Fieldwork report: Physical volcanology and hazards
Volcán de Fuego, Guatemala: January – February 2009
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Summary:

Fieldwork to gather information on the hazards and risk related to volcanic activity at Volcán de Fuego, Guatemala, was carried out during January and February 2009. The fieldwork had two main components: the first one focused on the physical characteristics of volcanic activity, mainly the examination of volcanic product deposits, to infer about hazards related to the past activity at Fuego. The second focused on the societal perspective and potential to manage the risk, and consisted of a series of interviews with government officials and the inhabitants of villages close to the volcano, to investigate perceptions and beliefs about potential future eruptions. This report describes some preliminary findings from the collected data related to the first component (physical volcanology and hazards) and the possible future directions that this research could follow.

Background:

Volcán de Fuego has been erupting explosively form at least the last 500 years (Vallance et al. 2001), with at least 7 eruptions in the VEI 4 range (GVP 2009). Since the beginning of the current eruptive episode in 1999, and especially since 2001, a series of 18 moderate eruptions that have triggered crisis involving civil defense organizations, and in some cases evacuations (Escobar-Wolf et al. 2008). Recognition of the potential for a disaster by the local population and the governmental authorities has generated the interest to manage the risk through an early warning system (Escobar-Wolf, 2009).

The threat of pyroclastic flows and associated ash cloud surges stands out among other hazards, because of the recent experiences during the large eruptions in the 60’s and 70’s (Bonis and Salazar, 1973, Davies et al. 1978) and even the minor eruptions of the current cycle, e.g. the June 2003 eruption and pyroclastic flow (Escobar-Wolf, 2008; 2009). During these events, pyroclastic flows traveled distances beyond the location of small villages, but mostly confined to the deep channels that drain Volcán de Fuego. The possibility that in the near future similar but slightly larger pyroclastic flows could be generated during moderate to large eruptions (VEI 3 – 4), and overflow the channel margins, destroying the interfluval terrain where the communities are settled, is a major concern that has to be addressed in the risk management effort.

Fieldwork on volcanic deposits related to Volcán de Fuego

The fieldwork was focused on the three main drainages on the W-SW-S flanks of Fuego: Barranca (Spanish for “ravine” or “channel”) Santa Teresa / Seca, Barranca Taniluya and Barranca Ceniza, with additional work done on a few sites on the E and SE flanks of the volcano. Over a period of one month, transects along the thalwegs of the barrancas and detailed description of deposits on 37 sites were gathered (see figure 1), mainly related to pyroclastic flow deposits. Samples from some of the sites were collected, especially from those sites in which charcoal was present in the deposit, with the aim to obtain dates on these units. GPS locations, pictures and field notes / sketches were taken on each site,
recording all the observations and field relationships. Other locations were also visited and observed in less detail, including transects on the interfluvial terrain.

Figure 1. Locations of the 37 sites studied in detail.

**General description of volcanic deposits and terrain morphology:**

A variety of products was observed on the outcrops visited. Good exposures were generally restricted to erosion cuts within the active channels of the Barrancas (figure 2a), and on road and quarry cuts (figure 2b). Due to the near vertical nature of these outcrops, access for a detailed description was usually only possible for the lower units at each site. Field relationships interpretations were fairly straightforward on most outcrops/sites, and although in most cases the outcrops only showed a 2D perspective of the deposit, in some broader outcrops, especially in quarries or channel sections were erosion had cut a wider and more sinuous channel, it was possible to reconstruct a 3D configuration of the paleoenvironment at the moment of the deposit emplacement, e. g. a paleochannel filled by a pyroclastic flow (figure 2c).
Different types of deposits can be casted within a lithofacies association model that corresponds to the processes and environments on which the different products were emplaced, following but slightly modifying the ideas of Vessell and Davies (1981) and Hackett and Houghton (1989). Access to the core / vent facies was not possible due to safety concerns on this very active volcano. Overall there was a progression from proximal facies dominated by lava flows and rock fall colluviums (figure 3a), to the intermediate facies dominated by diamictons (figure 3b). The proximal facies comprise the upper parts of the cone, at elevations above 1500 – 2000 masl, where the slopes are typically above 20°. The diamictons that dominate the medial facies are mostly interpreted to represent pyroclastic flow deposits. From these facies there is a transition to the distal facies dominated by diamictons interpreted as formed predominantly by lahar deposits. The transition of a predominance of pyroclastic flow deposits to a predominance of lahar deposits was observed at an elevation between 800 and 1000 masl,
and where the slope falls below 5º. A more detailed description of the diamictons interpreted as pyroclastic flow deposits is given below.

Channel morphology also seems to reflect these facies and their transitions. In the proximal facies the channels have two distinct morphologies. The channels are practically nonexistent above the 3500 masl elevation, and around that elevation they start to become recognizable, as the planes that separate them define their margins. For the first 1 – 2 km the channel is very poorly defined and broad (between 200 and 350 m), having a straight pattern and with a gently curved cross sectional shape and small to moderate cross sectional areas (1,000 to 10,000 m², with the exception of Barranca Honda). The thalweg
is very steep, with average slopes of >30° near the 3500 masl level contour, and 20 - 25° at 2 km downstream. These channels are carved in a sequence of lava flows and clastic material, however in most of them there is a predominance of recent talus material produced by rock fall and small avalanches associated to the current volcanic activity, which gives the channel bottom a rather aggradation aspect. These channels do not host active streams and carry water only during rain events. At ~2500 - 2800 masl the channels become narrower, funneling into the better defined and steeper sided channels that characterize the lower proximal facies.

In the lower proximal facies, the channels are well defined, with either a “v” shaped or a trapezoidal cross section, depending on the width of the channel bottom (figure 4a). The channels pattern is straight, and they enlarge in cross sectional area, becoming deeper downstream on this section; however their width tends to remain constant or even reduce slightly downstream. The cross sectional area increases downstream reaching a maximum near the transition to the medial section (with the exception of Santa Teresa) with values above 10,000 m². The depth of the channel increases to values in excess of 50 to 100 m. The average thalweg slopes fall from 20° at the beginning of the section, to 10° - 15° at the end. The channels are carved in a sequence of lava flows with interbedded pyroclastic material layers, similar to the upper proximal section, but with large ratio of pyroclastic vs. lava flow units. The channel itself tends to have some debris carried by water (mainly fluvial), but in many cases bare eroded lava surfaces are exposed on much of the channel bottom. Vertical steps and jumps in the thalweg profile are common, carved by differential erosion where relatively resistant lava flows end abruptly and are followed downstream by more erodible clastic material. Channels do not host active streams in this section, and carry water only during rain events. The interfluvial terrain is steep and to some degree it shows roughness associated with a clearly defined drainage pattern, but in general has much less relief than the main channels.

In the medial facies section the channels are well defined, having trapezoidal and in many cases “rectangular” cross sections, with the slope of the channel margins commonly exceed 70° and in some cases approach the vertical (figure 4b). Cross sectional areas and depth of the channel decrease from the maximum value reached at the transition between proximal and medial sections, to very low values of less than 1,000 m² near the transition to the distal section (with the exception of El Jute and Honda, which have cross sectional values above 3,000 m². The width for most barrancas remains relatively constant or changes in a more random fashion downstream, but in some cases (e. g. Taniluya) the channel narrows systematically downstream. In wide barrancas (e. g. Taniluya and Santa Teresa) the emplacement of pyroclastic flow deposits inside the channel and the subsequent erosion of these deposits by stream incision leaves a series of large terraces (up to 30 – 40 m high), in this section a meandering channel pattern starts to develop, as a smaller channel “nested” within the main larger channel is carved in the recent pyroclastic deposits. The thalweg slope falls from 10° - 15° in the upper part of the section to <5° in the lower part. The channel bottom tends to be flat, commonly covered with recent fluvial and laharc deposits, and in many cases forming small terraces (< 2m high). The local terrain consists mainly of pyroclastic flow deposits, although the abundance of diamictons related to other processes, mainly lahars, increases downstream. The presence of this relatively erodible material has played an important role in the characteristic morphology of the barrancas (e. g. the steep sided
walls). Infrequently, lava flows are interbedded in the sequence, intersecting the channels at rather low angles. The interfluvial terrain has a smooth topography and a relatively low relief; therefore the channels represent the strongest negative topography in this section, with the exception of the remnants of older volcanic rocks that rise above the recent deposits. Between 1000 and 1200 masl the channels become hosts to perennial water streams, often fed from springs located at the contact of permeable deposits of clastic origin that are on top of lava flows (e.g. at Ceniza).

Figure 4

In the distal facies section the channels become much shallower (< 5 m) losing cross sectional area (<1000 m$^2$), and sometimes almost vanishing in the alluvial plain. Eventually they merge with other larger drainage channels becoming their tributaries, joining one of three major river systems in the area: the Pantaleon-Coyolate, the Achigue and the Guacalate. After joining a major drainage system the
channel characteristics may change dramatically and the variation in the parameters we have described so far becomes less systematic with distance from the vent. The width of the channels remains approximately constant, before joining larger channels. The thalweg slope remains below 5° and slowly decreases, in some cases to values below 1° as it enters the coastal plain after joining a major river system.

Previous researchers have found that most of the products of Fuego fall within a rather narrow range of chemical compositions, especially during the recent and historic times (Rose et al, 1978, Chesner and Rose, 1984, Chesner and Halsor, 1997). This became obvious in our fieldwork as well. Most rocks exhibiting few vesicles (e.g. those found in deposits other than tephra falls) that were relatively non-altered, had a characteristic appearance in hand samples (Figure 5a), regardless of the origin (diamicton or lava flow). Typically they showed a fresh, dense, holocrystalline, porphyritic - aphanitic, phenocryst rich texture, dark gray to black in color. Most samples contained abundant phenocrysts of plagioclase (modal frac ~ 50-60%), most mm in size but some are as large as 1 to 1.5 cm. Other phenocryst phases present (< 5%) include olivine and pyroxene (cpx & opx ?). The matrix is aphanitic dark gray to black. Vesicularity varied among different types of deposits, the highest being in scoria found in tephra fall deposits.

A few samples, including some at the upper part of the studied sequence, showed some relatively uncommon features, including “magma mingled like” textures of dark and light colorations (Figure 5b), suggesting the eruption of different magma compositions in some of the eruptions.
Tephra deposits:

The tephra deposits examined are usually composed of well sorted scoria and lithic lapilli size clasts. Deposit thicknesses for the sites described in this report (at 2 to 10 km from the current vent) range from a few cm to ca. 1 m. The tephra deposits occur typically in sequences, intercalated with diamictons and soils (Figure 6a and 6b). In some cases the tephra deposits may be genetically related to the intercalating deposits, e.g. a pyroclastic flow deposit and a tephra deposit that were emplaced during the same eruption. Although the thickness of individual horizons or tephra layers was not tracked from one location to another, (in part due to the difficulty to differentiate different tephra layers, given the monotony of products encountered at Fuego), there is an obvious tendency of tephra layers to become thicker towards the vent. Tephra deposits thinner than a few cm, or deposits composed of material finer than lapilli tend to be more difficult to recognize in the field were therefore not logged and described in detail.
Lava flows, including deposits from recent eruptions (e.g. from 2002 to 2007); usually reach distances up to 5 – 6 km from the vent. They form distinctive units with upper and lower “rubble” layers and a dense core. Thicknesses vary over the range of 1-2 m to more than 5. Although not evident from older deposits, the recent lava flows have been efficiently channelized into the preexisting drainage. “High level marks” left by these flows in the form of levees and veneer of lava on the channel margins, suggest that at peak flow, these flows reached a much higher level than the deposit would suggest (Figure 7).
Diamictons

For most of the longitudinal transects along the barrancas and at the sites logged on the interfluvial terrain, the predominant type of deposit were diamictons. They usually share a common appearance in the field, being massive (non-sorted and non-stratified), non indurated, deposits of dense blocks and/or bombs (> 1m) set in a matrix of sand (figure 8a). As expected from the typical lithology of Fuego’s products, these deposits are gray to tan or pink in color. Although massive in general appearance, some basic structures can sometimes be seen, mainly coarse tail grading and horizontal trains or concentrations of larger clasts (blocks or bombs) separating more homogenous and massive portions of the deposit (figure 8b). These coarser clast trains or concentrations may represent the upper surface of individual pulses emplaced on a rapid progression during a single eruption, given that there are no signs of erosion, soil formation or deposition of any other remarkable layer in between. Despite not being indurated, these deposits can be fairly stable and form almost vertical cliffs over periods of decades (figure 8c).
The difficulty of elucidating or attempting to infer the process that gave origin to these deposits makes it impossible to differentiate between pyroclastic flow and lahar deposits, however a few pieces of evidence usually points in one or the other direction. Among these pieces of evidence we considered the abundance or charcoal, sometimes preserved as a layer or logs and burned vegetation at the base of the deposit (figure 9a), “baked” soils underneath the deposit (figure 9b), a predominantly monolithologic composition, and the presence in many cases of a coarse fragments depleted ash layer at the bottom of the deposit (figure 9c), suggesting an origin from an ash cloud surge perhaps associated to the pyroclastic flow. “Cauliflower blocks / bombs” textures are also very abundant on many of these flows (figure 9d), especially forming concentrations of blocks / bombs at the termini of individual flows or pulses.
Other lines of evidence also suggested that most of the diamictons, especially in the upper slopes of the volcano, were from a pyroclastic flow origin. Within the context of the lithofacies association, the thick deposits (usually between 10 and 50 m thick) emplaced on relatively steep slopes (10° - 20°) are considered to be unlikely the product of lahars and more likely to be deposits emplaced by pyroclastic flows. Many of the recent and historical deposits of pyroclastic flows (e.g. from the eruptions in the 70’s and from 2003 onwards) were compared in the field with deposits from large lahars that occurred during tropical storm Stan in 2005 (figure 10). The deposit of these lahars didn’t start to form significant deposits until reaching slopes of around 10° and most of the volume was deposited on slopes below 5°, and although the deposits are also massive, they do not form single deposits in excess of 3 m, show a higher content of clay (this is something that can’t be differentiated from older pyroclastic flow deposits) and a more heterolithic composition. Less preserved “cauliflower bomb” textures in the 2005 lahar deposits also suggest that a high concentration of cauliflower bomb textures in a deposit suggests an origin by a pyroclastic flow process.
Pyroclastic flows and related deposits, and paleoenvironment of emplacement

From the perspective of hazards assessment some very specific characteristics of the pyroclastic flows become highly relevant. As pointed out by Bonis and Salazar (1973), the pyroclastic flows that occurred during the eruptions in the 70’s didn’t produce any casualties because they were contained within the channels, however, slightly larger flows or even flow of the same volume flowing on channels with reduced cross section (e. g. due to previous aggradation) can overflow the margins of the channel and destroy the interfluvial terrain. This in fact occurred along channels in non inhabited areas during those eruptions, and happened again during a much smaller eruption in June of 2003. Moreover, the typical pyroclastic flows produced at Fuego could be considered a type of block (or bomb) and ash flow, composed by a dense avalanche like part and an overriding ash cloud accompanying the basal avalanche. In many instances it has been observed at other volcanoes that a more diluted component can detach from the denser basal avalanche and surmount the channel topography (Fisher, 1995). This has also been the case at Fuego during eruptions that have happened since 2002.

For these reasons, one of the aims of the fieldwork was to find evidence of past events that could have produces such types of overflowing phenomena. Deposits from overbank flows (Schwartzkopf, et al. 2005; Charbonnier and Gertisser, 2008) were observed in cases where the extension of the outcrop allowed for the reconstruction of the 3D morphology of the paleochannel in which the flow was deposited (figure 11).
These kind of deposits was also inferred in deposits found in the interfluvial terrain and adjacent to major drainage channels, e. g. on the village of Panimache I, next to the Barranca Taniluya, where at least two relatively thin block and ash flow deposits (figure 12), each between 1 and 2 m thick extends over hundreds of meters over the interfluvial terrain, containing very abundant charred logs and few blocks larger than 30 cm. The relative depletion of the coarse tail component, the low thickness and the abundance of charcoal suggest that these deposits were emplaced as overbank facies when a flow that initially was contained within a channel (Barranca Taniluya?) overflowed the channel margins and spread over the interfluvial terrain, which probably was covered by a thick jungle (as opposite to the active channel, which as can be seen currently on all drainages of Fuego have only sparse vegetation), providing the abundant vegetation for the charcoal found in the deposit. This vegetation must have presented additional resistance to the flow and in particular for the coarsest component of blocks. Perhaps only the higher level of the flow could overflow the channel margins, and if there was some normal clast size segregation in the flow at that point, only the smallest part of the coarse tail component made it that far. The relatively smaller thickness of the flow compared with most channel confined deposits at that distance and slope from the volcano could also be related to an overflow process.
Evidence for ash cloud surges was found also associated to many pyroclastic flow deposits, especially at the base of those deposits, usually in the form of a fine ash layer forming an erosive contact with the substrate and overlaid directly by the block and ash flow deposit (figure 13). The preservation of surge deposits in areas where they were not immediately covered by a pyroclastic flow is unlikely, but despite the evidence that these deposits extended beyond the reach of the associated block and ash flow, this is a likely situation.
To further assess the hazard related to pyroclastic flows, numerical flow models constrained with the observations here presented could be done, e.g. using Titan2D (Patra et al. 2005) or VolcFlow (Kelfoun, 2009), especially to explore the possibilities of overflow and interfluvial terrain inundation by pyroclastic flows, especially in populated areas. These results are aimed to be included in a more general “formal risk assessment” using a probabilistic tree framework, as part of my Ph D research project.

References


