IMPROVED TOPOGRAPHY OF THE CARRIZOZO LAVA FLOW: IMPLICATIONS FOR EMPLACEMENT CONDITIONS

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Abstract - The Carrizozo lava flow in New Mexico is an excellent location to study the emplacement of a 75-km-long basaltic flow field, the longest sub-aerial lava flow in the United States. Differential Global Positioning System data of the Carrizozo flow field have revealed important new details about the relief and emplacement of this compound group of flows. The topographic data show distinctive terracing along the flow margins in both the proximal and distal portions of the flow field, interpreted to indicate multiple episodes or scales for flow emplacement at these locations. A topographic transect ~10 km down flow from the vent, as well as elevations for the level upper surfaces of flows at the distal margin, support the interpretation that multiple flows banked against earlier episodes to build the field from east to west. The narrow central portion of the flow has a single medial ridge, interpreted to be a collapsed lava tube remnant. All observations indicate that the flow field is the product of relatively slow effusion, flow inflation, and subsequent deflation in the proximal reaches. These conclusions also have implications for long lava flows on other planetary surfaces.

INTRODUCTION

The 75-km-long Carrizozo flow field is one of the longest sub-aerial Holocene lava flow complexes in the United States. The great length and the excellent preservation of this flow make it a particularly favorable subject for detailed investigation. The current study is motivated both by a desire to understand how this particular flow field was emplaced, and for assessing its potential as an analog for long lava flows observed on volcanic terrains on many planetary surfaces. A preliminary examination of detailed topographic information of the Carrizozo flow was conducted as an aide for interpreting flow characteristics through remote sensing data. An assessment of the detailed topography of the Carrizozo flow provides new insight into the emplacement of long flows in general, with potential application to long flows visible on many terrestrial planetary surfaces (Zimbelman and Johnston, 2000).

The Carrizozo flow field is located in south-central New Mexico (33°15' to 49' N. latitude, 105° 52' to 106° 19' W. longitude; UTM zone 13 S, 377200 to 411400 E, 3680600 to 3742500 N), west of the community of Carrizozo (Fig. 1). The flow field already has been the subject of a previous study that related it to long lava flows on other planets (Keszthelyi and Pieri, 1993). The present work benefits from significant technological advances available subsequent to the previous study.

Analysis of the precise topographic data of the Carrizozo lava flow field presented here represents a unique opportunity to quantify the topographic attributes of long basaltic lava flows. New remote sensing instruments, such as the Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor (MGS) spacecraft (Smith et al., 1998, 1999), are providing unprecedented detailed topographic data for diverse planetary surfaces. Similar laser and radar sensors are generating new, detailed topographic data sets for many study areas on Earth, revolutionizing the way that many geomorphic problems can be addressed. The interpretation of these new data is aided significantly by the current availability of portable precision navigation and surveying equipment. This report provides some early results from an ongoing investigation of the Carrizozo flow field.

BACKGROUND

The Carrizozo lava flow is a well-preserved example of a compound (consisting of multiple flow components) tube-fed pahoehoe (relatively smooth glassy surface emplaced under limited strain conditions) flow field, traceable for 75 km from the vent area to the distal margin (Keszthelyi and Pieri, 1993). The flow field covers ~330 km^2 to an estimated depth of 10 to 15 m, for a total erupted volume of ~4.3 km^3 (Allen, 1952). The lavas are intermediate in composition between alkalic and tholeiitic basalts, and are consistent with the regional volcanism associated with the Rio Grande rift (Renault, 1970; Faris, 1980; Anthony et al., 1992, 1998). Various researchers (e.g., Anthony et al., 1998; Dunbar, 1999) have distinguished
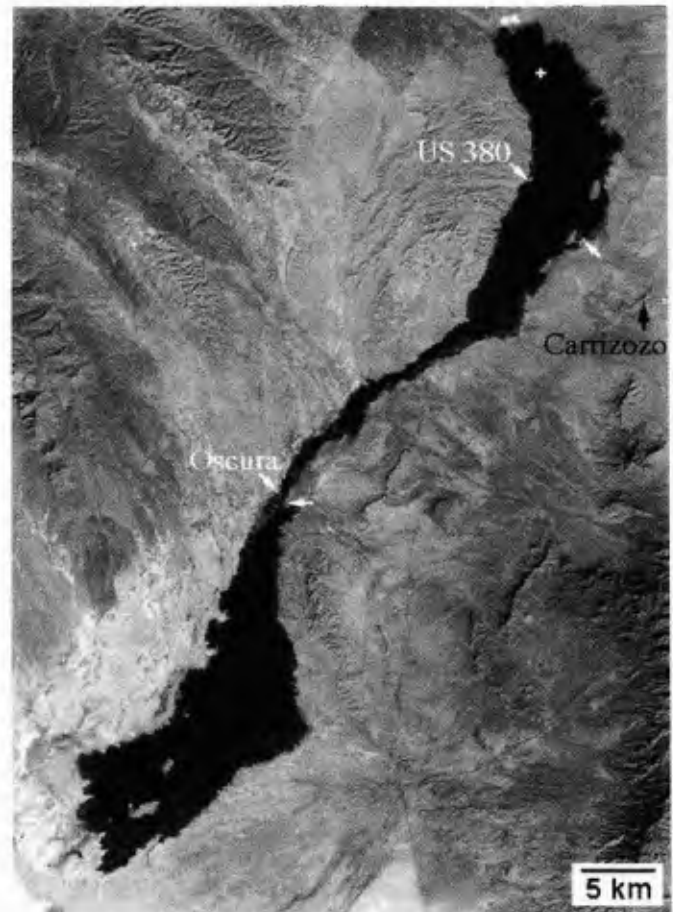

FIGURE 1.The Carrizozo lava flow in south-central New Mexico. Located west of the town of Carrizozo (black arrow), the flow extends 75 km southsouthwest from the apparent source vent at Little Black Peak (white cross). US Highway 380 crosses the northern portion of the flow (white arrows), and the Oscura Range Road crosses the narrow central portion (white arrows), on White Sands Missile Range. Portion of a Landsat Thematic Mapper Band 4 image, taken on 7/30/99, subsampled from the original 33 m/pixel georeferenced data. North is to the top.

FIGURE 2. Components of the Trimble 4800 Differential Global Positioning System (DGPS). The base station collects data at a fixed location for the duration of the survey. The roving unit (inset) collects the survey points. Postprocessing of data from both units provides the differentially corrected topographic data. Digital images taken by JRZ on 9/28/00; approved for publication by U.S. Army.

between upper and lower Carrizozo flow units, separated by a narrow "neck" in the medial reach (Keszthelyi and Pieri, 1993). However, chemical analyses to date have revealed no evidence for distinct differences between the lavas in the upper and lower units. Flow morphology was used to evaluate possible flow emplacement rates, leading to the conclusion that a typical Hawaiian rate (~5 m^3/s), consistent with tube-fed pahoehoe flows, indicates an eruption duration at Carrizozo of nearly 3 decades (Keszthelyi and Pieri, 1993). Recent cosmogenic (isotopic changes induced by exposure to high energy particles) studies indicate exposure ages of from 4,800 years (Anthony *et al.*, 1998) to 5,200 years (Dunbar, 1999) for the flow field, providing agreement well within the 1700 and 700 year associated error estimates, respectively. These dating results make the Carrizozo lavas the second youngest volcanism in New Mexico (Anthony et al., 1998), after only the 3000 year age of the McCartys basalt flow near Grants (Laughlin et al., 1994).

The emplacement of long lava flows has generated considerable controversy, particularly with regard to the rate and style of emplacement. Two models for emplacement of long lava flows within the Columbia River Basalt (CRB) group represent the extremes in the flow emplacement debate. Turbulent flow powered by the hydraulic head produced by the gently sloping upper surface of massive flows leads to emplacement times of days to weeks for flows hundreds of km in length (Shaw and Swanson, 1970). In contrast, obser-vations of inflation of active Hawaiian basalt flows (Hon et al., 1994) led to the interpretation of several CRB flows as inflated pahoehoe flows emplaced over periods of many years (Self et al., 1996, 1997). Long lava flows on several planetary surfaces were investigated recently in an attempt to understand their overall geometry, to provide constraints on possible modes of emplacement (Zimbelman, 1998). Geometric information about flows derived from imaging data alone usually is of insufficient precision to provide strong constraints on flow volume and related modes of emplacement. The Carrizozo flow provides a unique opportunity to obtain detailed information about long basalt flows that should be

very helpful in assessing the emplacement of compound flows on variety of planetary surfaces.

METHODOLOGY

Precise topographic data were collected from locations around the Carrizozo flow margin that could be readily reached. Easy access was complicated by the fact that the distal half of the flow lies within the boundary of 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, WSMR, access was granted to the lava flow on WSMR during two field trips to the area, the first in November, 1999, and the second in September, 2000. For the proximal half of the flow, access was hindered for portions of the flow located on private land. Transects across the entire flow width were obtained only adjacent to established roads; U. S. Highway 380 crosses the flow ~10 km down flow from the vent area, and the Oscura Range Road crosses the narrow neck of the flow ~40 km from the vent area (Fig. 1). At locations away from roads, short traverses across the flow margin were made, starting on the terrain adjacent to the flow and extending to where a relatively level upper flow surface was reached.

Topographic measurements were obtained using the Global Positioning System (GPS). Use of GPS allows high quality data to be collected over very large areas in relatively short periods of time.
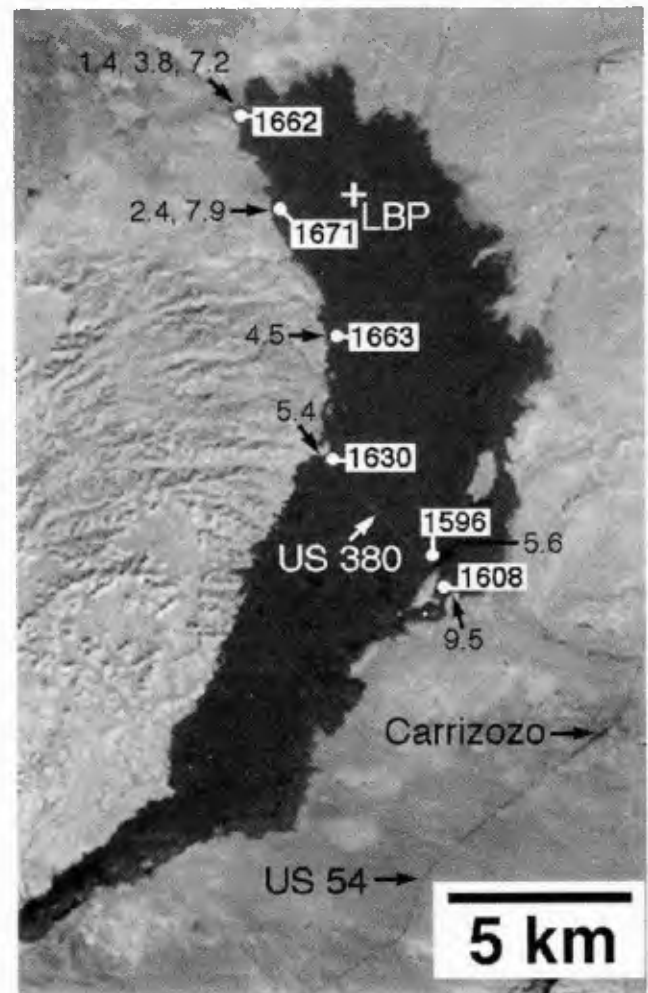

FIGURE 3. Proximal portion of the Carrizozo flow, with elevations (in white boxes, in m) on the flow surface at the location of the white dot, and flow margin thicknesses (in m) where indicated by the black arrows. Where the margin showed distinct terracing, multiple thicknesses are listed, all relative to the surface immediately adjacent to the flow. North is to the top.
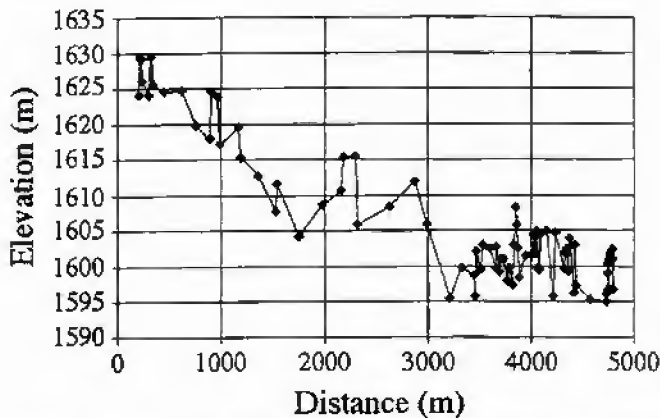
FIGURE 4. DGPS survey along the north side of US Highway 380, running west to east, across the northern portion of the flow (see Fig. 1). An east-dipping slope dominates the western 3 km of the flow, changing to a horizontal base level east of the sloping section. Precision of measured locations is much smaller than the size of the symbols. 74X vertical exaggeration.

The equipment used in this project was a Trimble 4800 Total Station, a carrier-phase Differential GPS (DGPS) system. This system includes a GPS base station that remains stationary (Fig. 2), and a roving receiver used to collect data points (inset, Fig. 2), equipped with a fixed-height pole and bubble level that allowed accurate positions to be determined even on the 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 GPS data from both the base station and the roving receiver were post-processed in the field using a laptop computer.

The DGPS survey was divided into two sections. For the southern part of the flow, the GPS base station was located within WSMR. For the northern part, the base station was relocated to the Valley of Fires Recreation Area, south of U. S. highway 380 on the lava flow (Fig. 1). These sites were required to be approximately in the center of the work area and were chosen to provide good satellite visibility. The base station positions were determined to an accuracy of ~1 to 2 m using a Trimble ProXRS GPS receiver equipped with a satellite-based differential correction system.

RESULTS

The proximal portion of the flow is distributed around Little Black Peak (LBP, Fig. 3), the inferred source for the flow field (Theilig, 1990). Public roads provide good access from the north to the western edge of the proximal flow, where three short transects were obtained over the flow margin. Results for margin measurements (Fig. 3) include flow thickness in meters above the level of the surrounding terrain (numbers by black arrows indicating the measurement location), and the elevation in meters of the flat upper flow surface (values in white boxes, corresponding to locations indicated by the white dots).

A remarkable aspect of the margin thickness values is the distinct terracing that is evident at some locations, indicated by multiple thickness values for a given location (see Fig. 3). Where terracing is present, the values represent the thickness (relative to the surroundings) as one progresses up the terrace levels. The terracing appears to result from distinct pulses of lava extrusion; the lowest outer level is typically caused by small pahoehoe squeeze-outs, while second and third levels correspond to massive flow components with quite level upper surfaces. Interior to the terraced margins, the proximal flow likely consists of a massive flow at least 8 m thick, the largest single thickness measured for the proximal portion of the flow. No obvious flow boundaries were evident within the proximal flow, either on the ground or in satellite images. The elevations of upper

flow surface along the northwestern margin are consistent with flow away from the Little Black Peak area, but as the eruption progressed, the vast majority of the flow found easier down-gradient access to the southeast than to the northwest.

U. S. Highway 380 (Figs. 1 and 3) provided good access for a transect across the entire flow width, at a distance ~10 km down flow from the Little Black Peak vent area. A transect parallel to the highway was obtained, documenting the surface topography ~20 m north of the flow surface disturbed by road construction (Fig. 4). Measure-ments were collected where there were obvious breaks in slope on the flow surface, which almost always corresponded to numerous pressure ridges oriented parallel to the flow direction. Individual pressure ridges cut by the highway all reveal massive, mostly non-vesicular interiors, often cut by medial cracks up to 5 m deep. A distinctive aspect of the highway transect is the eastward dip (~0.55°) of the western 3 km of the flow.

East of the east-dipping portion of the transect, the flow appears to have a very consistent minimum surface elevation, punctuated by many pressure ridges. The abundant pressure ridges are interpreted here to be indicative of significant flow inflation (that is, the original flow likely was at least as thick locally as any pressure ridge height) during emplacement, with subsequent deflation between the high-standing massive pressure ridges. While distinct flow margins were not evident in the field, topography along the transect is interpreted to indicate that the easternmost (relatively level) flow component was emplaced first, with subsequent flows emplaced on the gentle east-dipping surface by banking up against the western margins of previous flow components. There was no field evidence indicative of post-flow faulting to produce the eastward dip, consistent with limited tectonism anticipated to affect such a young flow. A portion of the flow east of the highway transect consists of a single massive
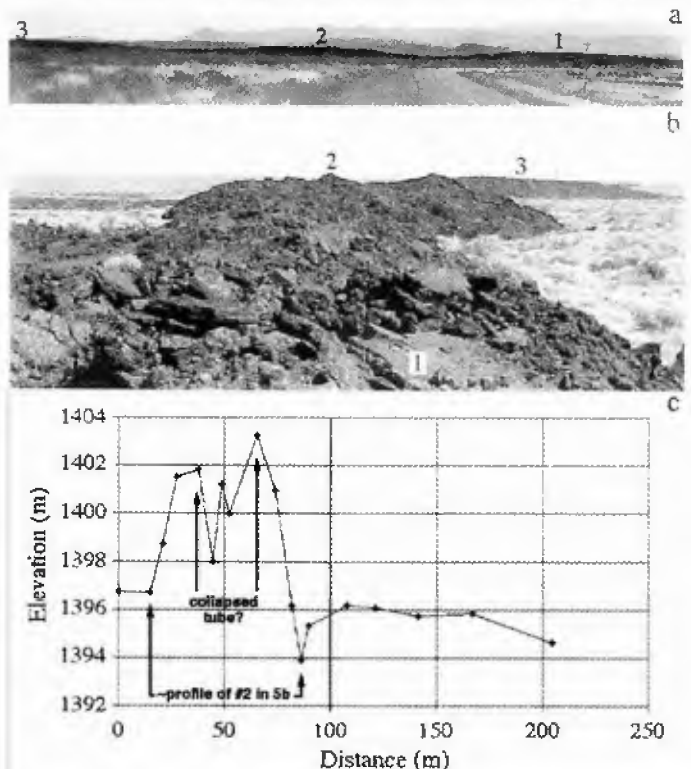

FIGURE 5. Medial ridge on the narrow central portion of the flow, north of the Oscura Range Road. a) Looking east, three highs (numbered) are evident on the sinuous ridge profile. b) Looking north, from high #1 toward high #2 (upper surface traced with black line for clarity) and high #3. c) DGPS survey of high #2, running west to east across the ridge to the eastern margin of the flow. The survey line does not correspond to the profile view in part b. 11X vertical exaggeration. Digital images taken by JRZ on 9/28/00; approved for publication by U.S. Army.
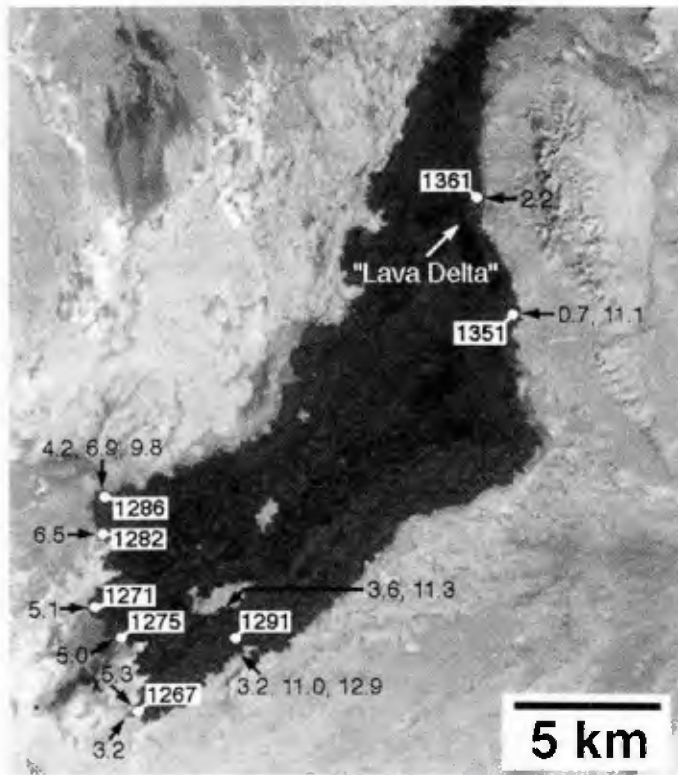
FIGURE 6. Distal portion of the Carrizozo flow, with elevations (in white boxes, in m) on the flow surface at the location of the white dot, and flow margin thicknesses (in m) where indicated by the black arrows. Where the margin showed distinct terracing, multiple thicknesses are listed, all relative to the surface immediately adjacent to the flow. The apex of a possible "lava delta" is labeled at the terminus of the prominent medial ridge that runs along the narrow central portion of the flow. North is to the top.

unit twice as thick as most pressure ridges along the transect, with an upper surface 12 m higher than the eastern end of the transect (1608 location, Fig. 3). This easternmost flow component experienced no significant deflation and may post-date all other flow components sampled along the transect.

The narrow central portion of the flow (center, Fig. 1) appears to result from two effects; constraint by the shallow but consistent slopes on both sides of the valley, and probable concentration of all effusion through a single central tube. Measurements around the Oscura Range Road on WSMR, crossing the flow where it is only ~500 m wide, show flow attributes distinctly different from both the proximal and distal reaches. One prominent medial ridge rises above broken pahoehoe slabs that comprise the remainder of the flow (Fig. 5). Viewed perpendicular to the flow, the medial ridge displays a regular sinuous profile where taller portions are separated by relative lows (Fig. 5a). Individual highs of the medial ridge consist of a complex jumble of pahoehoe plates ~20 to 30 cm thick (Fig. 5b), and cross-flow relief strongly suggests the ridge is the collapsed remnant of a single large lava tube (Fig. 5c). No actual preserved tube section was found at the Oscura Range Road locations. Off the medial ridge, exposed flow material is more consistent with broad pahoehoe squeeze-outs associated with terraced margins than with the level interiors of the proximal and distal components.

Distal portions of the flow field again display som of the flow attributes observed in the proximal portion of the flow. Distal margin measurements reveal terracing at several locations (Fig. 6); the lowest terrace level corresponds to pahoehoe squeeze-outs, with one or two distinct levels present above the squeeze-out level. Few individual pressure ridges were observed in the distal portions of the flow, where the flow interior is more reminiscent of an inflated 'platform' than of a deflated pressure ridge region. It is significant that thick

interior sections reappear shortly down flow from where the medial ridge terminates in a dark fan of material as revealed in the satellite image (right center, Fig. 6). During the field measurements, we observed that wherever the satellite image showed a localized dark region on the flow, this invariably corresponded to a region of intensely jumbled pahoehoe plates. A dark fan at the down flow termination of the medial ridge is interpreted to be a "lava delta" (center of Fig. 6), where effusion left the confines of a single large tube and once again fed broad inflated flows. This interpretation of the "lava delta" region will be tested during our next trip to WSMR

Margin thickness values at the distal termination of the flow field are consistently much less than the thickest values obtained either further up flow or deeper within the flow interior. The 3 to 5 m thickness level at distal margins may represent a distinct terminal phase of effusion when the massive (10 to 13 m thick) flow interiors were still mostly molten but perhaps no longer were being supplied by effusion from the vent. A westward increase in the elevation of the level upper surfaces for components of the distal flow (values in white boxes, lower left of Fig. 6) may result from the earliest component being emplaced along the eastern side of the final flow. Subsequent components banked against the previously emplaced flow
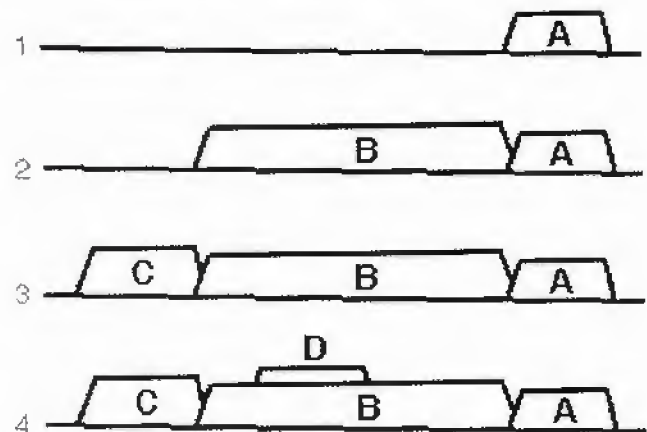

FIGURE 7. Hypothesized emplacement sequence of flow components at the distal end of the Carrizozo flow field (compare to Fig. 6). The annotated image shows separate flow components, identified from both the topographic characteristics of the flow surfaces and flow margin locations interpreted from the image. Four flow lobes were emplaced, with progressively higher flow surface elevations, as they banked against the western edge of previously emplaced flows. Flow component D was not visited in the field, but its surface is inferred to be at a higher elevation than the three components that make up the distal flow margin.
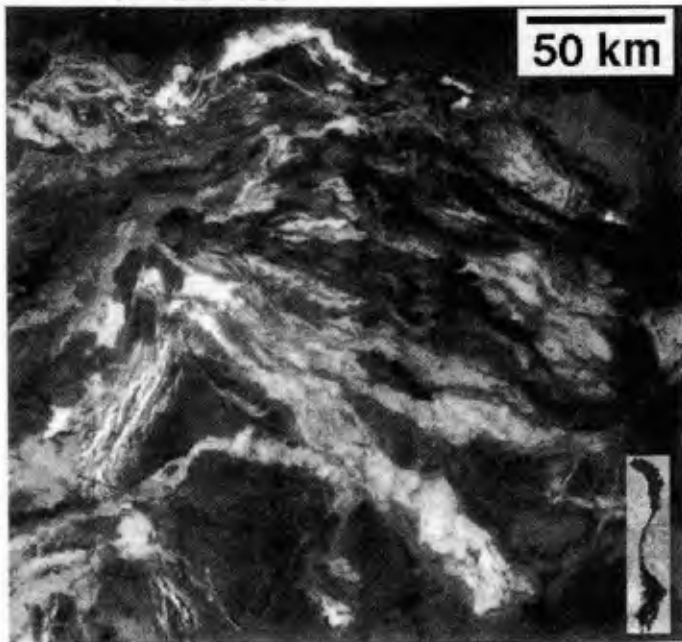
CARRIZOZO LAVA FLOW

FIGURE 8. Portion of the Strenia Fluctus flow field (41°N lat., 250° long.) on the northern lowland plains of Venus, with the Carrizozo flow field (lower right) shown at the same scale. The Venusian flows are longer and wider than Carrizozo, possibly due to the extremely shallow topographic gradient (~0.05°) of these plains (Zimbelman, 1998). Venus image is from a portion of a Synthetic Aperture Radar image (F-MIDR 40N251) taken by the Magellan spacecraft.

lobes (Fig. 7), similar to our interpretation of the highway transect. All of these results and interpretations are consistent with the previous interpretation that the Carrizozo flow is a compound field of inflated pahoehoe flow components (Keszthelyi and Pieri, 1993).

DISCUSSION

The topographic measurements and field observations reported here appear to be most consistent with a relatively slow effusion rate for the basalt that comprises the Carrizozo flow field. In particular, practically no examples of aa clinkers (blocks with spiny glass projections produced by strongly sheared flow) were observed anywhere on the flow. Pahoehoe flow texture has been shown to correlate well with relatively low effusion rates (<20 m³/s) for historic Hawaiian lava flows, while aa texture is most often associated with higher effusion rate flows with a levee-confined open central channel (Rowland and Walker, 1993). The abundant inflation and deflation features on the Carrizozo flow field also support relatively low effusion rates (e.g., Self et al., 1996). There was no evidence to indicate an open leveed channel was ever active at any time during the emplacement of the Carrizozo flow field.

Flow concentration in the narrow central reach might be in part a response to the local gradient, in that this region has a steeper down-valley gradient (~0.4°) than the distal gradient (~0.2°). However, there is no obvious topographic 'trigger' to cause the medial tube to form ~20 km from the vent, the location identified as the separation point for the upper and lower Carrizozo flows (Dunbar, 1999). Supply to the distal flow front through a single large tube implies prolonged and relatively continuous effusion, or else cooling lava could easily have blocked the tube if effusion had temporarily ceased, or even varied significantly in magnitude as a function of time. All of these inferences are interpreted to support prolonged, relatively steady-state, low effusion rate (<20 m³/s) flow for the Carrizozo flow field, consistent with previous estimates that flow emplacement likely spanned nearly three decades (Keszthelyi and Pieri, 1993).

The topographic attributes of the Carrizozo flow field may provide an excellent analog for interpreting the emplacement of similar compound pahoehoe flow fields on other planetary surfaces. For example, radar roughness properties of volcanic terrain on Venus indicates that virtually all of the volcanic flows visible in Magellan radar images are likely have a pahoehoe surface texture (Campbell and Campbell, 1992). Flow fields on the lowland plains of Venus, some with observable compound attributes, likely were also emplaced under low Hawaiian-style effusion rates like the Carrizozo lava flow (Zimbelman, 1998). The Venusian flow fields are typically much larger than the Carrizozo flow field (Fig. 8), perhaps a consequence of the extremely low gradient (~0.05°) present on the plains of Venus. Detailed topographic data of the Carrizozo flows should provide a documented terrestrial analog to which other planetary flow fields can be compared. The precise topographic data being obtained currently all over Mars through the MOLA instrument (Smith et al., 1998) means that the Carrizozo analog may soon be applied to analysis of potential compound flow fields on Mars.

CONCLUSIONS

The Carrizozo flow is an excellent location to study the emplacement of a 75-km-long basaltic flow field. Differential Global Positioning System (DGPS) data reveal important new details about the relief of the Carrizozo flow field. The topographic data document distinctive terracing along the flow margins in the proximal and distal portions of the flow field, interpreted to be indicative of multiple episodes or scales of flow emplacement at these locations. Both a topographic transect ~10 km down flow from the vent, and elevations of the level upper surfaces of flow components at the distal margin ~75 km from the vent, support the interpretation that multiple flows banked against earlier episodes to build the field from east to west. The narrow central portion of the flow is dominated by a single medial ridge interpreted to be a collapsed lava tube remnant. All observations indicate that the flow field is the result of relatively slow effusion, flow inflation, and subsequent deflation in the proximal reaches.

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Lava tube at Jornado del Muerto volcano. Photo by J. Aubele.