

lava surface (Figure 7d). In three dimensions, this cavity extends on all sides of a pillar, and its shape is like a wide, conical tent with a circular base and a very thick pole at the center. The new cavity again immediately becomes filled with a hot vapor phase as before, and new lava drips form on the underside of the stranded crust. To create a cavity, the crust of the lava shelf must be plastic enough to bend slightly as the lava lowers, but brittle enough to break when the lava has fallen too far. In fact, many of the lava shelves remaining on the sides of pillars are bent downward slightly (Figure 3) [*Gregg and Chadwick*, 1996; *Gregg et al.*, 2000]. When the stranded crust eventually fails, seawater rushes in, the lava drips are quenched, and the lava surface that had been exposed beneath the vapor cavity starts to form a new crust (Figure 7e). This next crust adheres to the pillar, the lava level continues to lower, and the process repeats, ending with a set of nearly evenly spaced lava shelves on the side of the pillar (Figures 7f–7h). An animation of the process depicted in Figure 7 is available in the auxiliary material.[1]

[29] The BPR data show that during drainback this rhythmic process of crust and vapor pocket formation occurred about every 2 min. Each lava shelf grew for about 24 s until it became stranded, after which a vapor pocket developed between the stranded crust and the subsiding lava for the next 85 s, until the crust failed and the cycle repeated (Figure 7h). This new model can explain the regular spacing and uniform thickness of lava shelves on the sides of lava pillars and walls without having to call upon rapid and recurrent changes in the rate of lava drainback.

[30] This same process could occur away from lava pillars, wherever there are vertical structures that support the upper crust (at least temporarily). For example, near the edge of a lobate sheet flow, where the flow is thin and has not inflated substantially, individual lobes may have a dome-shaped crust over a molten core. If such lobes are hydraulically connected to the rest of the flow, then during drainback the lava level within them may also subside, leading to the formation of a vapor cavity and possibly the collapse of the unsupported apex of the lobe crust. In such a case, lava shelves might then be rhythmically created on the sloping walls of the interior of the lobe during drainback. Evidence for this scenario can be found at south Cleft on the Juan de Fuca Ridge where detailed mapping of a lobate sheet flow shows that the base level within all the collapse features on either side of the eruptive fissure is the same, suggesting that they were all hydraulically connected during drainback [*Chadwick et al.*, 2001].

7. Discussion

7.1. Temperature and Pressure Within Vapor Pockets

[31] The evidence from lava drips indicates that the temperature in a vapor pocket between a stranded crust and the subsided molten lava surface must be maintained well above the solidus for basalt [*Engels et al.*, 2003; *Perfit et al.*, 2003]. The 1998 lava flow at Axial was erupted at ~1190°C and its solidus temperature is ~990°C (M. Perfit, personal communication, 2002). Each drop of seawater that is syringed into such a cavity would expand in volume by a factor of 20 when flashed to vapor at this temperature [*Keenan et al.*, 1969; *Francheteau et al.*, 1979; *Engels et al.*, 2003; *Perfit et al.*, 2003]. Since the thin, glassy lava

[1] Supporting materials are available at ftp://agu.org/apend/jb/2003JB002422.

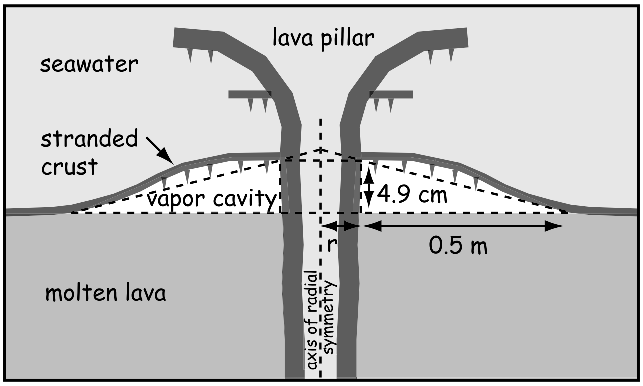


Figure 8. Diagram (not to scale) showing the interpreted shape of a vapor cavity (white) around a lava pillar, between subsiding molten lava below (medium grey) and a stranded crust above (dark grey), overlain by seawater (light grey). The volume of the vapor cavity is crudely estimated by assuming that it has the shape of a right circular cone (dashed black lines), minus the cylindrical volume that the pillar occupies at the center. In the calculations, the radius of the pillar, *r*, is assumed to be between 5 cm and 1 m, and the vapor cavity extends a fixed distance of 0.5 m away from the sides of the pillar. The height of the cavity at the edge of the pillar is 4.9 cm, the average size of gaps between lava shelves measured in this study.

shelves are not strong enough to hold much if any pressure difference across them, I envision that the vapor pockets are maintained very near ambient pressure in a self-regulating way ($\sim$15 MPa at 1520 m for Axial). If vapor expansion creates excess pressure within the cavity then the excess vapor leaks out the tiny cracks in the crust above. On the other hand, as the subsiding lava beneath the crust gradually increases the volume of the vapor cavity, the pressure may lower slightly, causing a little more seawater to be sucked in, which in turn will boost the vapor pressure back up and stop the seawater from entering. This feedback process ensures that only enough seawater enters the cavity to create a vapor phase that is maintained at high temperature and at ambient pressure.

7.2. Volume of Vapor Pockets

[32] During the drainback phase, the extent of most vapor cavities is confined to near individual pillars or wherever the lava crust above is supported by vertical structures. Consequently, the typical volume of most vapor cavities will be relatively small. To make a crude approximation, I estimate that a typical cavity might extend 0.5 m away from a lava pillar (Figure 8). If we assume that the shape of the cavity is a right circular cone (Figure 8) with a height of 4.9 cm (the average gap measured between lava shelves), a flat floor (the lava surface), and a solid vertical cylinder in the center (the pillar), the volume of the cavity depends on the radius of the pillar. For pillar radii between 5 cm and 1 m, the volume of the vapor cavity would range from 0.01 to 0.1 m^3. The surface area of molten lava exposed in the floor of such a cavity would range from 1 to 4 m^2. These volumes are relatively small, but if there are tens or hundreds of lava pillars and other vertical surfaces then the cumulative volume could be substantial.

[33] Near the VSM2 instrument evidence was also found that the volume of individual vapor cavities can sometimes be much larger. About 20 m southwest of the VSM2 instrument there is an embayment in the edge of the collapse area (Figure 1c) in which there are no lava shelves on the upper 40 cm of the lava pillars (pillar profile 3 in Figures 3c and 4c), and yet there are regular shelves below this horizon (Figure 9). In addition, pillars located on the boundary between the embayment and the main collapse area have shelves all the way to the pillar tops on the side facing the collapse area, but not on the side facing the embayment (compare pillar profiles 3 and 4 in Figures 3 and 4). Within the embayment, the interval without shelves has a texture indicative of having formed within a hot vapor cavity, including a dull brown surface texture and droopy lobes of lava residue that were clearly hot enough to flow part of the way down the vertical sides of the pillars before they were quenched. The shadows in the images in Figure 9 show that the bottom edges of these lobes are actually overhung and slightly separated from the pillar wall, suggesting they were evolving into giant lava drips.

[34] The size of this embayment is about 4 $\times$ 6 m in area (Figure 1c), which means the vapor pocket had a volume of 10 m^3, 1–2 orders of magnitude larger than estimated for smaller vapor pockets (above). The drainback rate from the VSM2 data implies that this large vapor cavity remained isolated from seawater for a full 11.5 min before it was breached, about 10 min longer than for the smaller vapor pockets.

[35] Apparently, the upper crust of the flow survived over this embayment longer than it did over the rest of the collapse area after drainback began. In addition, the upper part of the embayment had to have remained physically separated by a lateral barrier from the rest of the lava flow to keep out the seawater that had already flooded the rest of the collapse area, and yet, the lower part of the embayment had to have some fluid communication with the rest of the flow, because the lava level subsided within it along with the rest of the flow. The isolation of the embayment was apparently accomplished by a wall of coalesced lava pillars that existed temporarily between it and the rest of the collapse area. These closely spaced pillars also likely helped support the upper crust and allowed it to remain intact longer over the embayment. Eventually, however, seawater did invade the embayment, either when the upper crust or the lateral pillar wall finally failed or perhaps when seawater gained access to the conduit that was allowing lava drainback from the embayment. Thereafter, lava shelves formed within the embayment as they did throughout the rest of the collapse area. This kind of enlarged vapor cavity is most likely to form only beneath the uppermost crust of a flow, which is always thicker and stronger than the later lava shelves, and near the edges of collapse areas where groups of closely spaced pillars are most likely to form.

7.3. Comparison to Other Recent Models

[36] *Engels et al.* [2003] and *Perfit et al.* [2003] present an alternative model for how vapor is formed during a submarine eruption and how it relates to the formation of lava pillars and other collapse features. In their model,

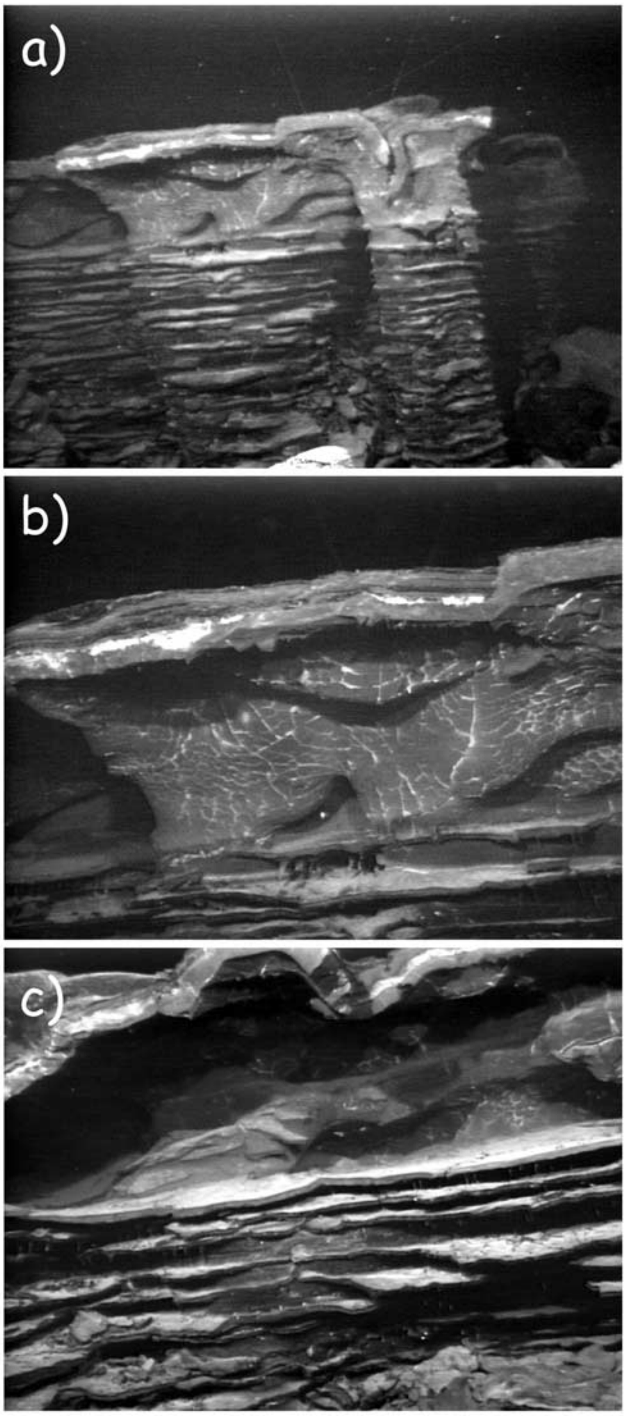


Figure 9. Video frame grabs from ROPOS dive R630 showing the droopy lava texture on the upper 40 cm of lava pillars inside the embayment (shown in pillar profile 3 of Figures 3 and 4, and discussed in the text in section 7.2). Location of the embayment is shown in Figure 1d. The slightly overhanging lobes within this interval are evidence that lava residue was hot enough to flow and that an unusually large cavity of vapor existed within this isolated embayment. See text for discussion.

seawater that is trapped beneath a lobate sheet flow is immediately vaporized to steam. The vapor expands, penetrates the lower crust, rises through the body of the lava flow, and finally collects beneath the upper crust. They envision that this occurs before or during lava flow inflation and that lava pillars could also form in this way. Finally, after inflation ends the vapor cools in place along with the rest of the flow, which leads to a decrease in pressure and collapse of the upper crust [*Engels et al.*, 2003; *Perfit et al.*, 2003].

[37] Their model is very different from the one presented here because all of the above takes place before lava drainback starts, whereas in my model vapor does not form and collapse does not take place until after drainback begins. In fact, in their model the formation of collapse features does not require lava drainback at all, but is primarily due to the widespread accumulation of vapor beneath the upper crust. In contrast, vapor formation and roof collapse are a direct consequence of drainback in my model. Another key difference is that in their model vapor enters a lava flow primarily from below, whereas in mine it enters primarily from above.

[38] On the basis of the VSM2 data and other observational evidence, I find their model problematic for the following reasons: (1) During flow emplacement in seawater the lava surface is cooled and an insulating crust begins to form within a fraction of a second on both the top and bottom of the flow [*Griffiths and Fink*, 1992; *Gregg and Fornari*, 1998]. Because of this, it would be difficult to transfer enough heat fast enough to vaporize a significant volume of water beneath the flow. A striking example of this problem is the temperature record from the VSM2 instrument at Axial Volcano. When lava flowed under the instrument and it became embedded in the upper crust, the temperature recorded inside one of its pressure cases only rose to 7.5°C [*Fox et al.*, 2001]. The three legs and the frame of the instrument, which were in direct contact with the lava, were made from an aluminum with a melting temperature of 600°C, but they did not melt. Clearly, a thin crust was already insulating most of the heat from the lava flow as it encountered the VSM2 instrument. (2) To become vaporized, seawater would have to be completely confined within a small space to prevent the buoyant heated water from circulating away and being replaced by cold water. However, given the rough irregular microtopography of volcanic areas, the generally smooth outer surfaces of lobate sheet flows, the permeable nature of the upper oceanic crust, and the presence of pillar conduits, it is difficult to envision how seawater would be prevented from circulating freely beneath the flow. Indeed, *Gregg and Chadwick* [1996] argued that for lava pillars to survive during lava flow inflation, seawater had to continually circulate up through the pillars from below to cool their inner walls, implying an interconnected network of channels beneath the entire flow, with inflow from the edges. (3) Laboratory analog studies [*Gregg and Fink*, 1995] show that lobate sheet flows do not spread very rapidly, but rather advance one lobe at a time like toey pahoehoe on land [*Hon et al.*, 1994], making it unlikely that such a flow would engulf seawater while advancing. (4) If vapor were to start accumulating beneath the upper crust while the flow was still thin and before inflation, that upper crust would stop growing, since it can

only continue to thicken while in contact with molten lava. However, this is not consistent with observations from Axial where the uppermost crust is always much thicker than the lava shelves and it's thickness is consistent with it having grown continuously up until drainback began. (5) All pillars are hollow pipes with a hole at the top. If vapor rising through the flow from below can create lava pillars, how would such pillars penetrate the upper crust? Also, why would they be systematically positioned at lobe junctions in the upper crust? The tops of pillars do not have a morphology suggestive of explosive penetration from below. Also why would vapor sometimes penetrate the upper crust to form a pillar but other times be trapped beneath that crust in the same flow? Also, how could hot vapor at magmatic temperatures form the glass-lined conduits inside lava pillars, which are indicative of rapid cooling? (6) The idea of the vapor cooling in place after the flow has inflated and before any drainback is not consistent with VSM2 data, which shows that inflation and drainback occurred in rapid succession. (7) If vapor collected under the upper crust before lava drainback, and these pockets were large enough to cause collapse, I would expect to commonly see thick intervals without lava shelves at the tops of pillars, like the one documented in the embayment near VSM2. Instead this is the exception rather than the rule. (8) There is clear evidence for vapor formation between lava shelves during lava drainback. If vapor penetrated the bottom of the flow early in its emplacement and accumulated beneath the upper crust, then that vapor would be released or condensed when the upper crust failed at the beginning of drainback, and would not be available when the lava shelves were forming. At Axial, the gaps between shelves indicate that vapor pockets formed repeatedly about every 2 min throughout the drainback phase, based on the VSM2 data. However, it is difficult to see how the vapor in these cavities could have come from beneath the flow, because by this time the bottom crust would be as thick as the upper crust of the flow, effectively preventing any subsequent water penetration from below.

[39] Both models agree that vapor is intimately involved in the formation of lava pillars and other collapse features in submarine lobate sheet flows. In general, however, I feel the VSM2 data and the other available evidence are more consistent with vapor formation from seawater entering from above after drainback starts, rather than coming from below before inflation begins.

8. Conclusions

[40] There has been growing evidence that sheet flow eruptions on mid-ocean ridges tend to be of short duration and moderately high effusion rate [*Gregg and Chadwick*, 1996; *Gregg et al.*, 1996b; *Perfit and Chadwick*, 1998; *Gregg et al.*, 2000]. In 1998, an eruption at Axial Volcano entrapped the VSM2 monitoring instrument, which survived and recorded the vertical movements of the lava flow's upper crust. The VSM2 data quantify the timescale of the inflation and drainback of a submarine lobate sheet flow for the first time and show that 3- to 5-m-high lava pillars formed in less than 2.5 hours [*Fox et al.*, 2001]. The rate of lava flow inflation that formed the pillars is similar to rates that have formed lava trees on land [*Moore and Richter*, 1962; *Jackson et al.*, 1975]. Both the inflation phase and the drainback phase were continuous and, for the most part, unidirectional. The maximum rate of inflation observed was 1.2 cm/s and the average rate of lava drainback was 0.058 cm/s. Measurements on the sides of lava pillars near VSM2 show that the uppermost crust is 10 cm thick, the average thickness of lava shelves is 1.4 cm, and the average width of gaps between shelves is 4.9 cm. On the basis of the known drainback rate, the lava shelves could only have been in contact with lava for ~24 s, consistent with theoretical cooling calculations. The 4.9-cm-wide gaps between lava shelves represent time intervals of ~85 s during which no crust was being formed. Lava drips within these gaps are evidence that a hot vapor phase existed temporarily beneath each lava shelf crust [*Engels et al.*, 2003; *Perfit et al.*, 2003]. The thickness of the uppermost crust is consistent with it having grown during the 72 min of inflation until lava drainback began.

[41] It is clear from the VSM2 data that lava shelves can form on the sides of lava pillars while lava drains out at a constant rate, and no fluctuations or standstills are required. As soon as drainback begins, small cavities form between the solid upper crust and the subsiding molten lava into which a small amount of seawater is immediately syringed through the permeable upper crust and is flashed to steam. Temperatures are maintained above the basalt solidus within the vapor pockets allowing lava drips to form on the underside of the crust. Eventually the lava has subsided too much and the upper crust fails where it is not supported from below. Seawater immediately condenses the vapor, quenches the upper surface of the suddenly exposed molten lava, and a new crust begins to form which attaches to lava pillars and other vertical surfaces. As the lava level continues to drop the attached crust becomes stranded against the pillars but bends enough to allow new cavities to form below it into which seawater again is syringed and flashes to steam. All subsequent vapor cavities form near pillars or walls, since the new crust stays in contact with the subsiding flow away from these structures. Each cavity lasts until the stranded crust breaks, seawater invades, and a new crust begins to form on the lava. A rhythmic process of alternating crust and vapor pocket formation continues in this way until drainback ends. The same process can occur away from lava pillars wherever there are vertical structures to hold up the upper crust (for example, in individual lava lobes if they are hydraulically connected to the rest of the flow). In this model, the formation of vapor cavities and the collapse of lava crusts are both the natural consequence of lava drainback.

[42] The thickness of lava crusts on lava pillars described from other locations [*Ballard et al.*, 1979; *Francheteau et al.*, 1979; *Gregg and Chadwick*, 1996; *Gregg et al.*, 2000] are similar to those observed within the 1998 lava flow at Axial (~10 cm on the top and ~1–2 cm on the sides), suggesting that the inflation and drainback rates and the overall duration of the eruption documented by VSM2 may be typical for submarine sheet flows. With additional observations these results could be applied to other submarine volcanic areas with lava pillars. Examination of the textures inside and outside pillars can give information about the inflation and drainback phases of the eruption that formed them. The thickness of the lava shelves on the

sides of pillars records the rate of lava subsidence during drainback. The gaps between shelves represent time intervals when a hot vapor phase existed temporarily below a lava crust within small cavities adjacent to each pillar. Documenting the characteristics of lava pillars in diverse mid-ocean ridge environments provides valuable information on lava flow dynamics in the deep ocean that is impossible to derive in any other way.

[43] **Acknowledgments.** Special thanks to Jim Kauahikaua for many helpful discussions about lava flow inflation in Hawaii. The ROPOS group helped rescue the VSM2 instrument in 1999 and collect the pillar profile measurements in 2001 with expert ROV piloting during dives at Axial. The skilled crews of the NOAA ship *Ron Brown* and the R/V *Thompson* and Chief Scientist Bob Embley also greatly contributed to the success of both operations at sea. Hugh Milburn, Chris Meinig, and Pat McLain of NOAA/PMEL's Engineering Division designed and built the VSM2 instrument that was deployed at Axial. Chris Fox generously made the VSM2 data available for this study and Andy Lau processed the data. Charley Weiland created the animation of the drainback sequence depicted in Figure 7 and available in the auxiliary material. Reviews by Dan Fornari and Tracy Gregg substantially improved the manuscript. This research was supported by NOAA's West Coast and Polar Regions Undersea Research Center and the NOAA Vents Program. PMEL contribution 2545.

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W. W. Chadwick Jr., Oregon State University/NOAA, Hatfield Marine Science Center, Newport, OR 97365, USA. (bill.chadwick@noaa.gov)