Pyroclastic Flow Hazard at Volcán Citlaltépetl

GIS Model for Volcanic Hazard Assessment: Pyroclastic Flows at Volcán Citlaltépetl, México

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(Received: 16 December 2002; accepted: 28 October 2003)

Abstract. Volcán Citlaltépetl (Pico de Orizaba) with an elevation of 5,675 m is the highest volcano in North America. Its most recent catastrophic events involved the production of pyroclastic flows that erupted approximately 4,000, 8,500, and 13,000 years ago. The distribution of mapped deposits from these eruptions gives an approximate guide to the extent of products from potential future eruptions. Because the topography of this volcano is constantly changing computer simulations were made on the present topography using three computer algorithms: energy cone, FLOW2D, and FLOW3D. The Heim Coefficient ($\mu$), used as a code parameter for frictional sliding in all our algorithms, is the ratio of the assumed drop in elevation (H) divided by the lateral extent of the mapped deposits (L). The viscosity parameter for the FLOW2D and FLOW3D codes was adjusted so that the paths of the flows mimicked those inferred from the mapped deposits. We modeled two categories of pyroclastic flows modeled for the level I and level II events. Level I pyroclastic flows correspond to small but more frequent block-and-ash flows that remain on the main cone. Level II flows correspond to more widespread flows from catastrophic eruptions with an approximate 4,000-year repose period. We developed hazard maps from simulations based on a National Imagery and Mapping Agency (NIMA) DTED-1 DEM with a 90 m grid and a vertical accuracy of ±30 m. Because realistic visualization is an important aid to understanding the risks related to volcanic hazards we present the DEM as modeled by FLOW3D. The model shows that the pyroclastic flows extend for much greater distances to the east of the volcano summit where the topographic relief is nearly 4,300 m. This study was used to plot hazard zones for pyroclastic flows in the official hazard map that was published recently.

Key words: Citlaltépetl, computer simulations, DEM, hazard zones, interactive viewing, México, Pico de Orizaba, pyroclastic flows, volcano

1. Introduction

Pyroclastic flows are incandescent mixtures of volcanic particles and gas that descend from collapsing eruption columns and volcanic domes at speeds that can exceed 100 m/s (Sheridan, 1979). The societal risk related to pyroclastic flows is a problem that public safety authorities around the world must face several times

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We have developed a methodology to evaluate the danger from these incandescent avalanches and clouds by using computer models of their flow paths to map hazard zones. This technique requires an accurate digital elevation model of the surface and reliable data on the flowing materials to constrain parameters for the computer simulations. Some recent pyroclastic flows that were used to constrain the effects of terrain on our model parameters are: Mount St. Helens (1980), Unzen (1991), and Colima (1991, 1994). In this paper we evaluate the results from three different, but related, flow models: energy cone, FLOW2D, and FLOW3D. Our procedure greatly extends the forecasting capability at poorly studied volcanoes by providing a rapid and easily interpreted product that is based principally on topography and flow parameters from observed eruptions.

2. Problem Statement

Volcán Citlaltépetl (Pico de Orizaba) is located in the State of Veracruz at the eastern end of the Trans-Mexican Volcanic Belt (Figure 1). Its elevation of 5,675 m creates considerable hazard for gravity-driven materials like avalanches, mudflows, and pyroclastic flows. Although this volcano has been relatively quiet since the Spanish conquest, there have been three well-documented catastrophic events that involved the production of pyroclastic flows at approximately 4,000, 8,500, and 13,000 years ago (Siebe et al., 1993; Carrasco-Núñez and Rose, 1995; Carrasco-Núñez, 1999). The approximate repose period of 4,000 years for catastrophic events justifies preparation for future activity of this type. Höskuldsson and Cantağrel (1994) map several zones with populations between 10,000 and 300,000 around the volcano. In Figure 1 we show the main population centers in the states of Veracruz and Puebla, Mexico. The results presented in this paper were used to create a hazard map of Volcán Citlaltépetl (Sheridan et al., 2002a) that is comparable to maps of other active volcanoes in Mexico such as Popocatépetl (Macías et al., 1995) and Colima (Martin del Pozzo et al., 1995).

3. Methods

3.1. MODELS

Although the three models used in this paper calculate several aspects of pyroclastic flows, the main characteristics of pyroclastic flows that concern hazard assessment are runout distance and flow coverage. Because pyroclastic flows destroy all life in their path, the simulated surface covered by the maximum expected pyroclastic flow defines the hazard zone. All three models in our study depend on an accurate DEM of current topography for flow calculation and visualization of flow distribution. Estimated values and limits for the models parameters are based on the known distribution of eruptive products from Citlaltépetl and experience with hazard assessments at other volcanoes. These parameters were determined empirically using simulations of flows that better fit observed flows of two distinct
Figure 1. Location map for Citlaltépetl (Pico de Orizaba-PO) at the eastern end of the Mexican Volcanic Belt. The large box shows the location of the study area in more detail, including the well-defined river drainage towards the coastal plain. Volcanic features (in triangles): (SN) Sierra Negra; (PO) Pico de Orizaba; (LC) Cerro Las Cumbres; (SD) South Derrumbadas; (ND) North Derrumbadas; (PI) Cerro Pinto; (PZ) Cerro Pizarro; (CP) Cofre de Perote. Cities in squares.
eruptive magnitudes. Low magnitude pyroclastic-flow eruptions (corresponding to level I) reached distances of about 10–13 km from vent and occurred approximately every 2,000 years. In the case of pyroclastic-flows of intermediate magnitude (Level II), they reach about 18–27 km with a recurrence period of about 4,000 years. Table I summarizes the input parameters used for each model as discussed in text, and compares them with those used in hazard assessments at other volcanoes. Further discussion of the relationship between our model results and the known distribution of pyroclastic flow deposits from prior eruptive episodes is provided later. Here we provide a brief description of each model and describe the designed output display format of both models and maps to facilitate interpretation by public safety officials as well as scientists. A detailed summary of the development of all three models is given in Hooper and Mattioli (2001).

3.1.1. Energy cone

Malin and Sheridan (1982) proposed the energy cone model to mimic the 1980 blast eruption of Mount St. Helens. Höskuldsson and Cantagrel (1994) used a variation of this concept to develop a hazard map of Pico de Orizaba for pyroclastic and debris gravity currents. Our methods differ from theirs in that we use GIS to develop and compare a variety of techniques which model pyroclastic flows.

The principle of the energy cone (and energy line) is that the height of the starting point of the flow \((H)\) ratios to the length of the runout \((L)\) acts as a type of friction parameter termed the Heim coefficient \((\mu)\) after Albert Heim, the originator of the energy line concept (Heim, 1932). The inclination of the energy cone is an angle defined by \(\arctan(H/L)\). The intersection of the energy cone, originating at the eruptive source, with the ground surface defines the distal limits of the flow. The vertical distance \((h)\) between the ground surface and the energy cone provides a means to estimate the flow velocity in this model.

\[
v^2 = 0.5 gh,
\]

where \(v\) is flow velocity and \(g\) is gravitational acceleration. For our level I simulation we used a Heim coefficient of 0.26 and for the level II hazard we used a value of 0.18. The model results are shown projected on the topography in Figure 2 and mapped in Figure 3. The energy cone has been applied to the assessment of hazard at Vulcano, Lipari, and Vesuvius (Sheridan and Malin 1983); Soufriere Hills Montserrat (Wadge and Isaacs, 1988) prior to it’s recent eruptive episodes; and most recently at Campi Flegrei Italy (Alberico et al., 2002).

3.1.2. FLOW2D

A weakness of the energy line models is that it assumes straight-line flow trajectories that pass through topographic obstacles. To resolve this problem in their study of Colima and El Chichón volcanoes Sheridan and Macías (1992) developed the FLOW2D code for use in small computers. This code assumes that shear resistance
Table I. Typical kinematic flow parameters used to model various pyroclastic flows (PF) and PF hazard zones at various volcanoes

<table>
<thead>
<tr>
<th>Volcano (PF-event or hazard zone level)</th>
<th>Flow algorithm/ hazard zone mapping method</th>
<th>Reference</th>
<th>Runout (km)</th>
<th>Frictional coefficient ($a_0$)</th>
<th>Viscous coefficient ($a_1$)</th>
<th>Turbulent coefficient ($a_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSH 18 May 1980 blast surge</td>
<td>EC</td>
<td>Malin and Sheridan (1982)</td>
<td>~22.5</td>
<td>0.123</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Soufriere Hills Montserrat zones 2–7</td>
<td>EC</td>
<td>Wadge and Isaacs (1988) (zone 7)</td>
<td>~5.0–8.0</td>
<td>0.22–0.36</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Campi Flegri Italy VEI = 3/4</td>
<td>EC</td>
<td>Alberico et al. (2002)</td>
<td>~1.1–1.6</td>
<td>0.105</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>MSH 18 May 1980 blast surge</td>
<td>FLOW * (BL1)</td>
<td>McEwen and Malin (1989)</td>
<td>~22.0</td>
<td>0.11</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>MSH 18 May 1980 pumice flows</td>
<td>FLOW * (PY5)</td>
<td>McEwen and Malin (1989)</td>
<td>~7.4–8.0</td>
<td>0.15</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>MSH 7 Aug 1980 pumice flow</td>
<td>FLOW * (PY1/PY2)</td>
<td>McEwen and Malin (1989)</td>
<td>~5.7</td>
<td>0.14–0.19</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Colima volcano, Mexico</td>
<td>FLOW2D</td>
<td>Sheridan and Macias (1992)</td>
<td>2–4</td>
<td>0.47</td>
<td>0.01</td>
<td>–</td>
</tr>
<tr>
<td>El Chichon, southnorth</td>
<td>FLOW2D</td>
<td>Sheridan and Macias (1992)</td>
<td>~?</td>
<td>0.09–0.13</td>
<td>~?</td>
<td>–</td>
</tr>
<tr>
<td>MSH 7 Aug 1980 pumice flow</td>
<td>FLOW3D</td>
<td>Kover (1995)</td>
<td>4.7</td>
<td>0.10</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>8 June 1991 Unzen block-and-ash flow</td>
<td>FLOW3D</td>
<td>Kover (1995); Sheridan and Kover (1996)</td>
<td>~5.5</td>
<td>0.06</td>
<td>0</td>
<td>0.0125</td>
</tr>
</tbody>
</table>
Table I. Continued

<table>
<thead>
<tr>
<th>Volcano (PF-event or hazard zone level)</th>
<th>Flow algorithm/ hazard zone mapping method</th>
<th>Reference</th>
<th>Runout (km)</th>
<th>Frictional coefficient ((a_0))</th>
<th>Viscous coefficient ((a_1))</th>
<th>Turbulent coefficient ((a_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996 Tar River valley pfs Soufriere Hills Montserrat</td>
<td>FLOW3D (MONT1/MONT2)</td>
<td>Hooper and Mattioli (2001)</td>
<td>~2.8–3.0</td>
<td>0.06–0.10</td>
<td>0–0.01</td>
<td>0.001–0.01</td>
</tr>
<tr>
<td>12 May 1996 Soufriere Hills Montserrat block-and-ash flow</td>
<td>(undocumented flow algorithm similar to FLOW and FLOW3D)*</td>
<td>Wadge et al. (1998)</td>
<td>2.7</td>
<td>0–0.13</td>
<td>0–0.1</td>
<td>0–0.034</td>
</tr>
<tr>
<td>Colima 1913</td>
<td>FLOW3D</td>
<td>Saucedo et al. (1997)</td>
<td>3.5</td>
<td>0.35</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8.2</td>
<td>0.17</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.12</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>Citlaltepetl Level I</td>
<td>EC</td>
<td>This study</td>
<td>10.2–14.7</td>
<td>0.26</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Citlaltepetl Level II</td>
<td>EC</td>
<td>This study</td>
<td>16.4–24.0</td>
<td>0.18</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Citlaltepetl Level I</td>
<td>FLOW2D</td>
<td>This study</td>
<td>10.2–13</td>
<td>0.15</td>
<td>0.01</td>
<td>–</td>
</tr>
<tr>
<td>Citlaltepetl Level II</td>
<td>FLOW2D</td>
<td>This study</td>
<td>18.4–26.8</td>
<td>0.05</td>
<td>0.01</td>
<td>–</td>
</tr>
<tr>
<td>Citlaltepetl Level I</td>
<td>FLOW3D</td>
<td>This study</td>
<td>8.1–11.5</td>
<td>0.17</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>Citlaltepetl Level II</td>
<td>FLOW3D</td>
<td>This study</td>
<td>17.7–26.3</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*“FLOW” code of McEwen and Malin (1989) calculates viscous and turbulent resistance as a function of several user-specified variables and constants, including: viscosity, yield strength, flow thickness, ground slope, change in flow depth with time, channel shape and drag coefficients for the ground and atmosphere. Many of these quantities are largely unknown and are accounted for in subsequent flow algorithms using empirically defined coefficients describing velocity dependent viscous \((a_1)\) and turbulent \((a_2)\) resistance. The model of Wadge et al. (1998) makes similar use of these coefficients, but also requires user-specified parameters that account for flow expansion as a result of atmospheric entrainment and sedimentation during motion. For comparative purposes, model results constraining \(a_0, a_1,\) and \(a_2\) are reported here only.
Figure 2. Visualization comparison of energy cone (shaded area) and FLOW3D (colored flow threads) simulations of Level I and Level II type events. In the Level I simulation the 4,000-year BP deposits are shown in red. In the Level II simulation the 8,500 y BP deposits are shown in blue. Mapped deposits, digitized as vectors, were color encoded to the topography using a raster bit map.
Figure 3. a and 3b: Maps showing Level I (a) and Level II (b) pyroclastic flow simulations. UTM coordinates are UL = 659450E, 2126045N, LR = 710647E, 2076017N. Major communications means are: highways in thick dashed lines, secondary paved road in thin dashed lines, and railways in alternated dotted and dashed lines. For reference the relative population of the major city Orizaba is 250,000 inhabitants, whereas Coscomatepec is around 25,000 inhabitants.
(\(\tau\)) depends on both basal friction \((a_0)\) and viscosity parameters \((a_1)\) [c.f. Mellor, 1978; Pariseau and Voight, 1979; McEwen and Malin, 1989].

\[
\tau = a_0 + v^* a_1
\]  

(2)

FLOW2D code mimics actual flow velocity better than does the energy line and it shows the runback of flows off large topographic barriers. It is also easily used in 2D on personal computers. However this code is limited by the need to tabulate topographic profiles along each flow path. Another disadvantage is that FLOW2D does not consider lateral movement of the pyroclastic flows. For our FLOW2D simulations of the level I pyroclastic flows we used an average value of 0.15 for \(a_0\) and 0.01 for \(a_1\). For the level II flows we used an average value of 0.05 for \(a_0\) and 0.01 for \(a_1\). These are empirical values that fit with the maximum extensions for pyroclastic flow eruptions of short and intermediate magnitude, respectively, as mentioned earlier. The results of the FLOW2D calculations are shown in the hazard maps of Figure 3. Development of FLOW2D has since been superseded by FLOW3D, which is further described in the following section.

3.1.3. FLOW3D

The FLOW3D code is based on the generation of a digital elevation model (DEM) representing the topographic surface along which the gravity flows move on a Triangulated Irregular Network (TIN) of elevations. This kinematic model is easy to construct from various types of data sets and a variety of geometric configurations (point source, radial distribution, linear or random) can be used to model flow initiation. The triangles are contiguous at their boundaries so that there are no discontinuities such as those that exist with raster data. The TIN also serves as the basis for the computations where gravitational acceleration is assigned to each triangular element of the network. The flow algorithm considers previous flow models for gravity slides and assumes a constant mass, thickness, and density of the flows. Within each specified triangle a single vector represents the driving acceleration due to gravity.

The FLOW3D code (Kover, 1995; Sheridan and Kover, 1996) provides velocity histories of particle streams along flow paths in three dimensions. It is similar to the “FLOW” model of McEwen and Malin (1989) in its calculation of frictional resistance, acceleration along the path of steepest descent for each terrain element, and the assumption that the center of mass is focused at the ground surface. However, FLOW3D calculates viscous and turbulent resistances by multiplying the user-defined coefficients of energy dissipation by the flow velocity, which is determined incrementally. Multiple flow paths are incremented every 0.1 seconds across triangular elements using as many as three parameters to calculate shear resistance \((\tau)\): basal friction \((a_0)\), viscosity \((a_1)\) and turbulence \((a_2)\) (cf. Mellor, 1978; Pariseau and Voight, 1979; McEwen and Malin, 1989).

\[
\tau = a_0 + v^* a_1 + v^{2*} a_2
\]  

(3)
FLOW3D simulations have been verified by laboratory tests and field studies at the 1991 Unzen eruption (Kover and Sheridan, 1993; Kover, 1995) and the 1980 Mount St. Helens pyroclastic flows (Kover, 1995). It has been applied to risk assessment at several other volcanoes including the creation of hazard maps at Popocatépetl (Macías et al., 1995) and Volcán Colima (Martín del Pozzo et al., 1995) and risk probability at Volcán Colima (Sheridan and Macías, 1995, Saucedo et al., 1997). Most recently, FLOW3D was used to simulate the velocity history and runout of block-and-ash flows from “Merapi type” dome collapses at Soufriere Hills Montserrat (Hooper and Mattioli, 2001).

For the level I pyroclastic flows we used $a_0$ as 0.17 and $a_1$ as 0.01. For the later level II flows we used $a_0$ as 0.15 with no viscous effects. Again, these parameters are determined empirically fitting to the spatial distribution of an observed flow. The runout distance for level I was 8–11 km and 18–26 km for level II. The appropriate flow kinematics is achieved by trial and error. Bit-mapped and color coded overlays of multiple themes were used to produce realistic images and maps. The interactive platform of FLOW3D allows the observer to adjust the perspective and distance for the desired view. The life-like appearance of scene facilitates the interpretation by non-professional observers. The use of cities and towns as a layer in the model allows the estimation of potential loss of life and property in the model simulations. These results are compared with those of the energy cone in Figures 2 and 3. The FLOW3D code is further documented in Kover (1995).

3.2. GIS PROCEDURES

FLOW3D and Energy Cone models were simulated on a topographic model constructed from a National Imagery and Mapping Agency (NIMA) DTED-1 DEM with a 90 m grid spacing and vertical accuracy of approximately ±30 m. The digital topography takes the form of a Dense Triangular Network (DTN) that, like a Triangular Irregular Network, conforms well to the morphology of topographic barriers and best resolves the path of deepest descent. But in contrast it resolves watersheds and drainage networks like grid-based DEMs (Jenson and Domingue, 1988; Jones et al., 1990; Band, 1993).

The final energy cone model was vectorized and filtered to eliminate pixel outliers and small “islands” within hazardous areas. FLOW2D results were digitized using the 1:50,000 scale INEGI maps as a base and major cities and towns as geographic control points. FLOW3D results were vectorized directly from a geo-coded, raster output of the program, taking into account shadow zones created by the multiple flow traces. All of the above themes were assembled as vector overlays in ARCVIEW with other themes such as population centers and 500 m contours derived from the DEM.
3.2.1. **Hazard map construction**

Siebe *et al.* (1993) mapped the distribution of young pyroclastic flows on the west of Pico de Orizaba. Carrasco-Núñez and Rose (1995) and Carrasco-Núñez (1999) expanded the mapped flows to include those to the east and showed that the repose period between this type of event is about 4,000 years. These mapped deposits provide an outer limit for products of catastrophic eruptions, here called level II hazards (Figure 3b). Smaller and more frequent pyroclastic flow eruptions that have a more limited extent (Höskuldsson and Robin, 1993) are here termed level I hazards (Figure 3a) and have a recurrence time of about 2,000 years (Sheridan *et al.*, 2002a). The parameters for the three models in the level I and II simulations (Table I) are set to mimic the distribution of these deposits and are comparable to the values used for hazard assessments at other volcanoes.

4. **Discussion**

There is a general agreement between the hazard maps that the three models produced. The energy cone map is easy to produce and it generates the most conservative map. Shadow zones behind topographically high area are weak in this model and the perimeter is relatively regular. In contrast, the FLOW3D maps show a much stronger conformation of flow boundaries with present topography and shadow zones are pronounced. The weakness of this model is that it has a strong dependence on weakly constrained parameters. FLOW2D map boundaries generally fall between those of the other two models.

These maps are very useful for forecasting future pyroclastic flow hazards at Pico de Orizaba. A convenient combination of the three models provides a good delimitation of hazard zones. The maps have been used as the principal instrument to produce the first hazard map for the Citlaltépetl Volcano (Sheridan *et al.*, 2002a), which is being used to help authorities in Mexico to design their mitigation plans for specific dangerous areas and to discuss the options with the general population. The question that arises in the use of models, is how much faith can be placed on any particular model? A conservative approach would be to draw boundaries in a regular fashion to include all towns that lie close to a border and to ignore the shadow zones forecast by the models that are more strongly influenced by topography. This would favor the energy cone simulations. However, if the shadow zones really are protected areas, there would be a considerable saving of resources during an emergency if these areas were treated as an asset rather than a liability.

5. **Recommendations for Future Research**

It is obvious that the effect of topography on the distribution of pyroclastic flows must be assessed in regard to development of hazard maps. Existing and new models of pyroclastic flows should be constructed for volcanoes with a high probability
of future pyroclastic flow eruption. The best models for hazard application can then be chosen based on actual prediction performance.

The next step in the GIS assessment of pyroclastic hazards at Pico de Orizaba is to estimate potential loss of life and property using polygon data, and inclusion of other important themes such as water supply, power lines and other vital infrastructure. Local authorities, which have detailed cadastral data, can incorporate that information into the hazard maps to assess the risk of a particular area. A logical extension beyond this would be to develop an interactive system for computation visualization and communication on high-performance computers (Sheridan et al., 2002b). Such a system would allow scientists, civil protection officials and the general public to have real-time access to potential hazards with realistic visualization of various scenarios at various scales. The hardware and interfaces for such a system currently exist at several research facilities in the USA.

Acknowledgments

The authors thank Michael Abrams of JPL for supplying the DEM and other digital data used in this study. Civil protection authorities in the city of Xalapa and the state of Veracruz provided valuable field assistance, vehicles, and aircraft for the field stage of this study. Special thanks go to Jose Luis Murrieta and Sergio Rodríguez Elizarrarás of the Universidad Veracruzana in Xalapa for providing hospitality and logistics throughout the study. This work was conducted with financial aid from NASA grant NAG57579 and CONACYT Grant No. 27554.-T.

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