New Mexico Geological Society Guidebook, 53rd Field Conference, Geology of White Sands, 2002, p. 121-127.

NEW PRECISION TOPOGRAPHIC MEASUREMENTS OF THE CARRIZOZO AND McCARTYS BASALT FLOWS, NEW MEXICO

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ABSTRACT.— The Carrizozo and McCartys basaltic lava flows in central New Mexico are excellent sites to study the emplacement of long compound flow fields. Differential Global Positioning System (DGPS) data of both flows have revealed new details about the relief and emplacement of these compound basaltic flows. The topographic data, with horizontal and vertical precision of ~ 2 to 4 cm, show distinctive terracing along the flow margins in the proximal and distal portions of both flows, interpreted to be indicative of multiple episodes or scales for the local flow emplacement. A topographic transect across the Carrizozo flow along Highway 380, ~10 km down flow from the vent, supports the interpretation that multiple flow elements banked against earlier episodes to build the field from east to west. Topographic measurements of the McCartys flow are consistent with results obtained for the Carrizozo flow, and help to constrain how the eruptions may have produced both flows. The dimensions of a very narrow neck on the McCartys flow, ~40 km down flow from the vent, provide strong constraints on the lava tube that must have fed the distal portions the flow, resulting in a maximum likely effusion rate of ~500 m^3/s. At Carrizozo, a single medial ridge along the narrow central portion of the flow can be interpreted as a collapsed lava tube similar to the McCartys flow neck, which suggests a maximum likely effusion rate of ~800 m^3/s. Both flows could have been emplaced at these rates within a period of a few months. The observations and inferences at Carrizozo and McCartys have implications for long lava flows observed on other planetary surfaces.

INTRODUCTION

The Carrizozo and McCartys basalt lava flows are among the best preserved Holocene flow complexes in the continental United States. The great lengths of both flows (75 km for Carrizozo, 48 km for McCartys), and their excellent state of preservation in the semi-arid environment of central New Mexico, make them particularly favorable subjects for an investigation aimed at improving our understanding of the emplacement of long lava flows. Preliminary assessments of the detailed topography of the Carrizozo flow provided new insights into its emplacement, including potential applications to long flows on terrestrial planetary surfaces (Zimbelman and Johnston, 2000, 2002). In this paper, we present new results from an ongoing investigation of the Carrizozo flow, together with the first results obtained from the McCartys flow.

The Carrizozo flow (Fig. 1) is located in south-central New Mexico (33°15'N to 33°49'N, 105°52'W to 106°19'W; UTM zone 13, 377000E to 411000E, 3681000N to 3743000N), west of the community of Carrizozo. The McCartys flow (Fig. 2) is in west-central New Mexico (34°42'N to 35°7'N, 107°41'W to 108°4'W; UTM zone 13, 220000E to 255000E, 3845000N to 3887000N), and is the latest of several eruptions within the Zuni-Bandera volcanic center (Theilig, 1990). Both lava flows have been the subject of several previous studies (summarized below), including one that related Carrizozo to long lava flows observed on other planets (Keszthelyi and Pieri, 1993). The present work makes use of recent technological developments to obtain precise topographic data of both lava flows, representing a unique opportunity to quantify the topographic attributes of long basaltic lava flows. New remote sensing instruments are collecting topographic data of lava flows from around the world, as well as from other planetary surfaces. The New Mexico lava flows are providing valuable new insights into understanding how the topographic attributes of lava flows can be related to their emplacement history.

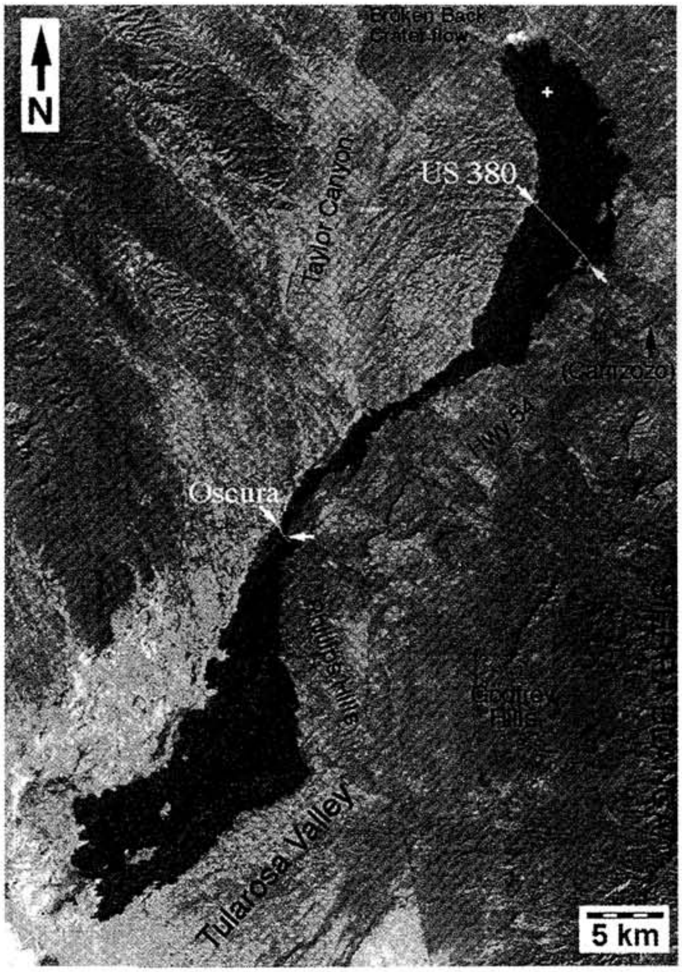

FIGURE 1. Landsat Thematic Mapper Band 4 image of the Carrizozo lava flow, taken on 7/30/99, subsampled from the original 33 m/pixel georeferenced data. Roads across the entire flow width are labeled in white, nearby geographic features are labeled in black. White cross indicates Little Black Peak, cinder cones at the inferred vent for the flow.

BACKGROUND

The Carrizozo lava flow (Fig. 1) is a well-preserved example of a compound (multi-flow component) tube-fed pahoehoe (smooth glassy surface emplaced under limited strain conditions) flow field, which extends 75 km from the vent area to the distal margin in the Tularosa Valley (Zimbelman and Johnston, 2002). The entire flow covers ~330 km^2 to an estimated thickness of 10 to 15 m, for a total erupted volume of ~4.3 km^3 (Allen, 1952). The lava is intermediate in composition between alkalic and tholeiitic basalt and is consistent with the regional volcanism associated with the Rio Grande rift (Renault, 1970; Faris, 1980; Anthony et al., 1992, 1998). The Carrizozo lava is relatively unweathered, in contrast to the nearby older lava flow associated with Broken Back Crater, which flowed into the northern end of Taylor Canyon (Fig. 1). Various researchers (e.g., Anthony et al., 1998; Dunbar, 1999) have distinguished between upper and lower Carrizozo flow units, separated by the narrow "neck" in the medial reach (Keszthelyi and Pieri, 1993). However, chemical analyses to date have revealed no evidence for distinct differences between the upper and lower lavas. Cosmogenic (isotopic changes induced by exposure to high energy particles) studies indicate exposure ages of 4800 yrs (Anthony et al., 1998) to 5200 yrs (Dunbar, 1999) for the Carrizozo flow, well within the 1700 and 700 yr error estimates, respectively. These results make the Carrizozo flow the second youngest volcanism in New Mexico (Anthony et al., 1998), after only the McCartys flow.

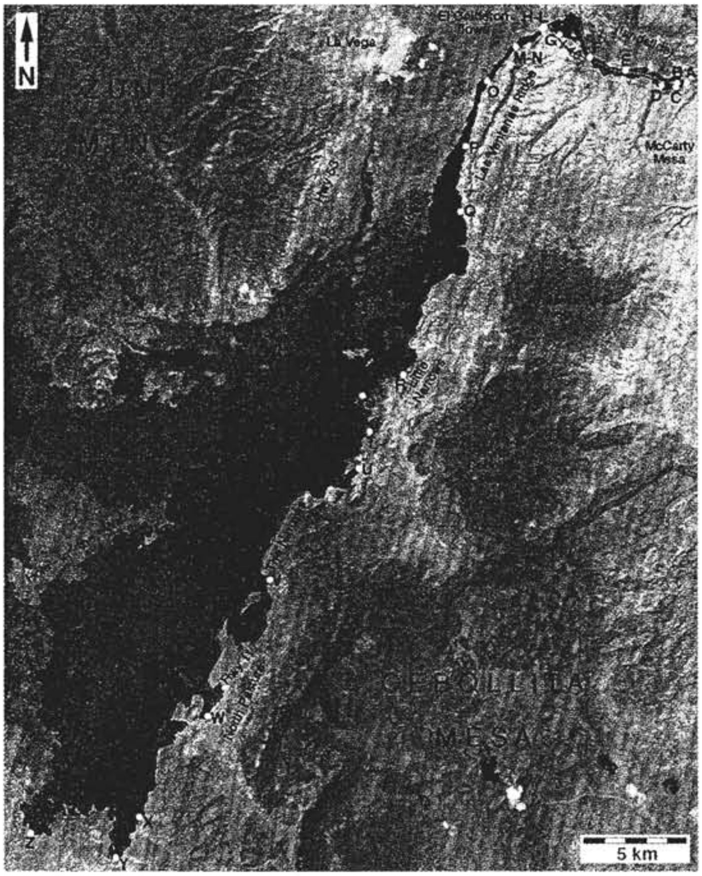

FIGURE 2. Landsat Thematic Mapper panchromatic image of the McCartys lava flow (outlined in black), taken on 4/14/00, subsampled from the original 15 m/pixel georeferenced data. Nearby geographic features are labeled in black; lava flows west of the McCartys flow are from Maxwell (1986). Black cross indicates cinder cone at the inferred vent for the flow.

The McCartys lava flow (Fig. 2) also is a well-preserved compound tube-fed pahoehoe flow field, extending ~48 km from the cinder cone vent area to the distal margin in the valley of the San Jose River. The entire flow covers ~189 km^2, as outlined using satellite image data (Fig. 2) aided by published geologic mapping (Maxwell, 1986), a value smaller than the one reported by Nichols (1946). By assuming an average thickness of 75 feet (22.7 m), Nichols (1946) estimated a total volume for the McCartys flow of 1.7 mi^3 (7.9 km^3). The McCartys lava consists largely of pahoehoe, although in many places the pahoehoe is broken up into jumbled plates that transition to a true a'a (lava clinkers with abundant glassy spines) texture, something that is extremely rare on the Carrizozo flow. The McCartys lava consists of tholeiitic basalt, initially considered to be undifferentiated (Renault, 1970). Subsequent extensive sampling and analysis revealed that the McCartys lavas are quartz-normative tholeiite with plagioclase phenocrysts within 4 km of the vent and olivine-normative tholeiite containing olivine phenocrysts at distances greater than 4 km (Carden and Laughlin, 1974). The detailed sample study also revealed considerable longitudinal variation in both major- and trace-element chemistry along the flow (Carden and Laughlin, 1974, table 1), but vertical chemical variations were found not to be significant. Cosmogenic and radiocarbon dating methods both give a young age of ~3000 yr for the McCartys flow, providing agreement within the analytical uncertainties of both methods (Laughlin et al., 1994).

METHODOLOGY

Precise topographic data were collected from accessible locations around both the Carrizozo and McCartys flow margins. Access to the Carrizozo flow is complicated by the distal portion of the flow being on the White Sands Missile Range (WSMR), administered by the U. S. Army. Through the considerable efforts of Mr. Robert G. Myers, Environment and Safety Directorate at WSMR, access was granted to the Carrizozo flow on WSMR during field trips in November, 1999, and September, 2000. Proximal portions of the Carrizozo flow have limited access due to the surrounding land being privately owned. U. S. Highway 380 crosses the Carrizozo flow ~10 km down flow from the vent (Fig. 1); a traverse along the highway was one focus of our early studies (Zimbelman and Johnston, 2000, 2002), as well as during a brief field trip in September, 2001. The Oscura Range Road crosses the narrow neck of the Carrizozo flow on WSMR, ~ 40 km from the vent (Fig. 1); see Zimbelman and Johnston (2002) for details about the Oscura area.

Most of the McCartys flow is within the boundaries of the El Malpais National Monument, which greatly facilitated access to the flow during field trips in October, 2000 and 2001. The distal ~8 km of the McCartys flow are crossed by Interstate 40 within the San Jose River valley, providing good access along the freeway right-of-way. At locations removed from roads, short traverses across the flow margin were made at both Carrizozo and McCartys, starting on the terrain adjacent to the flow and continuing to the local high on the flow, which was often a very level surface. Locations where traverses were made on the McCartys flow are shown in Figure 2; corresponding elevations and flow margin thickness, including multiple flow levels when present, are listed in Table 1.

Precision topographic measurements were obtained using the Global Positioning System (GPS), providing high quality data over broad areas in relatively short periods of time. The equipment used in this project was a Trimble 4800 Total Station, a carrier-phase Differential GPS (DGPS) system. This system consists of a stationary base station and a roving receiver used to collect the data points, equipped with a fixed-height pole and bubble level for accurate positioning even on a rough lava surface. The horizontal accuracy of this system, relative to the base station, is ~1 to 2 cm; vertical accuracy is ~2 to 4 cm. The data from both the base station and the roving receiver were post-processed in the field using a laptop computer. Base station positions at both flows were determined to an accuracy of ~1 to 2 m using a Trimble Pro XRS GPS receiver equipped with a satellite-based differential correction system.

TABLE 1. McCartys flow Differential Global Positioning System data, keyed to locations shown in Figure 2. Elevations are for the base of the flow margin. Thickness values are relative to the visible base of the flow margin; values in parentheses are for intermediate flow levels also present at these locations. At locations I through O, thickness values are for the west margin of the McCartys flow, where it is in contact with the El Calderon flow and sediment burial of the contact is a minimum.

Location	Elevation (m)	Thickness (m)
A	1884.1	3.6 (2.0)
B	1893.7	4.8
C	1895.1	5.9
D	1897.3	5.6 (4.2)
E	1904.7	1.1 (0.7)
F	1910.0	4.5
G	1930.2	5.1 (2.3)
H	1943.9	3.1
I	1938.5	8.4
J	1939.6	8.2
K	1939.2	8.4
L	1941.5	8.7
M	1953.5	8.2 (3.6, 0.4)
N	1953.3	8.5 (2.8)
O	1967.2	10.5 (4.6, 2.6)
P	1984.5	5.1 (2.4)
Q	2015.9	6.6
R	2079.4	6.7
S	2083.2	3.5
T	2091.8	6.2 (4.5)
U	2114.5	2.6
V	2163.1	3.4
W	2163.8	8.4 (3.2, 1.9)
X	2168.0	8.0 (0.6)
Y	2155.1	7.7 (4.0, 1.5)
Z	2157.6	5.9 (4.9, 2.9)

RESULTS

Previous work at the Carrizozo flow documented multiple flow levels characteristic of the margins at both the proximal and distal portions of the flow, where flow width exceeds 3 km (Zimbelman and Johnston, 2002). We were unable to collect new DGPS measurements at the proximal Carrizozo flow margin during the brief 2001 trip, but some locations not visited on previous trips were examined. Additional occurrences of multiple flow thickness along the margin of the proximal portion of the Carrizozo flow were identified. Using a tape measure and an inclinometer for horizontal reference, margin thickness values of 9.8 to 12.7 m were measured, with intermediate flow level thicknesses of 1.8 to 2.7 m at the same locations. These values are consistent with earlier DGPS results (Zimbelman and Johnston, 2002), although the total thickness is apparently greater than what we were able to measure earlier in the proximal part of the flow. It is significant that all locations revealing more than a single level at the flow margin are where the flow is wider than ~3 km and the regional slope is small. A recent study found that multiple flow levels at Carrizozo consistently occur at locations where the regional slope is <0.15° (Peitersen et al., 2002), suggesting that the multiple levels are a manifestation of pressure-driven extrusion from an inflated flow. This mechanism is in contrast to the gravity-driven flow used in most finite-difference methods for computing lava flow progression over a digital representation of elevation.

A transect adjacent to U.S. Highway 380 revealed a pronounced slope on the western portion of the Carrizozo flow at this location, which we interpreted to be the result of multiple flows banked against one another (Zimbelman and Johnston, 2002). During the 2001 trip, we collected data along the highway itself that sheds new light on the lava flow features adjacent to the road (Fig. 3). In particular, the highway provides a form of "low-pass filter" of the irregular surface of the lava flow, which helps to clarify distinctions between individual flow components. When combined with our measurements of flow feature elevations, the sequence of flow emplacement becomes clearer.

The first flow component (Fig. 3, number 1) is the easternmost flow lobe, which was not included in the previously published version of the transect (Zimbelman and Johnston, 2002, fig. 5). The nearly level upper surface of component 1 is interpret to be the "undeflated" top of this flow, in contrast to the relief of tumuli on the other flow components, interpreted to be the result of deflation following cessation of lava supply from the vent. Perhaps the easternmost flow component did not deflate because it became separated from the bulk of the flowing lava, which probably fed the second flow component, allowing the separated flow to solidify without draining. It is significant that the top of flow component 1 is nearly identical in elevation with the top of the highest tumulus in flow component 2. We consider this near-equivalence in elevation to be supportive of the lack of deflation of component 1, the interpretation that the tumuli of component 2 represent the remnants a deflated flow top, and that both of these components were emplaced over a nearly horizontal (E-W) surface. A kipuka (K in Figure 3) separates components 1 and 2, which represents a place where the Carrizozo lava did not flow, for whatever reason.

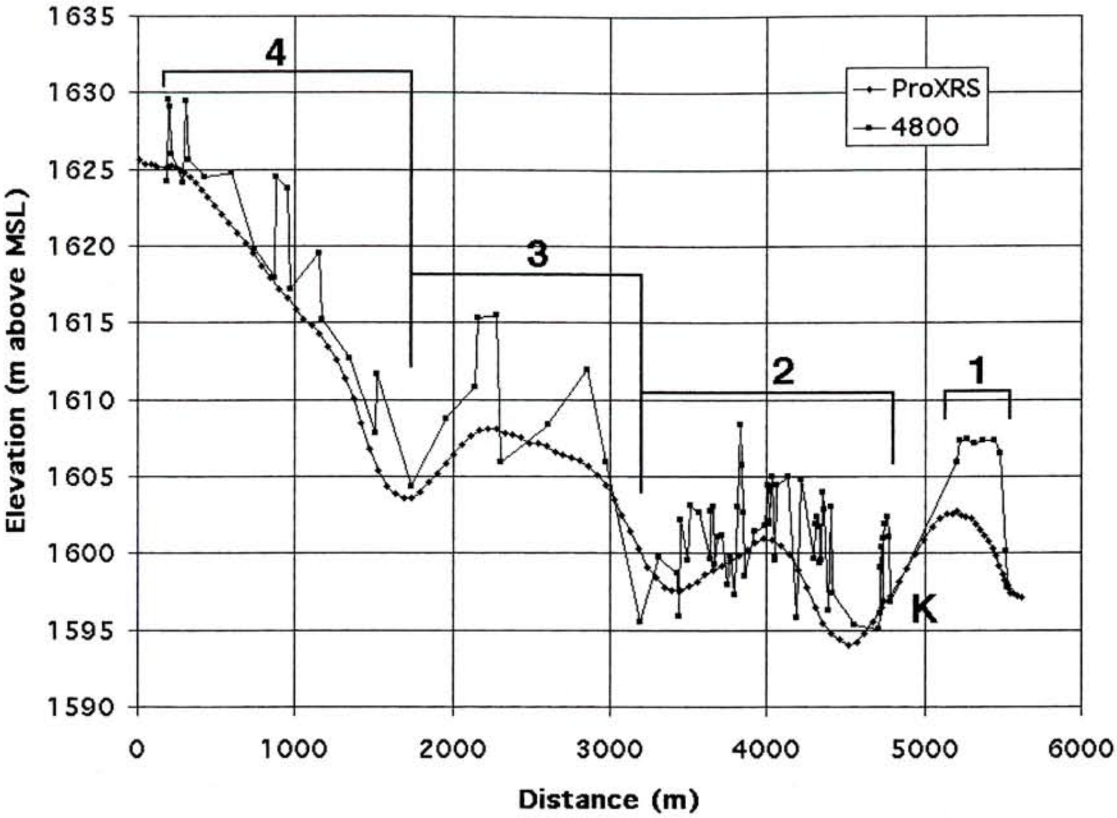

FIGURE 3. DGPS data along U.S. Highway 380, across the Carrizozo flow ~10 km down flow from the vent at Little Black Peak. Numbered sections correspond to flow components (see text); K is a kipuka, where the Carrizozo lava did not cover the pre-flow surface. Points measured with the Trimble 4800 system are for lava surface features north of the highway; they have horizontal precision of ~2 cm and vertical precision of ~4 cm. Trimble Pro XRS points, collected driving along the highway, have vertical and horizontal precision of ~2 m. West is to the left.

The highway roadbed is built up across the kipuka to the western margin of component 1 (Fig. 3), where the highway is entrenched into the thick flow representing component 1. The highway roadcut exposes a massive flow interior for all of component 1, again supporting the interpretation of a stagnated flow element.

Component 3 reveals a slight (~0.2°) eastward dip, interpreted here to indicate that this flow element was emplaced after component 2, possibly banked against the western margin of component 2 (Fig. 3). In the field, no evidence is visible of a flow contact at this location, but this interpretation is most consistent with the topographic data. It remains possible that component 3 is connected somehow (up-flow) to components 1 and 2, but the significantly higher elevations of the tops of tumuli in component 3 (relative to the highest points in components 1 and 2) argue for separate emplacement of these components. The elevation of the highest tumulus on component 3 is 7 m higher than the highest tumulus on component 2, which could result from a shift in the lava supply to the more western portions of the flow. Component 4 is more problematic, having potentially been emplaced against the western margin of component 3 after yet another shift to the west of lava supply, but the ~ 0.7° dip to the east beneath this component is difficult to explain. This is the steepest portion of the entire transect, something that is quite obvious while driving along the highway. We cannot rule out tectonic uplift of the western side of the lava flow, but we could find no evidence to support such tectonic activity in this area within the last 5000 years. Component 4 may in fact consist of more than one flow element, but use of the highway as a spatial filter of the flow topography (where highway construction corresponds to broad-scale topographic changes) argues against the recognition of more components at present.

Our investigation of the Carrizozo flow encouraged us to expand the scope of the study to include the McCartys lava flow (Fig. 2). Next, we summarize the results of our initial efforts at better understanding the McCartys flow through DGPS techniques. The McCartys flow is superposed on several adjacent flows from the Zuni-Bandera volcanic field (labeled flows in Figure 2); enhanced contrast of the satellite imaging data was used to identify the margins of the McCartys flow, aided greatly by the intensive mapping efforts of Maxwell (1986). Kipukas larger than ~500 m are outlined, based both on the higher reflectance of underlying older terrain (having increased vegetation on a thicker soil cover) and on the kipukas mapped by Maxwell (1986). Once the flow margins were identified on the image, the area of the flow was determined to be 189 km^2. If an average flow thickness of 15 m is assumed, the total volume of the McCartys flow is 2.8 km^3, considerably less than the volume estimated by Nichols (1946).

A distinctive aspect of the plan form of the McCartys flow is its progressive narrowing with distance from a low lava shield at the inferred vent location (Carden and Laughlin, 1974; Maxwell, 1986), surmounted by a cinder cone ("+" in Figure 2). Similar

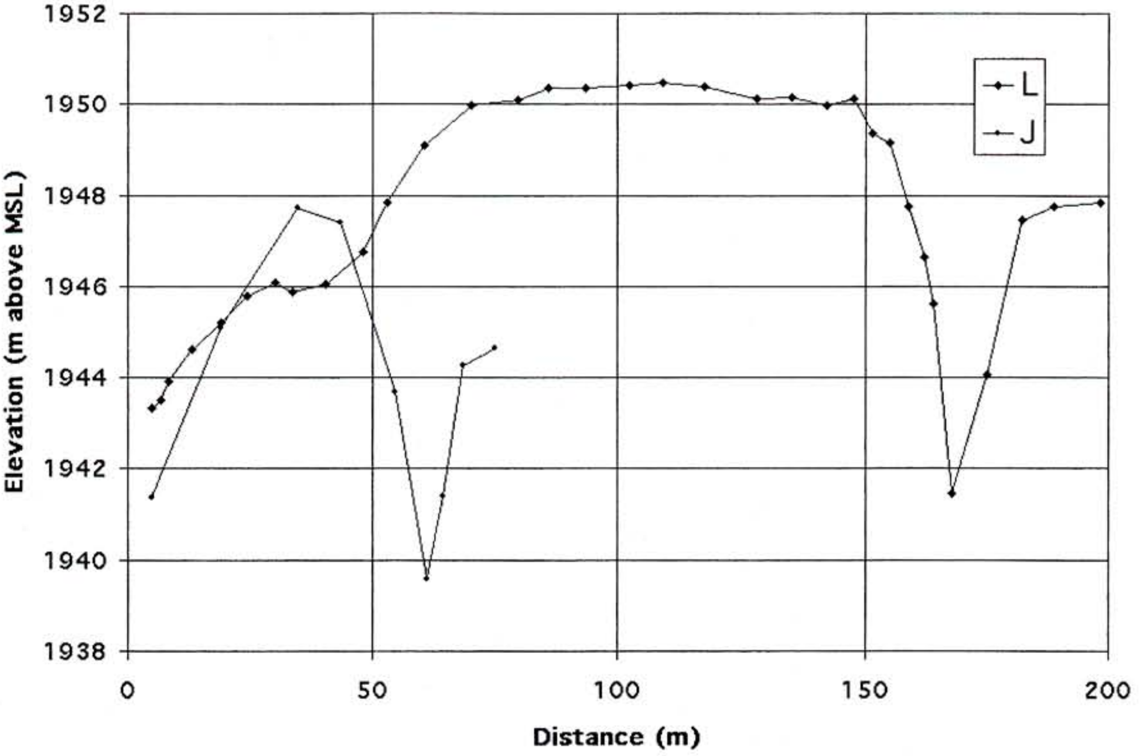

FIGURE 4. DGPS data from two traverses of the narrow neck of the McCartys flow, immediately south of Interstate 40 where it crosses the flow near the intersection with Highway 117. Both traverses include the margin of the topographically lower El Caldaron lava flow (to right). Precision of points is ~2 cm horizontal and ~4 cm vertical. East is to the left.

narrowing with distance is common for many other lava flows on both the Earth and Mars (Peitersen and Crown, 1999, 2000). The McCartys flow is constrained on its eastern edge by a major lineament that connects linear features such as the Las Ventanas Ridge, the Little Narrows, and The Narrows (Fig. 2), but the flow narrowing does not appear to be caused by this general topographic control of orientation.

Several transects across the entire flow width were obtained where the McCartys flow narrowed on its approach to the San Jose Valley (locations I to O in Figure 2). Each of the transects across the narrow portion of the flow shows the McCartys flow is adjacent to the topographically lower margin of the ~54 ka El Calderon flow (Laughlin and WoldeGabriel, 1997); two such transects are shown in Figure 4. The attribute of a relatively low topographic barrier halting the spread of what eventually is a larger lava flow is characteristic of the process of flow inflation associated with the modest effusion of many Hawaiian basaltic eruptions (Hon et al., 1994). Hon et al. (1994) document a case in Hawaii where an advancing pahoehoe flow was observed to encounter a modest rock wall, which halted the progression of flow in that direction, followed by inflation of the flow to a thickness much in excess of the wall height. The extremely narrow width of the McCartys flow just before entering the river valley (profile J in Figure 4) is a strong constraint that the flow rate within the McCartys flow likely was very constant. Large variations in flow supply into the narrow neck could have over-pressurized (causing breaches in) the narrow neck, or allowed gaps to develop above a waning flow within a tube. There is no field evidence of either pressure-driven breaching or partial tube collapse in the narrow neck region of the McCartys flow.

Multiple levels of flow thickness were observed at several locations along the McCartys flow (Table 1). These locations show a distinctive topographic profile, much like that observed at the Carrizozo flow, with more than one nearly-horizontal level evident at the margin (Fig. 5). Margin thicknesses reported in Table 1 are all referenced to the DGPS point obtained at the contact of the flow with the underlying terrain, regardless of the basal slope or relief. As at the Carrizozo flow, this flow behavior is interpreted to indicate distinct pulses of lava extrusion (Zimbelman and Johnston, 2002). At both flows, levels are observed ranging from that of individual pahoehoe squeeze-outs to sheets with a nearly horizontal upper surface (thickness generally 2 to 5 m), comparable to the nearly horizontal top of the flow always present at these locations. Also, as at Carrizozo, the multiple margin levels at the McCartys flow occur in places where the regional slope is very small (generally <0.2°). We consider this process to somehow be related to the pressure-driven flow inflation process on very shallow slopes, although we are not aware of this attribute being described in the literature of Hawaiian flows.

DISCUSSION

The dimensions of the narrow neck of the McCartys flow provide an opportunity to constrain the maximum likely effusion rate of the lava flow. The narrowest part of the neck is only slightly more than 50 m wide, with a nearly uniform 8.5 m of vertical

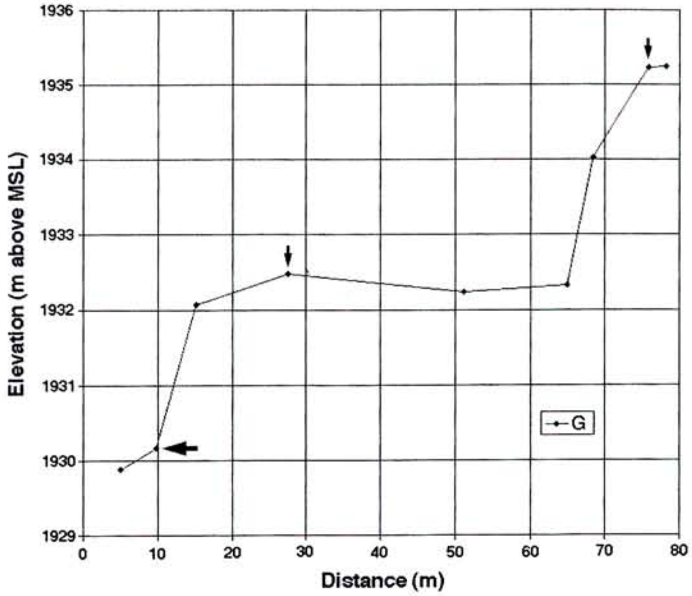

FIGURE 5. DGPS data showing two distinct levels for the McCartys flow margin at location G (see Fig. 2). The lowest level has a thickness (relative to margin base, large arrow) of 2.3 m (small arrow at left), adjacent to an level upper surface with a thickness of 5.1 m (small arrow at right). Precision of points is ~2 cm horizontal and ~4 cm vertical. North is to the right.

relief on the western margin next to the El Calderon flow (J in Figure 4). It is difficult to estimate the true shape of the surface beneath the McCartys flow, but it is not likely to represent much more than an additional meter of relief. A substantial lava tube within this section of the flow is about the only logical way to have fed lava to the distal portions of flow. Assuming a 1-m-thick crust on the top and bottom of the tube (more than adequate for thermal insulation), and perhaps 2.5 m of crust at the margins, an elliptically shaped tube within the McCartys narrow neck would have major and minor axes of ~ 45 and ~7.5 m, respectively. The cross-sectional area of such a tube would be 265 m^2. It is possible that a thinner crust would have allowed for a larger tube area, but the value derived above is representative of a near-maximum area. There is no simple way to estimate the actual flow velocity within such a tube, but the shallow regional slope at the McCartys neck and observations of flow within tubes in Hawaii suggest that the flow rate would not have been particularly rapid. Assuming an ~ 2 m/s flow rate typical of flow observed within Hawaiian lava tubes (Hon et al., 1994), often on regional slopes much steeper than the ~0.25° slope at the McCartys neck, the likely flow rate through the tube is ~ 500 m^3/s. This value is at best an upper limit, and it seems very likely that the flow rate could have been a much lower value during emplacement of the McCartys flow.

The narrow medial portion of the Carrizozo flow similarly had a single large tube feeding lava to the distal flow front. However, at Carrizozo the flow was not confined within a narrow (albeit a shallow) valley such as at the McCartys narrow neck, and a shallow sheet of pahoehoe surrounds the ridge that is interpreted to be the remnant of a collapsed tube (Zimbelman and Johnston, 2002). The ridge dimensions at Carrizozo allow a similar assessment of flow rate to that just carried out for the McCartys flow. The large ridge in the medial portion of the Carrizozo flow has a width of ~70 m and a vertical relief of 9.4 m (Zimbelman and Johnston, 2002, fig. 5). Assumptions similar to those above lead to an elliptical tube ~ 60 by 8.5 m, which gives a cross-sectional area of 400 m^3. At a flow rate of 2 m/s, such a tube would transport ~ 800 m^3/s as an upper limit, remarkably similar to the result obtained above for the McCartys narrow neck.

These effusion rates are substantially larger than those of typical Hawaiian eruptions (Rowland and Walker, 1990), but they are much smaller than the enormous effusion rates inferred for some long flows on other planets (>106 m^3/s; e.g., Schaber, 1973; Roberts et al., 1992). The effusion rate estimates provide insight into the duration of the emplacement of both lava flows. DGPS data for Carrizozo are consistent with the average thickness used by Allen (1952) to obtain a total volume for the flow of 4.3 km^3. At an effusion rate of 800 m^3/s, the volume of the Carrizozo flow could have been emplaced in 5.4 x 106 s, or 62 days. This duration is substantially less than the estimate of three decades by Keszthelyi and Pieri (1993), who assumed a typical recent eruption rate at Kilauea of 5 m^3/s. For the McCartys flow, the area of 189 km2 derived from satellite image data (Fig. 2) can be combined with an average flow thickness of ~ 8 m (see Table 1) to obtain a flow volume of 1.5 km^3. This total volume could have been emplaced at a rate of 500 m^3/s in 2.8 x 106 s, or 33 days, consistent with the duration derived above for the Carrizozo flow. Both lava flows could have been emplaced within a period of months, assuming constant effusion rates obtained from the probable area of lava tubes at the narrowest parts of each flow. The derived maximum effusion rates of the Carrizozo and McCartys flows are nearly two orders of magnitude greater than those of historical Hawaiian pahoehoe flows (<10 m^3/s; Rowland and Walker, 1990). Zimbelman (1998) used the historical Hawaiian pahoehoe rate to estimate the emplacement duration of several planetary lava flows, which might be considered close to the lower limit of likely effusion rates. Thus, the results obtained here may help to constrain possible flow emplacement rates and durations for long lava flows observed on other planets.

CONCLUSIONS

DGPS data for the Carrizozo and McCartys lava flows provide insights into the processes involved in their emplacement. The Carrizozo flow has topographic elements suggesting at least four distinct flow components in the emplacement of the broad proximal portion of the flow. Both the Carrizozo and McCartys flows have multiple levels of flow thickness exposed at their margins in areas of low regional slope, interpreted to be the related to multiple episodes of extrusion from these inflated flows. The dimensions of the narrowest portions of both flows constrain likely effusion rate upper limits to <1000 m^3/s, leading to a minimum emplacement duration on the order of months.

ACKNOWLEDGMENTS

Review comments by Steven Williams and Larry Crumpler were very helpful in improving the original manuscript. The authors are very grateful for the assistance of Robert Myers in gaining access to the portion of the Carrizozo lava flow on the White Sands Missile Range. This work was supported by grants NAG5-4164 and NAG5-10375 from the Planetary Geology and Geophysics program of the National Aeronautics and Space Administration. This paper was approved for public release by White Sands Missile Range; distribution unlimited. OPSEC review completed on August 14, 2002.

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