Journal of Volcanology and Geothermal Research 177 (2008) 837-847

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Emplacement of the 1907 Mauna Loa basalt flow as derived from precision topography and satellite imaging

James R. Zimbelman *, W. Brent Garry, Andrew K. Johnston, Steven H. Williams

Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20013-7012, United States

ARTICLE INFO

Article history:
Accepted 25 January 2008
Available online 11 July 2008

Keywords:
Mauna Loa
Hawaii
DGPS
topography
flow emplacement

ABSTRACT

An eruption in January of 1907, from the southwest rift zone of Mauna Loa, produced a substantial lava flow field. Satellite images and Differential Global Positioning System (DGPS) survey data, along with observations and photographs from the field, are combined to provide a new perspective on the 1907 eruption. Boundaries of the flow field from the satellite data, combined with field measurements of flow thickness, indicate an area of 25.1 km^2 and a volume of 86.6 million m^3. The eastern lobe of the flow field covers an area of 13.1 km^2, with a volume of 55.0 million m^3, and was emplaced with an average effusion rate of 119 m^3/s (at least, for the upper portion of the lobe). Ten DGPS topographic profiles across the eastern lobe aid in distinguishing the characteristics of, and transitions between, the zones identified during the emplacement of the 1984 Mauna Loa flow. Several subdivisions have been built directly on top of or adjacent to the 1907 lava flow. The strong likelihood of future eruptions from the Mauna Loa southwest rift zone makes these housing developments of particular importance for assessments of potential volcanic hazards.

Published by Elsevier B.V.

1. Introduction

Mauna Loa is recognized as the world's largest volcano (e.g., Macdonald and Abbott, 1970, p. 292; Lipman, 1980; Lockwood and Lipman, 1987; Lipman, 1995; Trusdell, 1995). A recent reassessment of the volume of this volcano, including isostatically depressed igneous materials beneath the present mountain, leads to a value of at least 80,000 km^3 (Lipman, 1995). Lavas from Mauna Loa cover 5125 km^2 of the Big Island of Hawaii, with lavas of known historical age (1843 and later) covering 13% of Mauna Loa's surface (Lockwood and Lipman, 1987). Recent mapping has revealed that lava flows have covered the surface area of Mauna Loa at a rate of 30–40% every 1000 years (Trusdell, 1995), with potentially high recurrence rates of burial beneath a new flow near the two major rift zones of the volcano (Kauahikaua et al., 1995). This report focuses on the 1907 eruption from the southwest rift zone, making use of new topographic transects and satellite imaging to provide new insights into the emplacement of this historic flow. Lessons learned regarding the emplacement of this relatively recent major eruption of Mauna Loa have important implications for the people already living on this remarkably active volcano, particularly where housing is situated near or downslope from a rift zone.

* Corresponding author. Tel.: +1 202 633 2471; fax: +1 202 786 2566.
E-mail address: zimbelmanj@si.edu (J.R. Zimbelman).

0377-0273/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.jvolgeores.2008.01.042

2. Background

2.1. Mauna Loa volcano

The subaerial portion of Mauna Loa volcano is the exposed top of an enormous pile of volcanic rock that rises ~9.5 km above the floor of the Pacific Ocean (Macdonald, 1972, p. 275), the result of countless superposed lava flows from eruptions that spanned ~600,000 yr, the first half of which the growing volcano was likely below the surface of the ocean (Moore and Clague, 1992). Enormous landslide deposits have been identified through bathymetry around all of the Hawaiian Islands, including several large slides originating from the southern end of the Big Island (Moore et al., 1989; Eakins et al., 2003). The enlongate shape of the volcano (Mauna Loa means ‘long mountain’ in Hawaiian) is the result of two principle rift zones extending downslope from Mokuaweoweo caldera that have concentrated the growth of the volcanic construct along the axes represented by the southwest rift zone (SWRZ) and the northeast rift zone (NERZ) (Macdonald and Abbott, 1970, p. 303). The SWRZ makes a bend at its southern end to form an en-echelon series of N–S vents, three of which were the sources for lava flows erupted in 1868, 1887, and 1907 (Wolfe and Morris, 1996). The 1907 lava flow is the westernmost of the three historic eruptions on the southernmost subaerial portion of Mauna Loa (Fig. 1) (Barnard, 1995). The primary source for the 1907 flow is a fissure located between 1820 and 2000 m elevation, with small secondary vents east of the main flow at elevations of ~740, ~780 and ~920 m (Wolfe and Morris, 1996). The 1907 lava, outlined in white in Fig. 1, covers 25 km^2, of which 13 km^2 is included within the easternmost branch of the flow field.

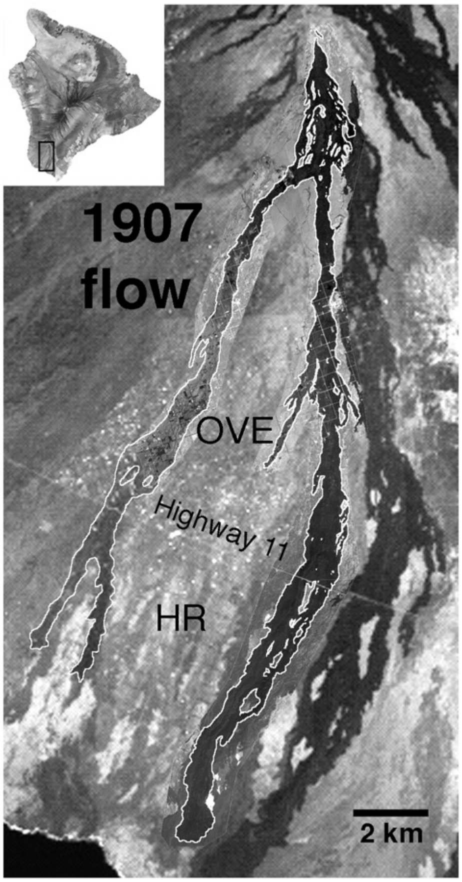

Fig. 1. Regional view of the 1907 flow, surrounded by a white line. OVE stands for Ocean View Estates, HR stands for Hawaiian Ranchos; both are subdivisions with extensive road grids. Landsat image with superposed Ikonos mosaic (data from Hawaii Synergy, 2002).

The general characteristics of all historical eruptions of Mauna Loa from 1843 to 1984 are given in Table 18.1 of Lockwood and Lipman (1987), which indicates a total of 806 km^2 was covered by 4.12 km^3 of lava from 33 separate events. A plot of the cumulative number of historical eruptions as a function of time shows a pronounced increase in eruption frequency between 1870 and 1880 and a definite decrease in eruption frequency since 1950, as compared to what appears to be the more typical eruption frequency for other times (Fig. 1 of Decker et al., 1995). Cumulative rates of coverage by lava flows were derived from mapped relationships where the flows are well dated, a technique that has been applied to the abundant volcanism along the SWRZ of Mauna Loa (Lipman, 1980). Eruptions since 1907 along the SWRZ occurred in 1916, 1919, 1926, all from vents at elevations above 2000 m, including several large flows from the eruption in 1950 (Lockwood and Lipman, 1987; Wolfe and Morris, 1996). The Ka'apuna flow from the 1950 eruption of the SWRZ originated at 2400 m elevation and reached the ocean (on the Kona side of the island) in just over 2 h from the beginning of the eruption (Finch and Macdonald, 1953).

'Surges' must also be considered in relation to the final shape and morphology of Hawaiian lava flows. Surges were commonly observed in the early Kilauea eruptions, as first described by Neal and Decker (1983), where an upflow obstruction can pond lava that is subsequently released in a large pulse. For example, a surge was observed from within the Royal Gardens subdivision on March 3, 1983; a 2-m-high flow front was moving downslope at <1 m/min, but then thickened slowly to 6 m and surged ahead ~200 m in only 30 min, during which time it thinned back down to 2-m thickness (Wolfe et al., 1988). Surges are now recognized as important contributors to overflows that build up levees, and may be a prime factor in breaches of channels that lead to new flow lobes.

Wright et al. (1992) produced a hazard zones map of the island of Hawaii; hazard zone 1 (confined to summit calderas and rift zones) has >25% of the surface covered by lava in the past 200 years, 15 to 25% of the surface area of hazard zone 2 and 5% of hazard zone 3 have been covered by lava during the same time period, with hazard zones 4 through 9 reflecting progressively decreasing frequency of eruptions or areas that are shielded from lava flows by topography. Not surprisingly, the entire 1907 flow field falls within their hazard zones 1 and 2.

2.2. 1907 eruption

Barnard (2002) provides an extensive collection of newspaper and other published accounts of historic eruptions of Mauna Loa, and the following is summarized from his compilation of several eye-witness accounts. The eruption started during the late evening of January 9, 1907, with a strong red glow from the summit area of Mauna Loa clearly visible from Hilo throughout the night, but which rapidly subsided by about 5 am. On January 10 the eruption shifted to the lower SWRZ, where lava reached and crossed the 'Government Road' within two days, on the Kona side of the lava flow of 1887. A second flow lobe later cut the government road a few miles to the west of the first lobe. Visitors who eventually reached the flow itself reported thicknesses of 15 to 30 ft (4.6 to 9.1 m) where both flows crossed the government road, and at the (distal) end it attained a thickness of over 50 ft (15.2 m). The 1907 SWRZ eruption ended after 15 days.

Tabulated data for all historical eruptions of Mauna Loa list the area covered by 1907 lava as 3 km^2 inside the Mokuaweoweo (summit) caldera and 25 km^2 outside the caldera, with estimated lava volumes of 5 and 116 million m^3 inside and outside the caldera, respectively (Table 18.1 of Lockwood and Lipman, 1987). Lipman (1980) gives a volume for the 1907 SWRZ lava of 110 million m^3 as a refinement of the 85 million m^3 volume estimated by Stearn and Macdonald (1946). Decker et al. (1995) use 75 million m^3 as the volume of lava erupted during the 1907 event, without an explanation for the discrepancy with the Lockwood and Lipman (1987) estimated volume. Below we present a new estimate of both the area and volume of the 1907 flow based on mapping of satellite imaging data and numerous field measurements of the margin thickness.

2.3. Development near the 1907 flow

The area around the 1907 flows is the site of the largest subdivision project within the state of Hawaii. The Hawaiian Ocean View Estates subdivision was officially established in September of 1961 (Trusdell, 1995), but the project development started in the late 1950s by the Crawford Oil Company, consisting of Walter and Lillian Crawford and their two sons (Ocean View Chamber of Commerce, 2006). The area is now known collectively as "Ocean View", which encompasses the original Hawaiian Ocean View Estates (north of state highway 11) along with the subsequent developments of Hawaiian Ocean View Ranchos, Kahuku Country Gardens, Kula Kai View Estates, Kona Garden Estates, Keone's Ranchos, and Kona View Estates, cumulatively consisting of ~1500 homes at present (Ocean View Chamber of Commerce, 2006). Here we use the name Ocean View Estates (OVE) to refer to all of the subdivision located north of state highway 11, and Hawaiian Ranchos (HR) for a subsequent development south of the highway and west of the eastern lobe of the 1907 flow (Fig. 1).

An extensive array of paved roads covers OVE in a 1/4-mile (400 m) grid set at a diagonal relative to north, but which allows cars to climb the Mauna Loa slope at an angle that is typically oblique to steepest local slope. Nine ovals are also scattered throughout the road pattern. Lillian Crawford, one of the original developers, named all of the 156 miles (250 km) of roads built within the subdivision (Ocean View

Chamber of Commerce, 2006). South of highway 11, the HR road system has a larger separation between the streets than in OVE itself, and the HR road grid is oriented generally parallel and perpendicular to the direction of steepest local slope. The OVE and HR road system provides excellent access to the central portion of the 1907 flow field, but it has also contributed to much of the original flow surface around the roads to be bulldozed in preparation for future houses, and thus of little use in terms of documenting the lava flow surface attributes. The Kula Kai View Estates and the Kona Garden Estates are on the distal portion of the western 1907 flow lobe, located south of the highway and west of HR, but each is separated from the HR road system and from each other, and both are only accessible from the highway by a single (gated) road.

3. Methodology

3.1. Precision topography

Precision topographic data were collected throughout the OVE area by using a Trimble 4800 (and later a Trimble R8) Total Station, both of which are a carrier-phase Differential Global Positioning System (DGPS). These systems consist of a fixed base station and a roving receiver used to collect the survey data points. The survey rod is equipped with a fixed-height pole and bubble level for accurate positioning of the rod even on a rough lava surface. We also surveyed many of the roads in the OVE area by attaching the roving receiver to a car and collecting data points every 10 s. The data from both the base station and the roving receiver were post-processed in the field using a laptop computer. The horizontal accuracy of locations measured by a DGPS system is ~1 to 2 cm and the vertical accuracy is ~2 to 4 cm, both relative to the base station position; consequently, we report below differences between two DGPS points to the nearest 0.1 m. Base station locations for the different transects were tied together through surveying a common point on the Puu o Kamaoa benchmark (part of the U.S. Geological Survey benchmark system) located immediately south of highway 11 and ~50 m west of Kohala Boulevard. Field notes and digital photography are keyed to the measured point locations along each profile. For reference, the regional slope along the eastern flow lobe, obtained from 1:100K U.S.G.S. topographic maps, is 4.6° above 1680 m elevation, 5.7° between 1680 and 560 m elevation (to highway 11), 4.2° between 560 and 120 m elevation, and 2.4° below 120 m elevation (the flow field is contained between 1980 and 60 m elevation).

3.2. Satellite imaging data

Ikonos commercial satellite images (at 1 m/pixel ground resolution) obtained in January and August of 2001 were merged and georeferenced by researchers at the University of Hawaii–Manoa in order to facilitate the civil defense personnel of Hawaii County in locating houses and road access throughout the OVE area (Hawaii Synergy, 2002). This extraordinary data set reveals information about flow structures and relationships at the decameter scale across the entire eastern half of the 1907 flow field, and the proximal portion of the western half of the flow field. We used the mosaiced Ikonos images (Hawaii Synergy, 2002) at a resolution of 2 m/pixel (1 m/pixel images are available wherever the mosaic included roads and/or houses, but the majority of the flow is presented at 2 m/pixel), in conjunction with Landsat Thematic Mapper data (30 m/pixel) for regional context, as our database for mapping the various zones of the lava flow field, and for interpreting the context of the DGPS survey data.

3.3. Flow emplacement zone documentation

Four morphologic zones (stable, transitional, dispersed flow, flow toe) are used to describe the downstream changes in morphology for the 1984 flow, Mauna Loa Volcano, Hawaii (Lipman and Banks, 1987). Each zone is defined by characteristics of the channel, levees, or lack there of (Lipman and Banks, 1987). Other channeled flows of varying compositions and length scales also exhibit similar morphologic zones (Sparks et al., 1976; Harris et al., 2002; Bailey et al., 2006; Garry, 2006). We identify the stable, transitional and dispersed flow zones for the eastern lobe of the 1907 flow (Fig. 2) based on characteristics of the flow margin and channel from mapping of the Ikonos mosaic and DGPS transects. We only identify three zones because the flow toe represents the active front; therefore, it is not identified here because the flow is already emplaced.

4. Results

4.1. Topography of the eastern flow lobe

Ten DGPS transects across the eastern lobe of the 1907 flow were obtained during field trips in January of 2004, February of 2005, and January of 2006 (Fig. 3). Reduced versions of all ten of the measured profiles are included to the left of the Ikonos mosaic in Fig. 3, shown at the same horizontal scale and at a vertical exaggeration of a factor of three. These profiles, along with field observations and photographs obtained while collecting the DGPS data, provide an assessment of the main events that were part of the complex emplacement sequence represented by this first major effusive activity of the eruption (based on the descriptions of observers published around the time of the

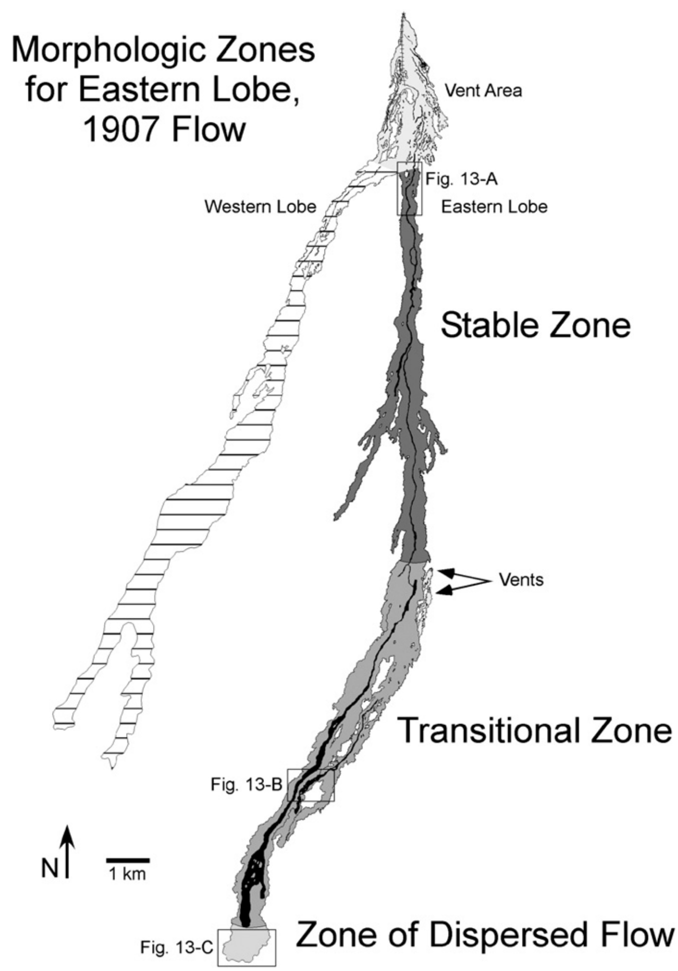

Fig. 2. Map of the morphologic zones (Stable, Transitional, Dispersed Flow) for the eastern lobe of the 1907 flow. Location of the channel is colored black. Boxes indicate field of view for Ikonos image in Fig. 13.

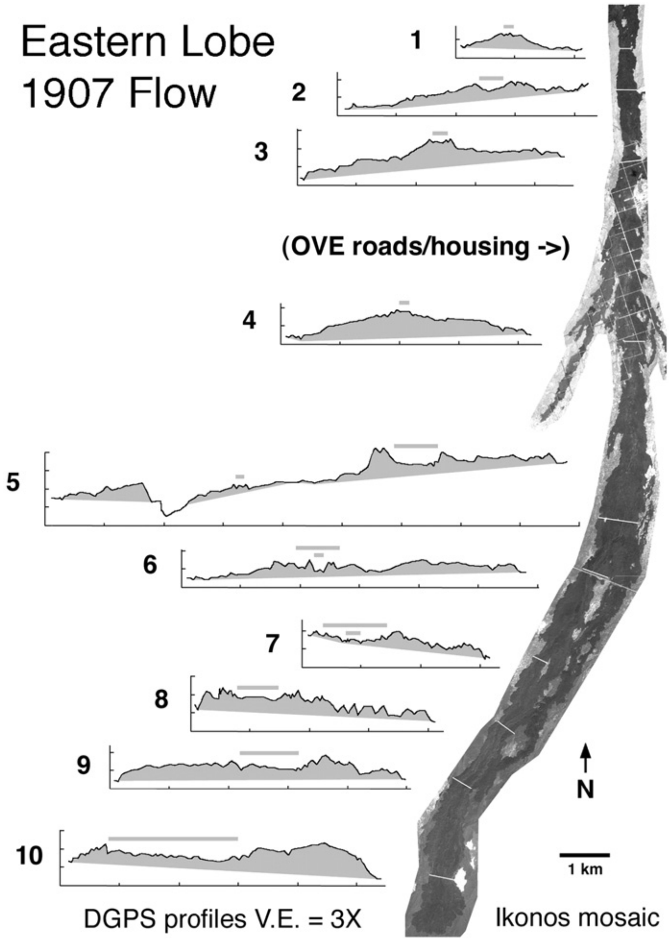

Fig. 3. East lobe of the 1907 flow (Ikonos mosaic), with ten DGPS topographic profiles adjacent to white lines that indicate their location on the mosaic. Flow area within each profile is indicated by dark grey, by connecting low points along base of each profile. All profiles are shown at the same scale; ticks on horizontal axis are 100 m, ticks on vertical axis are 10 m. Light grey bars are above channels in the profile, including two nested channels in profiles 6 and 7.

eruption). Our results benefited greatly from the detailed descriptions and observations of the emplacement of the 1984 Mauna Loa lava flow as documented by Lipman and Banks (1987); the following discussion necessarily includes numerous citations of their work. Several of the profiles show similar topographic and field relationships to those of adjacent profiles, so next we focus on five of the profiles as illustrative of the major components of the eastern flow lobe.

The proximal portion of the eastern lobe (represented by profiles 1 through 3 in Fig. 3) is dominated by emplacement from a single central channel. The Ikonos mosaic provides indications that the eastern lobe was likely beheaded when lava became diverted to the western lobe. In profile 1 (Fig. 4), the central channel is 15.3 m wide (measured between the breaks in slope at the bottom of the interior levee walls), is mostly filled with lava, and is surrounded by levees produced by repeated overflow of lava. The surface exterior to the channel dips 9.2° to both the east and west, away from the elevated central channel, as part of a total width of 187.9 m along profile 1. The overflow levees correspond to ~50 m to either side of the central channel in profile 1, a dimension consistent with the inferred size of the overflow levees in profiles 2 and 3 as well. The lava surface texture in the proximal part of the eastern lobe consists of primarily slabby a'a mixed with some irregular scoriaceous a'a clinkers (using terms from Lipman and Banks, 1987), which suggests that relatively limited collision and grinding occurred between the slabs and clinkers during flow emplacement. This condition is consistent with the Lipman and Banks (1987) observations that slabby a'a is present downslope of the a'a-pahoehoe transition on the 1984 Mauna Loa flow, and the change from slabby to scoriaceous a'a occurred about 5 km from the 1984 source vent. Proximal margins of the 1907 eastern lobe generally are <1 m in thickness, emplaced over a pre-flow surface with relief comparable to or greater than that of the flow itself (e.g., the small kipuka behind the researcher in Fig. 5).

Profiles 2 and 3 are generally similar to profile 1 (see Fig. 3), except that the overall flow width has expanded to 397.2 and 431.5 m, respectively. The central channel on profile 2 is 35.7 m wide and has up to 3 m of relief between the levees and the channel floor, likely related to the expanded channel width at this location. The channel in profile 3 is 26.5 m wide and the channel floor level is intermediate between the filled state of profile 1 and the lowered level in profile 2. We interpret the channel floor variations between profiles 1 and 3 to reflect the local conditions of the last lava to move down the flow as it passed over slight slope variations resulting from the pre-flow topography.

The topography along profile 4 (Fig. 6) is generally similar to that of profiles 1 through 3, with the clear exception of the central channel. The channel narrowed to only 15.9 m wide (measured at the top inner edges of the channel), with nearly vertical walls above a very deep channel. Since we were unable to receive GPS signals from the floor of the channel, a laser ranger and inclinometer was used to measure the channel depth from a position upslope from the profile line (Fig. 7); the measurement gave a channel depth of 12.7 m at a point along the line of the profile path. We interpret this deep channel to be the result of the beheading of the main channel, most likely as lava was diverted to produce the side flow on the western side of the flow lobe, consistent with mapped channel locations immediately north (upslope) of this section of the main flow (Fig. 2).

The channel at profile 4 is paralleled by overflow levees resulting from numerous fluid spillovers (Fig. 7), as was the case for profiles 1 through 3; presumably overflow levees are built up as surges bring lava along the channel at thicknesses that exceed the local channel depth (Lipman and Banks, 1987). The levee slope to the west of the central channel is 4.5° over a distance of 117.6 m, so the overflow levees become less steep and extend further away from the channel as one proceeds from the proximal to more distal portions in the upper reaches of the eastern lobe. This 'spreading' of the levee zone is potentially related to the evolution in lava properties such as crystallinity and bulk density, but we collected no samples with which to test such possibilities. Note that the surface of the levee east

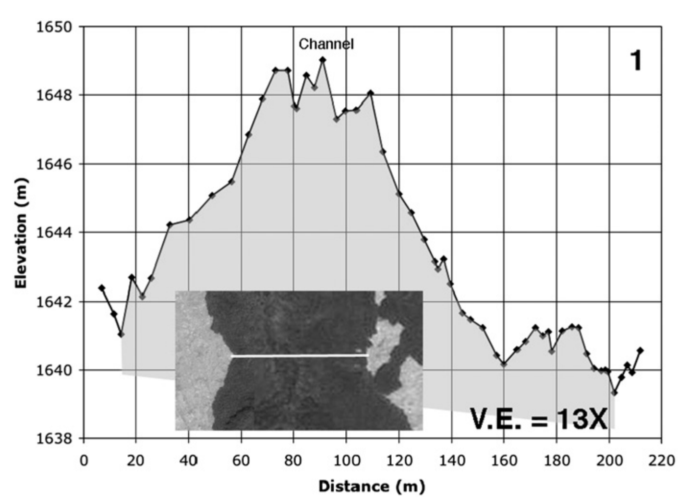

Fig. 4. DGPS profile 1 from the proximal portion of the east flow lobe. Dark grey indicates lava flow portion of the profile. A mostly filled channel is at the top of the profile. Inset shows a portion of the Ikonos mosaic, with a white line at the profile location.

Fig. 5. East margin of eastern lobe of the 1907 flow, along profile 1. Survey rod is on top of the relatively thin margin. Kipuka behind surveyor also illustrates the flow thickness. Flow texture is slabby a'a, indicative of proximal lava.

of the channel is disturbed by a paved road as well as bull-dozed areas adjacent to it, so that we were not confident that the profile near the road was representative of the original flow surface.

The flow reaches a total width of 833.8 m at profile 5, divided into three segments (150.7 m, 202.4 m, and 405.0 m wide, respectively, west to east), separated by two kipukas (Fig. 8). Margin thicknesses for the three flow segments (going west to east) are 2.9 and 10.2 m, 1.7 and 0.2 m, and 0.9 and 5.1 m, for the west and east margins, respectively. Topographic steps in the western segment correspond to three superposed flow units visible in the Ikonos images, stepping up to the thick eastern margin. The largest (western) kipuka includes an 8.0-m-deep channel with 'early' levees (as described by Lipman and Banks, 1987) on a pahoehoe surface weathered to a rusty brown color. The next flow segment includes a small (11.5 m wide) channel with overflow levees, visible in the Ikonos mosaic. The third flow segment includes the main channel (61.0 m wide) that fed the portions of the east lobe further downslope. The channel levees are a mixture of 'deformation' (highly deformed overflow levees) and 'accreted' (channel flanked by ridges of a'a rubble bounded by discrete shear zones) types, as defined by Lipman and Banks (1987); the western levee has 11.3 m of relief and the east levee has 7.3 m of relief. The floor of the channel itself is essentially level across the profile, suggesting that the differing levee heights are indicative of how the flow built up levee heights as needed to confine the channeled flow across the irregular pre-flow topography. The east margin of the flow consists of 'clinkery' a'a, where a'a clots ground against each other (Lipman and Banks, 1987), removing the sharpest spines from the clinkers (Fig. 9).

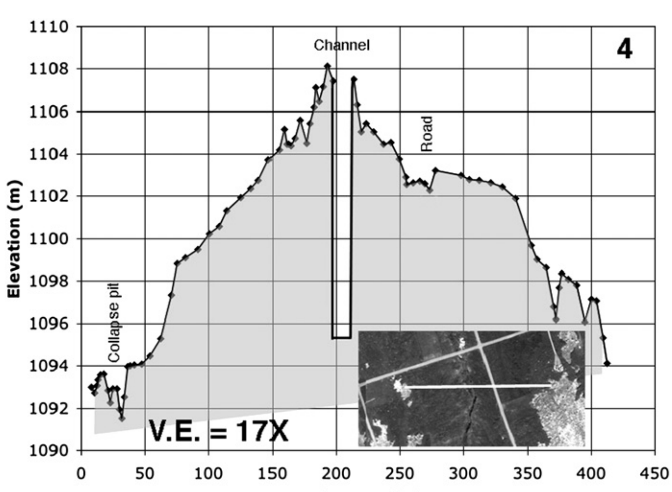

Fig. 6. DGPS profile 4 from the upper central portion of the east flow lobe. Dark grey indicates lava flow portion of the profile. A deep channel is at the top of the profile, a collapse pit is near the western margin, and one of the OVE roads crosses the eastern half of the profile. Inset shows a portion of the Ikonos mosaic, with a white line at the profile location.

Profile 6 (Fig. 3) is a 554.8-m-wide multiple flow located ~50 m north of state highway 11 (roughly the location of the Government Road at the time of the eruption), ~20 m north of an old road over which the highway was built. The western half of the profile includes deformation levees bounding a 89.7-m-wide channel that includes an inner 17.8-m-wide leveed channel. The eastern half of the profile (east of 305 m distance) is a separate flow component superposed on the western section of the flow, covered with a'a that is considerably more spiny than that present on the channeled portion of the flow. We interpret the spiny a'a component to be a breakout flow that likely resulted from an upslope diversion of some late-stage lava; the well-preserved spines suggest limited transport distance for the breakout lava.

Profile 7 (Fig. 3) crosses a section of the flow 292.1 m wide, which includes a channel 107.2 m wide, with a 52.7-m-wide inner channel, analogous to the western portion of profile 6. The east margin of the broad channel is now an isolated 'island', suggesting that much of the eastern levee was eroded and probably carried down flow. Deformation levees dominate the dual-channeled sections of both profiles 6 and 7. Portions of the 1907 flow east of profiles 6 and 7 indicate a complex interleaving of flow segments, consistent with multiple breakouts once well within the transitional channel zone.

Fig. 7. Evacuated lava channel along profile 4 (see Fig. 6). White line denotes the steep channel margins and the approximate location of the channel floor. Overflow levees consist of numerous individual lava deposition events.

The flow is 391.7 m wide at profile 8 (Fig. 10), with the westernmost 235.5 m consisting of a channelized flow component superposed on an earlier portion of the 1907 flow with several 'islands' of remnant levee segments. The main channel is 79.4 m wide, bounded by both deformed and accreted levees having 6.1 m and 5.9 m of relief, west and east. The older eastern flow component has a series of ridges parallel to the flow direction that we interpret to represent the 'lens-shaped ridges' common in the transitional channel zone of an a'a flow, as described by Lipman and Banks (1987). These ridges have from 4.4 to 7.1 m of relief along the eastern half of the profile. Garry et al. 2007) documented and described in detail one of the large remnant 'islands' south of the profile track. Margin thickness is 10.2 and 5.4 m, west and east. Profile 9 (Fig. 3), much like profile 8, is a channelized flow 409.3 m wide, including a 100.3-m-wide channel between accreted levees. The floor of the channel is sloped 2.5° to the east, suggestive of banking of the lava surface as it curved toward the southeast. Flow margin thickness is 8.7 m and 10.4 m, west and east.

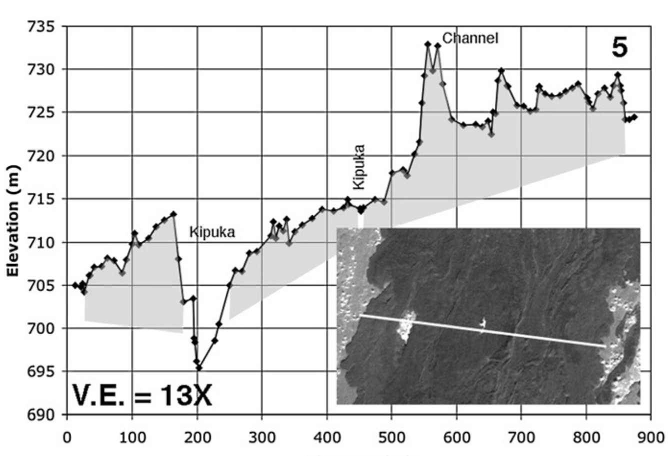

Fig. 8. DGPS profile 5 from the central portion of the east flow lobe. Dark grey indicates lava flow portion of the profile. Three flow components are separated by two kipukas. A mostly filled channel is at the highest part of the profile. Inset shows a portion of the Ikonos mosaic, with a white line at the profile location.

Profile 10 is our most distal survey, where the flow is 510.4 m wide and includes a diffuse channel that is 222.6 m wide (Fig. 11). The channel floor is again sloped 1.0° to the east, as for profile 9, again suggestive of banking as the flow curved toward the southeast. The west margin is 9.7 m high for the irregular outside portion of an accreted levee. The east margin is a broad accreted ridge (and the eastern levee to the diffuse channel), and at 19.3 m of relief it is the thickest margin encountered during our surveying (Fig. 12). The a'a along this profile is clinkery to blocky, including several 1-to-3-m-scale lava balls (some are visible on the thick margin shown in Fig. 10).

South of profile 10, the Ikonos mosaic indicates digitate budding throughout the flow terminus. No apparent channel–levee system is observed.

4.2. Area and volume estimates for the 1907 flow field

The Ikonos mosaic provides an excellent base from which new estimates of the area and volume of the 1907 flow can be derived. The mosaic has a spatial resolution of 2 m per individual picture element (pixel), so that the smallest area that could be measured is 4 m^2. The distal portion of the western lobe is not part of the Ikonos mosaic, so we used instead a portion of a Landsat image (30 m/pixel resolution) to complete the outline of the distal western lobe. Given the uncertainties of mapping the flow outline, plus the larger pixel size for the distal portion of the western lobe, we report areas to the nearest 0.1 km^2 and volumes to the nearest 0.1 km^3. We obtained an area for the entire 1907 flow field of 25.1 km^2, and the area of the eastern flow lobe (beginning where the lobe is distinct from the portion that fed the western flow lobe) is 13.1 km^2, or 52% of the entire flow area. The area of the entire flow field is in good agreement with the value listed in Table 18.1 of Lockwood and Lipman (1987), although we are now confident of the new result to a third significant figure.

The flow outline was then separated into polygons to which we applied thicknesses based on measurements of the flow margin from both the DGPS profiles and from dozens of individual locations along both flow lobes. While the flow definitely includes many irregularities

Fig. 9. East margin of eastern lobe of the 1907 flow, along profile 5. Lava texture is a mixture of scoriaceous and clinkery a'a, where many of the spines have been removed as the clinkers rubbed against each other during transport.

that result in thicknesses greater than (and even less than) the thickness revealed at the margins, we are confident that the margin thickness is the best representative of the vast majority of the flow volume. However, we also recognize that these uncertainties make it unreasonable to cite volumes to better than three significant figures. Application of measured margin thicknesses to the polygons throughout the flow result in an estimated volume for the entire flow field of 86.6 million m^3, and the volume of the eastern lobe of 55.0 million m^3, or 64% of the entire flow volume. The volume estimate is intermediate between values cited by previous authors (summarized above); we are confident that our data are sufficiently precise to lend strong credence to this new estimate. Both the area and volume estimates show that the eastern (earliest) flow lobe contains the majority of material emplaced during the 1907 eruption. We next use these results to refine estimates of the effusion rates for the eruption.

4.3. Effusion rate estimates

Eye witnesses reported that the first (eastern) lobe of the flow crossed the Government Road 'within two days' of the commencement of the flank eruption (Barnard, 2002). Using our volume estimate polygons, we conclude that 20.6 million m^3 of lava was emplaced within the first 48 h, leading to an average effusion rate of 119 m^3/s. At this rate the entire flow field volume could have been emplaced in 128 h, or 5.4 days. Eye witness accounts document the 1907 flank eruption continuing for 15 days (Barnard, 2002), so the east lobe rate clearly was not maintained through the entire eruption. The total flow field volume emplaced within 336 h (15 days) leads to an average effusion rate of 66.8 m^3/s. If the eastern lobe rate of 119 m^3/s was maintained for only the first two days of the eruption, the total

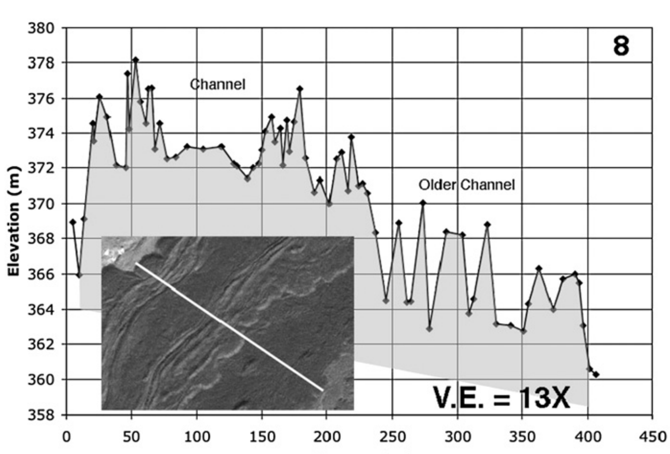

Fig. 10. DGPS profile 8 from the central portion of the east flow lobe. Dark grey indicates lava flow portion of the profile. A broad channel is at the top of the profile; the eastern half of the profile crosses ridges within an older channel. Inset shows a portion of the Ikonos mosaic, with a white line at the profile location.

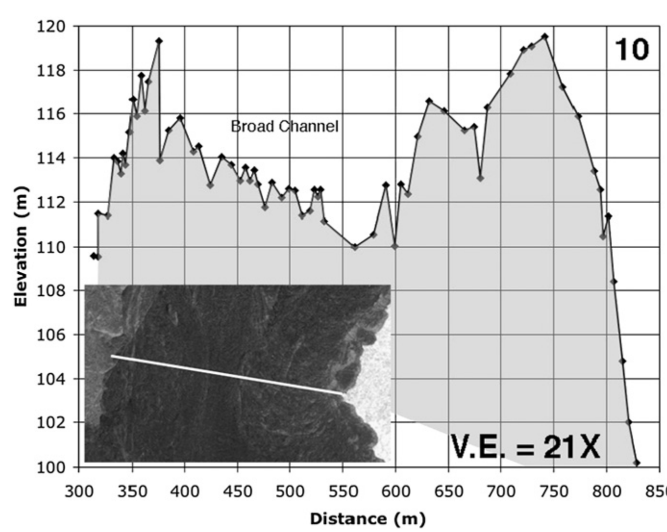

Fig. 11. DGPS profile 10 from the distal portion of the east flow lobe. Dark grey indicates lava flow portion of the profile. A very broad channel is dominates the right (western) part of the profile. Inset shows a portion of the Ikonos mosaic, with a white line at the profile location.

Fig. 12. East margin of eastern lobe along profile 10, showing the thickest margin (19.3 m) measured on the 1907 flow. Several lava balls are visible on the margin talus slope.

flow volume implies the subsequent 13 days of the eruption supplied lava at a rate of 58.8 m^3/s.

The effusion rate estimates derived above are near the middle of the range of effusion rates that can be obtained from the volume and duration values in Table 18.1 of Lockwood and Lipman (1987), where effusion rates for SWRZ eruptions range from a high 356 m^3/s (for the 1868 eruption) to 30 m^3/s (for the 1916 eruption), with the majority of the eruptions in the range of 90 to 120 m^3/s. It is important to realize that rift zone eruptions on Mauna Loa are likely to slow considerably after a very intense start, much as we surmised from the eastern lobe rate. For example, the 1984 eruption (on the NERZ) had an observed effusion rate at the source fissure as high as 800 m^3/s during first 6 h, followed by 140 to 280 m^3/s for the next 12 days, and then slowly diminished thereafter (Lipman and Banks, 1987). Moore (1987) determined a volume flow rate of 55.6 m^3/s in the 1984 channel at a location 15 km from the vent. We conclude that the 1907 eruption sequence was likely comparable to the well-documented 1984 eruption. For comparison, lava flux rates documented for the first 18 episodes of the on-going Kilauea eruption include an initial eruption rate of 308 m^3/s at the source fissure on January 7, 1983, with rates of 10 to 50 m^3/s for phases 2 through 18, although the second flow of phase 13 reached a rate of 146 m^3/s (derived from data in Table 1.3 of Wolfe et al., 1988).

4.4. Emplacement zone mapping

The morphology of the eastern lobe of the 1907 flow changes systematically downstream as evident in both the Ikonos mosaic and DGPS transects (Figs. 2 and 3). These changes are consistent with the morphologic zones defined by Lipman and Banks (1987) for the 1984 flow on Mauna Loa volcano. We have adopted this classification scheme and applied it to the 1907 flow. All four profiles 1 to 4 have both the topographic and mapped characteristics associated with the stable zone of channeled a'a flow emplacement as described by Lipman and Banks (1987). The upper 9 km of the eastern lobe exhibits a relatively consistent flow width (~0.3–0.5 km) (Fig. 13A) as well as a narrow and deep channel (Fig. 3). We classify this section of the eastern flow lobe as the stable zone.

The beginning of the transitional zone is marked by an increase in both flow width and channel width, as indicated in both the mapping (Fig. 2) and the DGPS profiles 5 to 10 (Fig. 3). The transitional zone is also ~9 km long and multiple, accreted levees bound the channel (Figs. 8 and 13B). The presence of accreted levees is a clear indication that we are now in the transitional zone of the flow (Fig. 2). Channel width continues to increase downstream to nearly ~0.5 km at the widest part of the channel, near the boundary with the zone of dispersed flow, where the channel also exhibits braiding (Fig. 2).

We interpret the zone of dispersed flow to be confined to the distal ~ 0.8 km of the eastern flow lobe (Figs. 2 and 13C). The morphology of the flow in the zone of dispersed flow indicates the flow fanned out as individually coalesced fingers, with no indication that a channel–levee system had formed.

The branching of the channel, braiding, and overflows indicate that the emplacement of the eastern flow lobe was complex. The boundary of the stable and transitional zone is consistent with a change in both the flow velocity and rheology (Lipman and Banks, 1987). The short length of the zone of dispersed flow indicates that lava maintained a high enough flow rate to form a channel along the majority of the length of the lobe until influx of lava was cut off and most likely diverted to form the western lobe. A similar incident occurred during the 1984 flow, where lava was diverted during a breakout of a levee to form Flow 1A, while lava in the original lobe, Flow 1, stagnated (Lipman and Banks, 1987). If a significant amount of lava continued to flow down the eastern lobe in the 1907 flow once the western lobe had been established, we would expect to see a longer zone of dispersed flow. The short length of the zone of dispersed flow indicates that once the western lobe began to form, the majority of the lava was diverted to feed the western lobe, allowing the lava in the eastern lobe to stagnate.

5. Discussion

5.1. Future eruptions from SWRZ

Given the extent of historic lava flows from the SWRZ (e.g., Lipman, 1980; Trusdell, 1995; Trusdell et al., 2002), it seems inevitable that

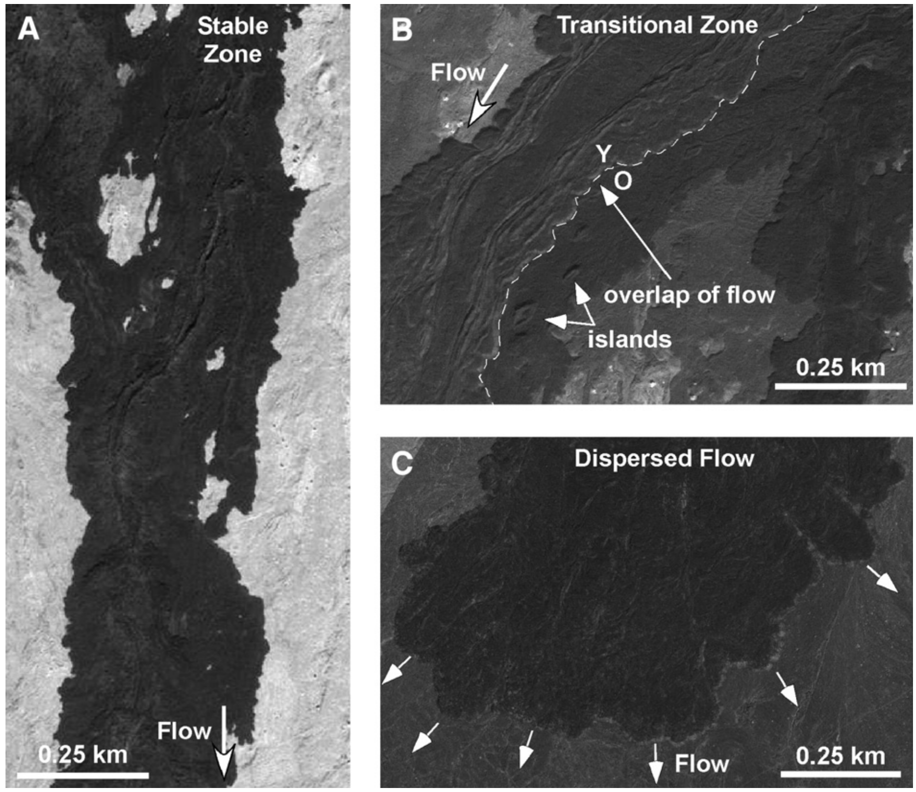

Fig. 13. Ikonos images of the morphologic zones for the eastern lobe. (A) Stable Zone, (B) Transitional Zone, and (C) Zone of Dispersed Flow. (A) Stable zone exhibits a consistent flow width and channel width. Image resolution = 2 m/pixel. (B) Channel width increases and multiple levees are present in the Transitional Zone. Dashed line marks flow margin of a relatively younger portion "Y" that has overlapped a relatively older portion "O" of the same flow. Islands are present in part of the older channel. Image resolution = 1 m/pixel. (C) Individual flow lobes have coalesced forming a fan-shaped flow front. Individual arrows show general flow directions for the lobes. Image resolution = 1 m/pixel. Locations of each image are shown in Fig. 2. Ikonos images courtesy of Hawaii Synergy (2002).

eventually future eruptions from the SWRZ of Mauna Loa will send lava flows through the OVE area. At least 13% of OVE lies within hazard zone 1 (as defined by Wright et al., 1992) and the remaining 87% lies within hazard zone 2 (Trusdell, 1995). The entire OVE area between the eastern and western lobes of the 1907 flow lie within one of 17 mapped 'lava inundation zones', areas on the flank of Mauna Loa that could potentially be inundated by future eruptions (Sheet 7 of Trusdell et al., 2002). The relatively low relief (generally < 1 m thickness) of the proximal 1907 lava flows means that these flows would pose very little impediment to lavas from a fissure eruption upslope of the 1907 flows; that is, it is very unlikely the 1907 flows would significantly divert a subsequent flow, much like the 1907 flow was able to bury portions of the 1887 flow. We conclude that a future SWRZ eruption from a vent upslope of the 1907 flow could threaten OVE houses.

The threat of surface lava flows to OVE is not only from possible fissure eruption upslope of the subdivisions, but also from fissure eruptions potentially within OVE itself. Three short fissure sections are mapped as part of the 1907 eruption, located at ~740 m, ~780 m, and ~920 m elevation to the east of the eastern flow lobe (Sheet 3 of Wolfe and Morris, 1996). The lowest two vents are visible in Figs. 2 and 3. We visited the lowermost of these fissure flows during our DGPS surveying, where we observed pahoehoe toes and bulbs that erupted out of a still-visible fissure (Fig. 14). The flows from these low-elevation fissures are primarily pahoehoe in texture, although sections of a'a develop when the flow is >200 m from its source vent. We also located the contact between the flow from the second-highest fissure and the east margin of the eastern flow lobe, where the pahoehoe from the fissure is clearly beneath the a'a of the main flow lobe. Our interpretation is that the small fissures were active early in the eruption sequence, but with a fairly limited magma supply; these low-elevation flows were subsequently covered by the eastern flow lobe, probably during the second day of the flank eruption, shortly before the flow crossed the Government Road which was near the approximate location of the present highway 11. If this eruptive sequence were to be repeated 2 to 3 km to the west of the eastern lobe, the low fissure vents could be within the most built-up portion of OVE. Such low-elevation fissure eruptions are not typically considered when discussing potential lava flow hazards but this possibility should not be overlooked.

The on-going eruption of Kilauea volcano provides insight into the hazards potentially facing those living on Mauna Loa. The early phases of the eruption inundated the Royal Gardens subdivision, including the destruction of numerous houses (Wolfe et al., 1988). The Kilauea eruptions then shifted from Pu'u O'o to the Kupaianaha vent in July 1986 and continued for nearly 6 years, which led to the inundation of much of the town of Kalapana (Heliker et al., 1998). There is little that can be done to protect housing and other property that is in the path of an advancing lava flow. Determining the path that will be followed by a lava flow is tricky at best, but topographically defined drainage basins have proved to be useful predictors of where lava flows are likely to be constrained during their emplacement (Kauahikaua et al., 1995; Hanley and Zimbelman, 1996), although this is far from a perfect predictor of flow paths.

Should a future eruption send lava into the OVE or HR subdivisions, we decided it would be helpful to have precise information for comparison with the post-eruption flows. Car-mounted DGPS surveys were obtained along several roads within the subdivisions, which would provide precise data on the base of any future lava flows emplaced across the surveyed roads. Such data represent a substantial improvement on the technique used to determine thickness transects through some of the lava flows that entered the Royal Gardens subdivision in 1983 (Fink and Zimbelman, 1986, 1990), where pre-flow

Fig. 14. Pahoehoe coming out of a ground crack source vent, east of profile 5 (see labeled vents in Fig. 2). Inset: Ikonos view of flow from ground crack vent; white arrow shows location of field photo.

street levels could only be inferred from topographic maps and exposed road segments adjacent to the flow margins. We certainly do not hope that these data will be used in the near future, but we also felt that it was prudent documentation to have in hand.

5.2. Implications for future hazards

Precise prediction of volcanic eruptions remains a somewhat elusive goal, but substantial progress has been made through the monitoring and documentation techniques available with modern technology. Our observations of the 1907 flow emplacement lead us to conclude that it is unlikely that someone could divert a lava flow, as was attempted (without significant success) by bombing of active lava channels on Mauna Loa flows in 1935 and 1942 (Lockwood and Torgerson, 1980). In our opinion, the best way to limit future property loss to Mauna Loa lavas is to constrain the growth of development on this active volcano. Between 1989 and 1994, permits were issued for 7972 single-family buildings located on the slopes of Mauna Loa (Trusdell, 1995). Such expansion needs to be closely monitored by government agencies, with particular attention paid to existing hazard assessments (Wright et al., 1992; Decker et al., 1995; Trusdell, 1995; Trusdell et al., 2002). In January of 2004, Hawaii Volcanoes National Park purchased property adjacent to (east of) OVE, previously known as Kahuku Ranch (Ocean View Chamber of Commerce, 2006), which comprised the southern part of a large extension of the park (National Park Service, 2006). Hopefully additional portions around the rift zones of both Mauna Loa and Kilauea can be set aside from future development in a similar fashion.

6. Conclusions

Boundaries of the flow field from the satellite data, combined with field measurements of flow thickness, indicate an area of 25.1 km^2 and a volume of 86.6 million m^3.

The eastern lobe of the flow field covers and area of 13.1 km^2, with a volume of 55.0 million m^3, and was emplaced with an average effusion rate of 119 m^3/s (at least, for the upper portion of the lobe).

Ten DGPS topographic profiles across the eastern lobe aid in distinguishing the characteristics of, and transitions between, the morphologic zones identified during the emplacement of the 1984 Mauna Loa flow.

The strong likelihood of future eruptions from the southwest rift zone of Mauna Loa indicates that the Ocean View Estates subdivision has considerable potential for seeing surface flows at some point in the future.

Acknowledgements

Support for this work was provided by grant NNG04GJ21G from the Planetary Geology and Geophysics Program of NASA. Don and Martie Nitsche provided food, fellowship, and a great place to stay at the Bougainvilla B&B in Ocean View, Hawaii. Three of the four authors benefited greatly from learning volcanology under Mike Sheridan at both Arizona State University and the University at Buffalo.

References

Bailey, J.E., Harris, A.J.L., Dehn, J., Calvari, S., Rowland, S.K., 2006. The changing morphology of an open lava channel on Mt. Etna. Bulletin of Volcanology 68, 497–515. doi:10.1007/s00445-005-0025-6.

Barnard, W.M., 1995. Mauna Loa volcano: historical eruptions, exploration, and observations (1779–1910). In: Rhodes, J.M., Lockwood, J.P. (Eds.), Mauna Loa Revealed. American Geophysical Union Geophysical Monograph, vol. 92, pp. 1–19.

Barnard, W.M., 2002. Chapter 29: An ascent in 1905 and eruption of 1907. Mauna Loa: a source book, (CD-ROM), 345–355. Previously available (1999) from Department of Geosciences, State University of New York at Fredonia, 452 pp.

Decker, R.W., Klein, F.W., Okamura, A.T., Okubo, P.G., 1995. Forecasting eruptions of Mauna Loa volcano, Hawaii. In: Rhodes, J.M., Lockwood, J.P. (Eds.), Mauna Loa Revealed. American Geophysical Union Geophysical Monograph, vol. 92, pp. 337–348.

Eakins, B.W., Robinson, J.E., Kanamatsu, T., Naka, J., Smith, J.R., Takahashi, E., and Clague, D.A., 2003. Hawaii's volcanoes revealed. U.S. Geological Survey Geologic Investigations Series Map I-2809, scale 1:85,342. Map available at http://geopubs.wr.usgs.gov/i-map/i2809/.

Finch, R.H., Macdonald, G.A., 1953. Hawaiian volcanoes during 1950. U.S. Geological Survey Bulletin 996-B, 27–89.

Fink, J.H., Zimbelman, J.R., 1986. Rheology of the 1983 Royal Gardens basalt flows, Kilauea volcano, Hawaii. Bulletin of Volcanology 48, 87–96.

Fink, J.H., Zimbelman, J.R., 1990. Longitudinal variations in rheological properties of lavas: Puu Oo basalt flows, Kilauea volcano, Hawaii. In: Fink, J.H. (Ed.), Lava Flows and Domes. Springer-Verlag, New York, pp. 157–173.

Garry, W.B., 2006. The emplacement of channeled flows in subaerial, submarine, simulated, and extraterrestrial environments. Ph.D. dissertation, SUNY-University at Buffalo, New York. 240 pp.

Garry, W.B., Zimbelman, J.R., and Gregg, T.K.P., 2007. Analysis of a long channeled lava flow near Ascraeus Mons volcano, Mars. Journal of Geophysical Research - Planets 112. doi:10.1029/2006JE002803.

Hanley, D., Zimbelman, J.R., 1996. Reliability of defining drainage basins in order to understand and predict lava flow directions (abstract). Transactions of the American Geophysical Union 77 (46), F679.

Harris, A.J.L., Flynn, L.P., Matias, O., Rose, W.I., 2002. The thermal stealth flows of Santiaguito dome, Guatemala: implications for the cooling and emplacement of dacitic block-lava flows. Geological Society of America Bulletin 114, 533–546.

Hawaii Synergy, 2002. Landsat and Ikonos satellite images of Hawaii County. http://infomart.pdc.org/ikonos.

Heliker, C.C., Mangan, M.T., Mattox, T.N., Kauahikaua, J.P., Helz, R.T., 1998. The character of long-term eruptions: inferences from episodes 50–53 of the Pu'u O'o-Kupaianaha eruption of Kilauea volcano. Bulletin of Volcanology 59, 381–393.

Kauahikaua, J., Margriter, S., Lockwood, J., Trusdell, F., 1995. Applications of GIS to the estimation of lava flow hazards on Mauna Loa volcano, Hawaii. In: Rhodes, J.M., Lockwood, J.P. (Eds.), Mauna Loa Revealed. American Geophysical Union Geophysical Monograph, vol. 92, pp. 315–325.

Lipman, P.W., 1980. Rates of volcanic activity along the southwest rift zone of Mauna Loa volcano, Hawaii. Bulletin of Volcanology 43–4, 703–725.

Lipman, P.W., Banks, N.G., 1987. Aa flow dynamics, Mauna Loa 1984. In: Decker, R.W., Wright, T.L., Stauffer, P.H. (Eds.), Volcanism in Hawaii. U.S. Geological Survey Professional Paper, vol. 1350, pp. 1527–1567.
Lipman, P.W., 1995. Declining growth of Mauna Loa during the last 100,000 years: rates of lava accumulation vs. gravitational subsidence. In: Rhodes, J.M., Lockwoood, J.P. (Eds.), Mauna Loa Revealed. American Geophysical Union Geophysical Monograph, vol. 92, pp. 45–80.
Lockwood, J.P., Lipman, P.W., 1987. Chapter 18: Holocene eruptive history of Mauna Loa volcano. In: Decker, R.W., Wright, T.L., Stauffer, P.J. (Eds.), Volcanism in Hawaii. U.S. Geological Survey Professional Paper, vol. 1350, pp. 509–535.
Lockwood, J.P., Torgerson, F.A., 1980. Diversion of lava flows by aerial bombing: lessions from Mauna Loa volcano, Hawaii. Bulletin of Volcanology 43–4, 726–737.
Macdonald, G.A., 1972. Volcanoes. Prentice-Hall, Inc., Englewood Cliffs, New Jersey. 510 pp.
Macdonald, G.A., Abbott, A.T., 1970. Volcanoes in the Sea. University Press of Hawaii, Honolulu. 441 pp.
Moore, H.J., 1987. Preliminary estimates of the rheological properties of 1984 Mauna Loa flow. In: Decker, R.W., Wright, T.L., Stauffer, P.H. (Eds.), Volcanism in Hawaii. U.S. Geological Survey Professional Paper, vol. 1350, pp. 1569–1588.
Moore, J.G., Clague, D.A., 1992. Volcano growth and evolution of the island of Hawaii. Geological Society of America Bulletin 104 (11), 1471–1484.
Moore, H.G., Clague, D.A., Holcomb, R.T., Kipman, P.W., Normark, W.R., Torresan, M.E., 1989. Prodigious submarine landslides on the Hawaiian ridge. Journal of Geophysical Research 94 (B12), 17,465–17,484.
National Park Service, 2006. http://www.nps.gov/havo/visitor/map.htm.
Neal, C.A., Decker, R.W., 1983. Surging of lava flows at Kilauea volcano, Hawaii (abstract). Transactions of the American Geophysical Union 64 (5), 904.
Ocean View Chamber of Commerce, 2006. http://kaubusiness.stores.yahoo.net/oceanview.html and http://www.ovchamber.com/ov_history.html.
Sparks, R.S.J., Pinkerton, H., Hulme, G., 1976. Classification and formation of lava levees on Mount Etna, Sicily. Geology 4, 269–271.
Stearn, H.T., Macdonald, G.A., 1946. Geology and groundwater resources of the Island of Hawaii. Hawaii Division of Hydrology Bulletin, vol. 9. 363 pp.
Trusdell, F.A., 1995. Lava flow hazards and risk assessment on Mauna Loa volcano, Hawaii. In: Rhodes, J.M., Lockwood, J.P. (Eds.), Mauna Loa Revealed. American Geophysical Union Geophysical Monograph, vol. 92, pp. 327–336.
Trusdell, F.A., Graves, P., and Tincher, C.R., 2002. Map showing lava inundation zones for Mauna Loa, Hawaii. U.S. Geological Survey Miscellaneous Field Studies Map MF-2401, scale 1:50,000. Map available for http://geopubs.wr.usgs.gov/map-mf/mf2401/.
Wolfe, E.W., and Morris, J., 1996. Geologic map of the island of Hawaii. U.S. Geological Survey Geologic Investigations Series Map I-2524-A, scale 1:100,000. Map available at http://pubs.usgs.gov/ds/2005/144/.
Wolfe, E.W., Neal, C.A., Banks, N.G., Duggan, T.J., 1988. Geologic observations and chronology of eruptive events. In: Wolfe, E.W. (Ed.), The Puu Oo Eruption of Kilauea Volcano, Hawaii: Episodes 1 through 20, January 3, 1983, through June 8, 1984. U.S. Geological Survey Professional Paper, vol. 1463, pp. 1–97.
Wright, T.L., Chun, J.Y.F., Esposo, J., Heliker, C., Hodge, J., Lockwood, J.P., and Vogt, S.M., 1992. Map showing lava-flow hazard zones, Island of Hawaii. U.S. Geological Survey Miscellaneous Field Studies Map MF-2193, scale 1:250,000.