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Mapping and assessing volcanic and flood hazards and risks, with emphasis on lahars, in Arequipa, Peru

R.D. Vargas Franco*
RDVGeoconsulting, Enschede, the Netherlands

J.-C. Thouret*
G. Delaite
PRES Clermont, Université Blaise Pascal, UMR 6524 CNRS, Laboratoire Magmas et Volcans,
Institut de Recherche pour le Développement-R163, 5 rue Kessler, 63038 Clermont-Ferrand cedex, France

C. van Westen*
International Institute for Geoinformation Science and Earth Observation, P.O. Box 6 7500AA, Enschede, the Netherlands

M.F. Sheridan*
Department of Geology, University at Buffalo, State University of New York, Buffalo, New York 14260, USA

C. Siebe*
Departamento de Vulcanología, Instituto de Geofísica, Universidad Nacional Autónoma de México,
Ciudad Universitaria CP, 04510 México D.F., Mexico

J. Mariño*
Instituto Geológico Minero y Metalúrgico, Av. Canadá, San Borja 1470, Lima 41, Peru

T. Souriot*
PRES Clermont, Université Blaise Pascal, UMR 6524 CNRS, Laboratoire Magmas et Volcans,
Institut de Recherche pour le Développement-R163, 5 rue Kessler, 63038 Clermont-Ferrand cedex, France

A. Stinton*
Department of Geology, University at Buffalo, State University of New York, Buffalo, New York 14260, USA

ABSTRACT

Studies of the type, extent, and volume of Holocene pyroclastic and lahar deposits have concluded that future eruptions of El Misti volcano, even if moderate in magnitude, will pose a serious threat to the city of Arequipa, Peru. After describing the

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*E-mails—Vargas Franco: vargasfranco@itc.nl; Thouret: J.C.Thouret@opgc.univ-bpclermont.fr; van Westen: westen@itc.nl; Sheridan: mfs@geology.buffalo.edu; Siebe: csiebe@tonatiuh.igeofcu.unam.mx; Mariño: jmarino@ingemmet.gob.pe; Souriot: T.Souriot@opgc.univ-bpclermont.fr; Stinton: adamstinton@yahoo.com.

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most probable volcanic scenarios at El Misti, this paper concentrates on lahar and flood risk assessment. Scenarios were derived with the help of the simulation codes LAHARZ and TITAN2D. The lahar risk assessment varies significantly depending on the method selected. LAHARZ simulations indicate that a considerable part of the urban areas and infrastructure could be severely affected. Losses due to impacts inflicted by lahars in three selected parts of the urban area are estimated to be in the order of 40–100 million U.S. dollars. In the case of TITAN2D, the resulting lahar-affected area only includes infrastructure assets mainly located along the Río Chili.

Results indicate that although simulation codes could be useful tools in the analysis of lahar hazard scenarios, it is still premature to regard them as accurate sources of information for actual decision making related to risk mitigation at the local level. More research is required to further adjust simulation codes and refine risk scenarios. The first priority for the mitigation of the volcanic hazard faced by the city of Arequipa should be improvement of the risk map (a hazard map has already been drawn and is under scrutiny) and the preparation of contingency plans.

INTRODUCTION

Traditional assessment of volcanic hazards has been based mainly on heuristic approaches assisted by detailed ground-based geological and geomorphological survey (Blong, 1984, 2000; Crandell et al., 1984). Recent advances in information technology have led to the development of computer codes coupled with geographic information systems (GIS), which allow realistic simulations of natural events like hurricanes, floods, tsunamis, and impact scenarios. In the assessment of volcanic hazard and risk, such programs have also been applied successfully (Araña and Felpetoa, 2000; Gómez-Fernández, 2000; Canuti et al., 2002; Alberico and Lirer, 2002; Crowley et al., 2003; Stevens et al., 2004; Santos Daag and van Westen, 2003; Sheridan and Patra, 2005; Rupp et al., 2006). However, there are still few references to cases where computer-based volcanic hazard information has been actually used during risk assessment, planning, and decision making for risk reduction (Druitt and Kokelaar, 2002; Sheridan et al., 2005; Magill et al., 2006). This paper shows some of the difficulties faced when trying to implement computer-based modeling tools for volcanic hazard and risk assessment using as reference the city of Arequipa, Peru.

As of 2005, more than 500 million people live in the shadow of an active volcano, among them at least 50% in large cities (>1,000,000 people) in developing countries (Thouret, 1999; Chester et al., 2001; Chester, 2005). The serious threat of volcanic eruptions in large cities must be addressed by volcanologists as a challenge in terms of assessing the magnitude, frequency, and extent of the hazard in populated urban areas.

Arequipa, capital of the province of the same name, is the second largest city in Peru and the second most important economic center in the country. The population of Arequipa in 2005 was estimated at 850,000 inhabitants (Delaite, 2003). Arequipa is exposed to seismic, volcanic, and flash flood hazards, which can be associated with rainstorms, and both natural and man-made lake breakouts (Thouret and Calvache, 1998). The seismic hazard is principally related to the subduction of the Nazca plate underneath the South American plate, and in the area of Arequipa itself, to the active regional WNW-ESE–trending fault system (Tavera et al., 2001; Fig. 1). The volcanic hazard specifically originates from the location of the city within the area of influence of El Misti volcano (Figs. 2 and 3; Thouret et al., 1999a; Delaite et al., 2005; Degg and Chester, 2005). Arequipa, which is referred to as the "White City" due to the color of the ignimbrite commonly used as building material for colonial monuments (Paquereau-Lebti et al., 2006), is located only 17 km to the southwest and 3.5 km below the summit of the active volcano El Misti (Figs. 1 and 2). The city itself has been built on volcaniclastic fans consisting largely of pyroclastic-flow and lahar deposits. Furthermore, although the potential hazards posed by El Misti were briefly acknowledged in the 2002–2015 Arequipa strategic development plan, the plan itself does not include any specific project or program aimed at reducing the volcanic risk.

The considerable magnitude of the threat for Arequipa represented by a potential volcanic event (as defined in Blong, 1984, 2000; Magill et al., 2006) at El Misti requires urban development planning aided by a sound volcanic hazard *and* risk assessment. Whereas volcanic hazards in the surroundings of Arequipa have been identified extensively, limited work has been done in regard to risk assessment (Delaite et al., 2005). This paper represents an initial step toward a combined hazard and risk assessment.

The approach followed for the volcanic risk assessment is based on the combined analysis of the hazard and corresponding vulnerability components (Blaikie et al., 2004). In relation to vulnerability, and given the scope of this paper, only aspects concerning unsafe conditions will be discussed in detail. In the case of Arequipa, "unsafe conditions" include a qualitative and quantitative description of the buildings (number, type, construction materials, etc.) and the infrastructure, including lifeline utilities (type, relevance, significance) located in the areas that might be affected by volcanic phenomena.

The structure of this paper can be briefly described as follows: First, a general framework for volcanic, lahar, and flood hazard and risk assessment in the city of Arequipa is presented.

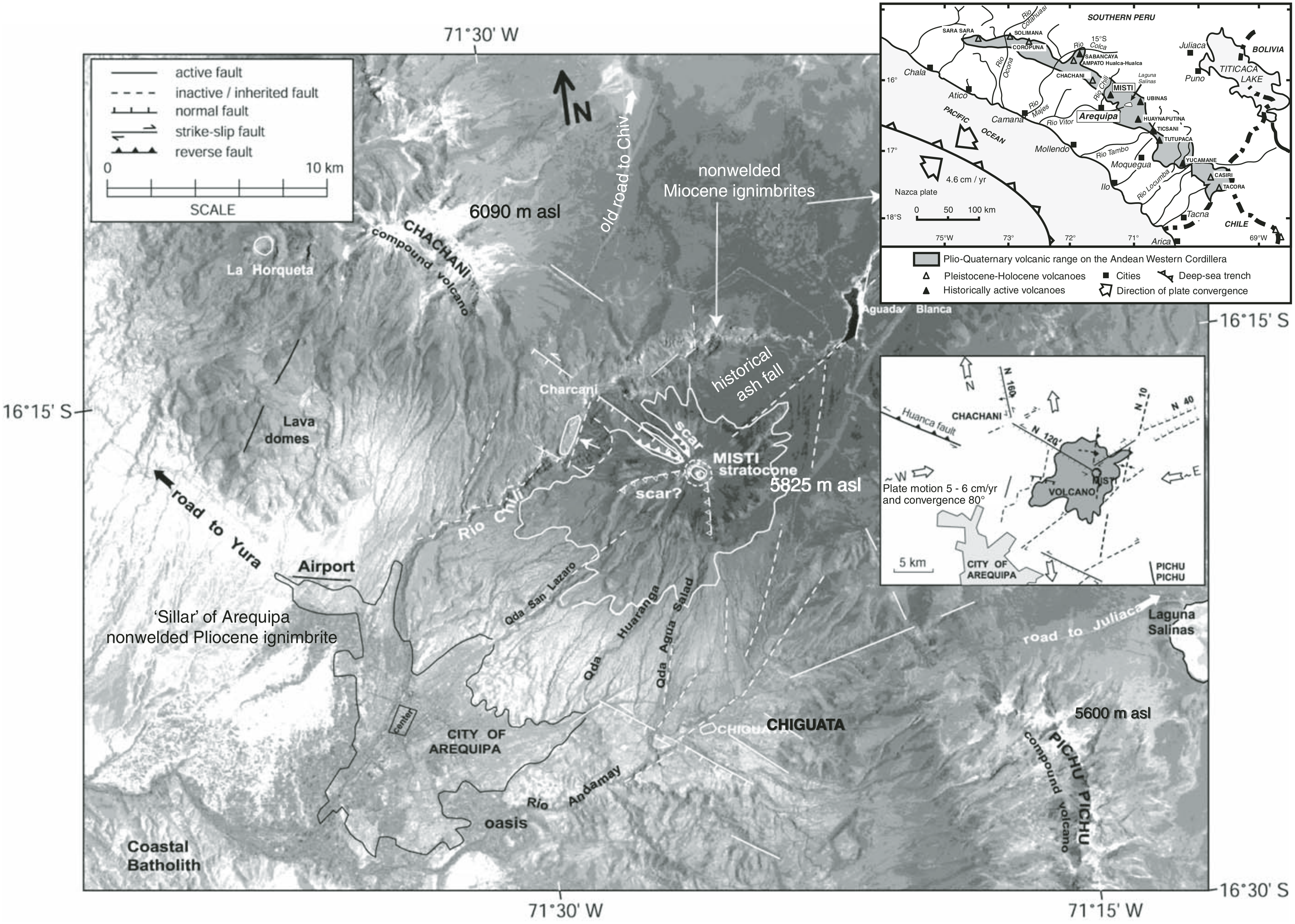


Figure 1. Landsat image as of 1991 showing the basin of Arequipa, the Coastal Batholith to the SW, the three volcanoes of El Misti, Chachani, and Pichu Pichu on the flank of the Western Cordillera, and main tectonic features. Insert maps show the Pliocene-Quaternary volcanic range and active volcanoes in southern Peru, and the tectonic setting of the "pull-apart" basin of Arequipa.

This includes a brief description of the current situation related to the volcanic hazard assessment, in particular, with respect to pyroclastic flows and lahars (both debris flows and hyperconcentrated flows). Second, aspects concerning a vulnerability assessment are described. Third, efforts to assess risk using available lahar hazard information are discussed. A risk analysis was carried out in two pilot areas (Fig. 4): (1) the urban stretch along the Río Chili from its confluence with the Quebrada San Lázaro to the Fierro Bridge across the western margin of the city center; and (2) the upper and middle reaches of the Quebrada (Qda.) Huarangal (which is termed "Mariano Melgar"), from the populated apex of the fan to the intersection with Castilla Avenue, east of the city center.

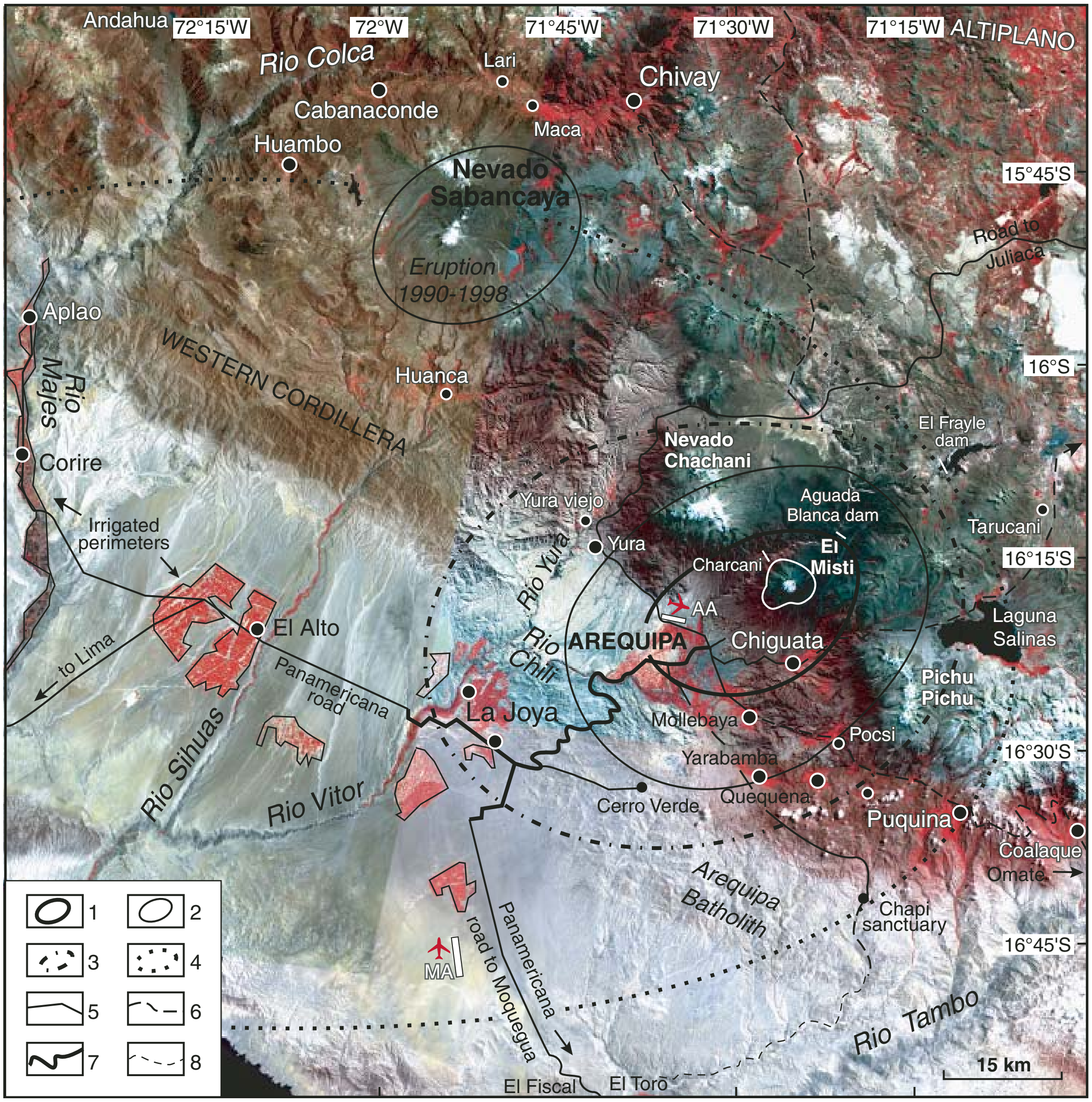


Figure 2. Landsat satellite image showing the general setting of the Arequipa depression at the base of El Misti volcano, and areas potentially affected by tephra fallout from El Misti eruptions. 1—Area covered by at least 5-cm-thick tephra-fall deposit whatever explosive eruption scenario is to be expected. For the purpose of comparison, the 1-cm-thick isopach of the 1990–1998 ash-fall deposit is outlined around Nevado Sabancaya, 70 km NW of Arequipa (after Gerbe and Thouret, 2004). 2—For the purpose of comparison, 10 cm isopach of the 2050 yr B.P. sub-Plinian pumice-fallout deposit (after Thouret et al., 2001). 3—Isopach of potential sub-Plinian and Plinian fallout, 10 cm and 50 cm, respectively. 4—Approximate area covered by ash fallout in case of a Volcanic Explosivity Index 6–sized Plinian eruption comparable to the A.D. 1600 Huaynaputina event (Thouret et al., 1999b, 2002). 5—Paved road (two lanes). 6—Firm dirt road. 7—Road to be enlarged to 2 × 2 lanes as a preventive measure in case of a Plinian eruption. 8—Road to be constructed as evacuation route to the S and to the E, in case of a Plinian eruption. AA—Airport of Arequipa. MA—La Joya Military Airport, which could be used for evacuation and relief procedures if there was a large eruption.

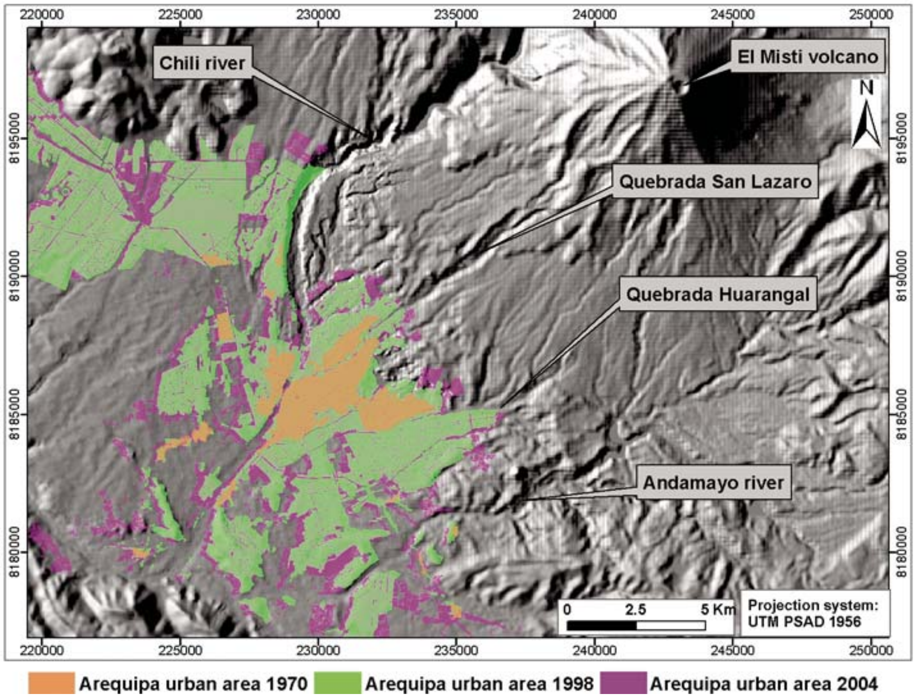


Figure 3. Urban development of Arequipa between 1970 and 2005.

Volcanic Hazards in Arequipa

The eruptive history of El Misti volcano has been studied by several authors (Bullard, 1962; de Silva and Francis, 1990; Thouret et al., 1995, 1999a, 2001; Delaite et al., 2005). A simplified geological map of El Misti is given in Figure 5. Based on the type, extent, and volume of the Holocene and historical deposits, it is possible to assume that future volcanic events of El Misti, even if moderate in magnitude, will pose a serious threat to the densely populated areas in Arequipa. Tephra-fall deposits as thick as 50 cm could cover the city and its airport. Pyroclastic flows and surges could reach the suburbs, and pyroclastic flows

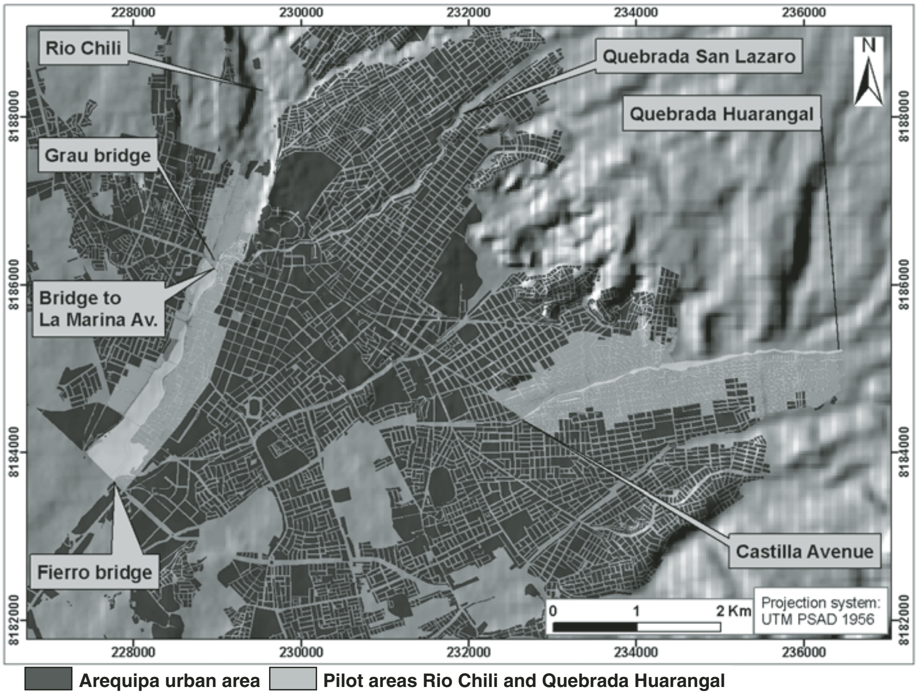


Figure 4. Sketch map showing the Quebrada Huarangal (starting at the crossing of Avenida Castilla and the Quebrada Huarangal) and Río Chili pilot study bridges (between the Fierro and Grau).

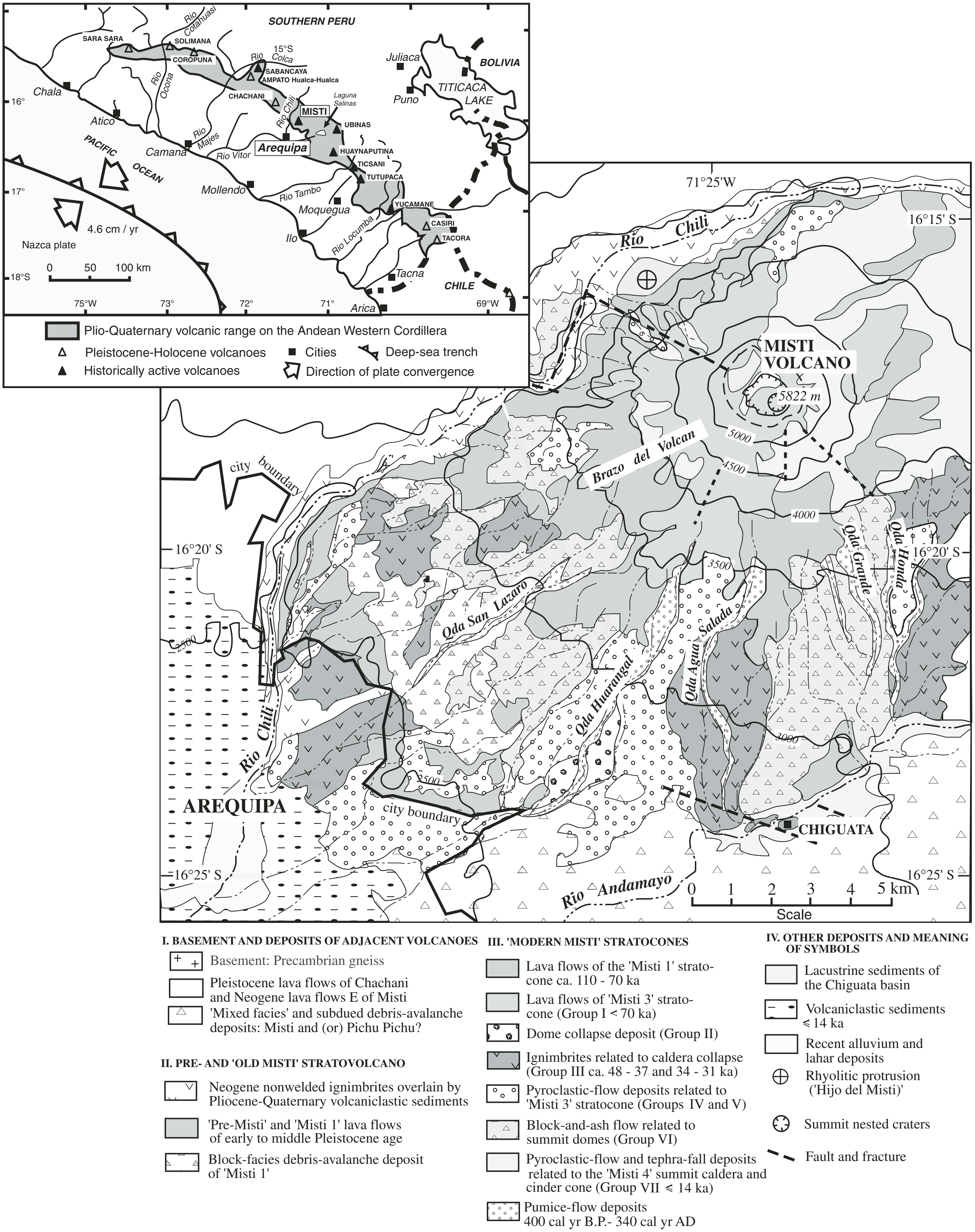


Figure 5. Simplified geological map of El Misti volcano (modified from Thouret et al., 2001).

would even reach the city center once they were channeled in the radial drainage network that includes Pastores, Qda. San Lazaro, Qda. Venezuela, and Qda. Huarangal–Mariano Melgar (Figs. 3 and 4), which converge toward Arequipa on the SW flank of El Misti (a quebrada [Qda.] is a temporarily-fed stream in a narrow, deep valley). Debris flows and flash floods induced by rainstorms, as well as rockslides and debris avalanches on the WNW and the S flanks of El Misti, could get to the Río Chili following streams originating on the upper slopes of the volcano (Thouret et al., 1999a, 2001). These flows would reach and cause great destruction in the urban areas of Arequipa, which have been constructed since the 1960s on the volcaniclastic fans of Qda. San Lazaro, Qda. Huarangal–Mariano Melgar, and Qda. Paucarpata (Fig. 4), as well as on low terraces along the Río Chili. It is also worth noting that the Río Chili is the main source of drinking water and power for a hydroelectric plant supplying the city of Arequipa (in addition to its importance for the agricultural sector). Even a small volcanic event or a small landslide affecting the W and SW slopes of the volcano would represent a serious threat to the water supply.

Thouret et al. (1999a) and Delaite et al. (2005) described three possible volcanic events and hazard scenarios for El Misti volcano. According to Thouret et al. (1999a), from the three main scenarios envisaged, the third one, termed “worst-case scenario” portrays the effects of a Plinian eruption for which the recurrence interval is on the order of 15,000 yr. The effects of such an event would be so catastrophic that the only viable mitigation measure would be to evacuate the city entirely. Because this scenario is unlikely in the present circumstances, the current risk assessment focused on the two most probable eruption scenarios for El Misti (Thouret et al., 1999a, 2001; Delaite et al., 2005). In these scenarios, pyroclastic flows and lahars seem to pose the largest threat to the city (Figs. 5 and 6), in addition to tephra-fall deposits (Fig. 2).

This paper addresses the case of potential lahars and recent flash floods. The eruptions could trigger lahars of small to moderate volumes, i.e., 0.5–4 million m^3 (Delaite et al., 2005). It should be noted that lahars could also be triggered without a direct relation to volcanic activity by rainstorms during the December–March rainy season (Delaite et al., 2005). During an interval of quiescence such as the current period, the active hydrothermal system of the El Misti summit cone (Finizola et al., 2004) would provide fluids and weathered material that could be mobilized by a landslide or a debris avalanche, and subsequently be incorporated in lahars.

On the basis of geologic and geomorphological studies, Thouret et al. (2001) pointed out that the urban areas most likely to be struck by pyroclastic flows and lahars are located along the Río Chili, as well as two main drainage systems that originate on the upper slopes of the volcano and cross the center of the city (Figs. 4, 5, and 6): Qda. San Lázaro and Qda. Huarangal. Two additional streams, originating on the SE slopes of the volcano, could convey flows that might indirectly affect the city: Qda. Agua Salada and Qda. Honda-Grande (Figs. 4 and 5). These two quebradas are tributary to the Río Andamayo, a permanent stream, which debouches into the Río Chili in the southern part of the now-urbanized depression of Arequipa. Hyperconcentrated flows along the Río Andamayo (such as those registered in 1997) could affect the cultivated areas around Chiguata (an inhabited oasis 20 km east of Arequipa), as well as the volcaniclastic fans that today are occupied by semi-urban (combined urban and rural) dwellings that are part of the oasis of Arequipa.

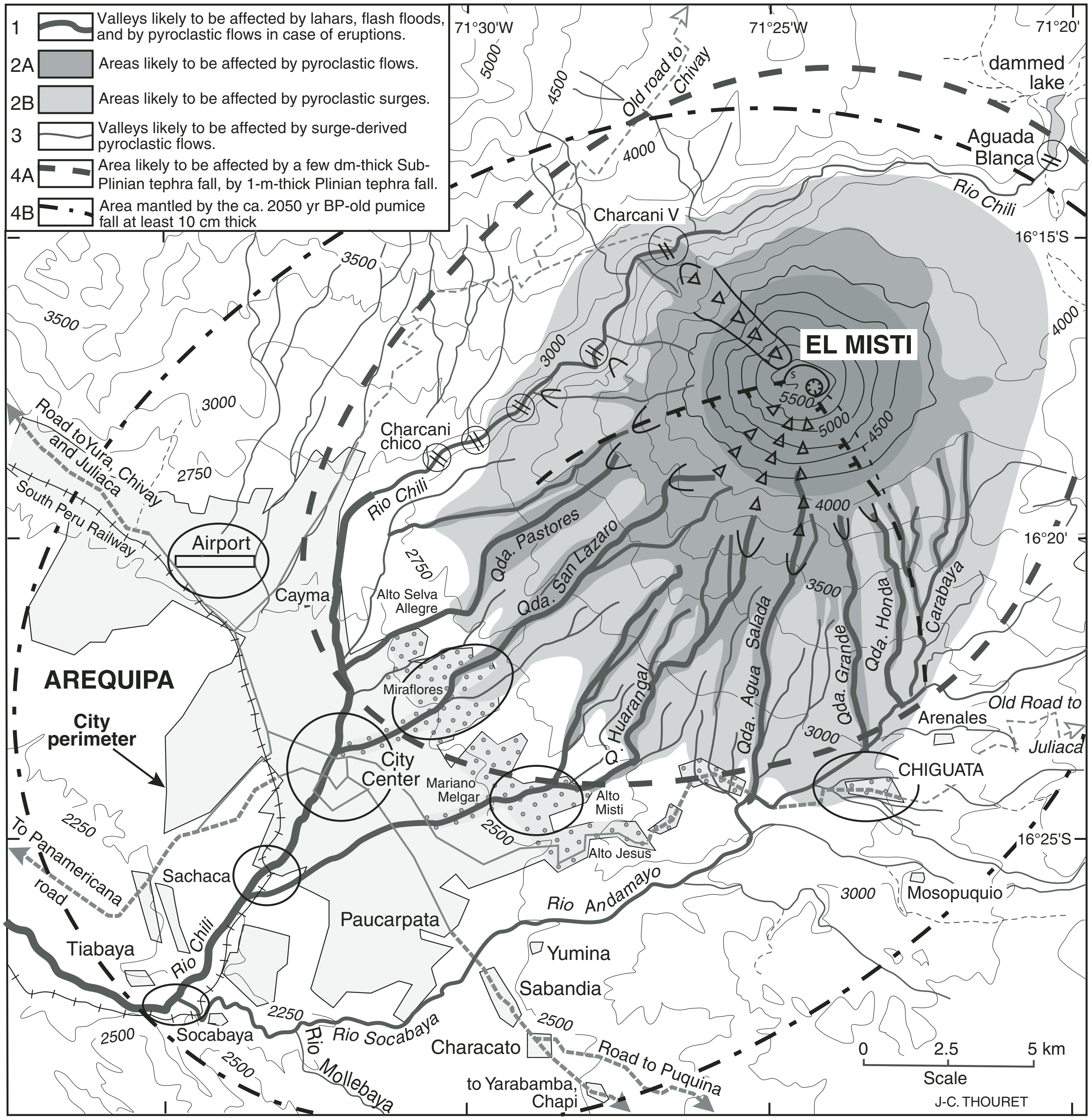
Lahar Modeling

For a proper lahar risk assessment, a more precise delimitation of the areas that could be affected is required. In order to provide this information, lahar modeling carried out since 2003 was based on extensive field mapping of past lahar deposits (Thouret et al., 1995, 1999a, 2001; Delaite et al., 2005). For the lahar modeling, two simulation programs were used: LAHARZ (Schilling, 1998; Iverson et al., 1998) and TITAN2D (Stinton et al., 2004; Sheridan et al., 2005; Sheridan and Patra, 2005). LAHARZ is a statistically based method for delineating lahar-prone zones running as interface under ArcInfo (Schilling, 1998). TITAN2D is a depth-averaged, thin-layer computational fluid dynamics program suitable for simulating a variety of geophysical mass flows (Stinton et al., 2004). Detailed descriptions of how TITAN2D and LAHARZ simulation codes operate can be found in Sheridan and Patra (2005) and Iverson et al. (1998), respectively.

Figure 7 shows the lahar hazard scenarios for selected lahar volumes as obtained using the simulation codes LAHARZ (Delaite et al., 2005) and TITAN2D (Stinton et al., 2004), respectively. These hazard scenarios were prepared using an enhanced 30 m digital elevation model (DEM), which was made based on a combination of several elevation data sources, including radar interferometry using European Remote Sensing (ERS) satellite images, and digitalized topographic maps (1:50,000 scale). Pilot areas of Qda. San Lazaro and Qda. Huarangal were enhanced using a 10 m DEM, which was prepared based on stereophotogrammetry of a set of 1:30,000 scale aerial photos provided by the Instituto Geográfico Nacional del Peru (IGN; Delaite et al., 2005). Vertical and horizontal accuracy is estimated to be less than 30 m. The lahar volumes used in the simulations were based on the estimated volume of existing lahar deposits surrounding El Misti, an estimate of the amount of material that could be mobilized into the channels, a rainfall threshold (e.g., 33 mm in 3 h), and the area of the seasonal snowfield on the volcano summit (Delaite et al., 2005; Stinton et al., 2004). Table 1 briefly describes the main parameters used for the selected lahars.

METHODOLOGY

Global observations of the effects of lahars confirm that these can easily crush, abrade, or shear off at ground level just about anything they encounter in their path. As a result of their high density, meter-sized blocks can be incorporated and transported over long distances, increasing their destructive effect (Rodolfo, 2000). In addition, buildings and valuable land may



5	Area probably hit by ballistic ejecta.
6A	Area likely to be affected by rockslides.
6B	Area liable to flank failure in case of large eruption or of growth of summit dome.
6C	Steep slopes and channels swept by recent and current rockslides.
7	Probable outreach of potential lava flows.
8	Seasonal streams potentially affected by snowmelt- or rain-induced lahars or flash floods.
9	Principal valley channels and low terraces at risk in all cases.
10	Urban districts and suburbs at high risk, to be evacuated in case of small- to medium-sized events.
11A	Principal asset at risk in all cases.
11B	Secondary asset or asset at risk in the case of medium-sized eruptions or of large lahars.
12A	Paved road usable for evacuation.
12B	Old dirt road not usable in case of medium-sized eruptions.

Notes of caution: The entire area enclosed in the map is liable to tephra fall a few centimeters thick in case of Plinian eruptions. The map integrates seasonal variations of prevailing winds. The distribution of tephra therefore may vary from this map.

become partially or completely buried by cement-like layers of mud and rock debris, rendering them useless. Besides, people can be trapped in areas exposed to other hazardous volcanic phenomena if bridges and key roads are destroyed by lahars (e.g., Pinatubo and Mayon ring plains in The Philippines). Thus, using a conservative approach, it can be assumed that all the structures (buildings, infrastructure) within the footprint of the lahar path would be destroyed (total or partial burial is also regarded as destruction), regardless of their type of construction material or structural design. We use this conservative approach because data on actual damage inflicted by lahars to the city is still lacking; such data would help to define a more specific vulnerability function, which at this moment is quite vague due to the inherent uncertainties regarding the lahar-flow properties and spatial distribution. Therefore, the vulnerability to lahars in the city of Arequipa could be defined as a function of the number and type of buildings and infrastructure located within a specified lahar path.

Vulnerability of the population, not analyzed in this paper, would be given by its level of preparation (e.g., early warning) and the existence of infrastructure allowing them to escape to safe ground (e.g., roads, bridges).

Mapping Elements at Risk

The starting point for the preparation of the elements-at-risk database was a land-use map, which was prepared as part of an *Environmental Atlas of Arequipa* (International Institute for Geoinformation Sciences and Earth Observation [ITC]; the atlas has not yet been published). In this map, city blocks are assigned to conventional land-use categories: residential, commercial, industrial, agricultural, etc. Table 2 shows the elements considered in the preparation of the elements-at-risk database. Through a more detailed survey within the pilot areas, and based on the type of construction materials, residential buildings were classified into three main categories: bricks and concrete (structural design); bricks and field stone (mixed structure), and bricks. These classes were further divided on the basis of the number of stories of the buildings. Information on the average price per square meter for the buildings was also collected. This information was later used to estimate the economic value of the buildings for each hazard scenario. Table 3 shows a detailed classification of the residential type of buildings in the Huarangal and Río Chili pilot areas (Fig. 4). It should be mentioned that the resolution of the available cadastre map of Arequipa is at the city block level, and individual buildings thus cannot be differentiated. Buildings characteristics were generalized at the city block level with the information gathered during fieldwork surveys. In the Huarangal–Mariano Melgar pilot area, the surface area of the city blocks fluctuates between 3000 and 10,000 m^2; the number of houses per city block varies from 15 to 40. The average building footprint size is 80 m^2, but the size of the total parcel is larger. Population density is low to moderate, varying between 100 and 120 inhabitants per hectare (Arequipa, Municipalidad Provincial, 2002). In the Río Chili area, the size of city blocks is more homogeneous (~10,000 m^2); the number of houses per city block varies from 15 to 20. The average building footprint size is larger than 120 m^2, and the population density is moderate to high, ranging from 120 to 150 inhabitants per hectare.

Figure 6. El Misti hazard-zone map and the city of Arequipa with principal assets (based on Thouret et al., 2001, and Delaite et al., 2005). Hazard zones: 1—Valleys likely to be affected by lahars and flash floods, even without eruption, and by pyroclastic flows in case of eruptions. 2A—Areas likely to be affected by pyroclastic flows. 2B—Areas likely to be affected by pyroclastic surges. 3—Valleys likely to be affected by surge-derived pyroclastic flows. 4A—Area likely to be affected by a few-decimeter-thick tephra fall in case of sub-Plinian eruptions; 1 m thick in case of Plinian eruptions. 4B—For the purpose of comparison, area known to have been mantled by the 2050 yr B.P. pumice-fallout deposit at least 10 cm thick. The map integrates seasonal variations of prevailing winds. The actual distribution of tephra may therefore vary from this map. The entire area shown in the map is liable to ash fallout at least 1 cm thick. 5—Area probably hit by ballistic ejecta. 6A—Area likely to be affected by rockslides. 6B—Area liable to flank failure in case of large eruption or by dome growth at the summit. 6C—For the purpose of comparison, steep slopes and channels swept by recent and current rockslides. 7—Probable outreach of potential lava flows. 8—Quebradas (seasonal streams) potentially affected by secondary, snowmelt- or rain-induced lahars or flash floods. Principal assets at risk: 9—Principal valley channels and low terraces at risk in all cases. 10—Urban districts and suburbs at high risk, to be evacuated in case of small- to medium-sized events. Note: The city center and the airport are at risk from ash fallout in all cases. 11A—Principal asset at risk in all cases. 11B—Secondary asset or asset at risk in the case of medium-sized eruptions or of large lahars. 12A—Paved road usable for evacuation. 12B—Old dirt road not usable in case of medium-sized eruption.

Information on roads and bridges was also collected during the field visit to the pilot areas. Preliminary observations show that this infrastructure is not only vulnerable to lahars, but in some cases, it can also contribute to increase the hazard levels due to the type of their design. Most bridges, especially those along the Qda. Huarangal, are very low (under 3 m) in relation to the river bed: a lahar could easily become clogged at these points, destroying the bridge and causing overflow and flooding of surrounding areas (Figs. 8 and 9). In February 1992, a Río Chili flood event (260 $m^3 s^{-1}$) overran the 4-m-high modern bridge just downstream of the Puente Grau and flooded residential areas on the low terrace of the left river bank (S. Girard, 1999, personal commun.). Figures 8 and 9 show typical buildings as well as other types of infrastructure identified in the pilot areas.

Results: Lahar Hazard and Relevant Risk Scenarios

Risk scenarios were defined by overlapping the land-use and the lahar hazard maps with the help of a geographic information system (GIS). All the city blocks intersecting the specific simulated lahar footprint areas were regarded as completely destroyed. For the purpose of the analysis, it was assumed that all

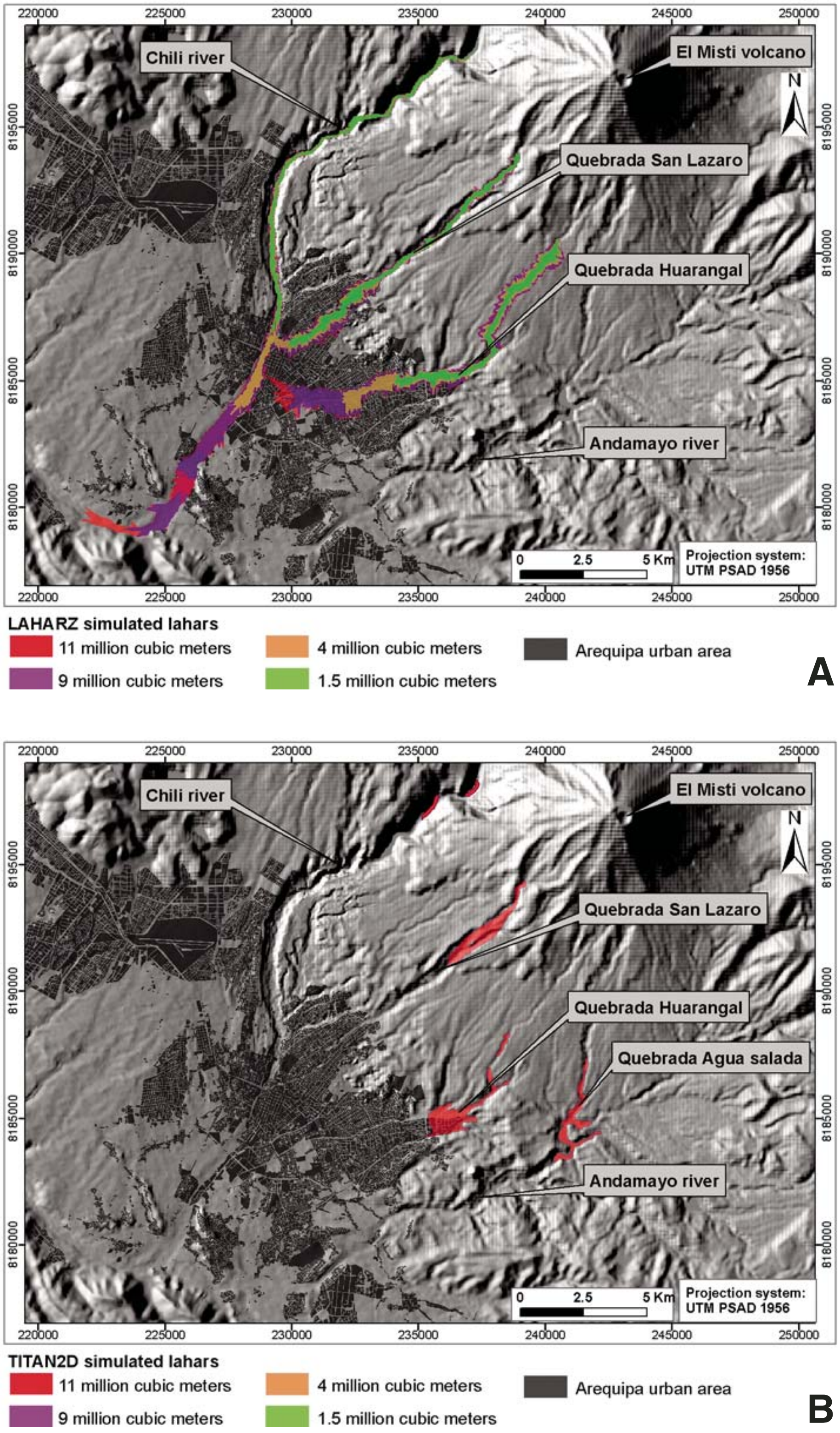


Figure 7. Lahar hazard scenarios for Río Chili and Quebrada Huarangal. (A) Results from the simulation code LAHARZ. Volume values used to run the simulations were defined based on field observations and information on climatic conditions in the region. Boundaries of the inundation zones may vary if a more detailed Digital Terrain Model is used. The 11 × 10^6 m^3 scenario is very unlikely. (B) Results from the simulation code TITAN2D. According to the results, only the 11 × 10^6 m^3 scenario would inflict some damage to the city of Arequipa.

TABLE 1. VOLCANIC AND NONVOLCANIC LAHARS (HYPERCONCENTRATED FLOWS AND DEBRIS FLOWS): ESTIMATED FLOW VOLUMES AND RECURRENCE INTERVALS

Scenario for lahar generation	Minimum lahar volume ($\times 10^6$ m^3)	Maximum lahar volume ($\times 10^6$ m^3)	Recurrence interval (yr)
First, nonvolcanic, small to moderate size, and frequent	0.01 to 0.1	0.1 to 0.5	2 to 10
Second: moderate and probable, even if small eruption	0.5 to 1.5	1.5 to 4.0	300 to 1000
Third: large but infrequent, if large eruption	4 to 9.0	9 to 11	1000 to 5000

Note: The lahar volumes used in the simulations are based on: the estimated volume of Holocene lahar deposits surrounding El Misti; the approximate amount of material that can be mobilized in channels; rainfall threshold of at least 10 mm/h (e.g., February 1997); and surface area of the seasonal (December–July) snowfield on the volcano summit (1 to 4 km^2; up to 7 km^2 in case of heavy snowfall).

TABLE 2. CLASSIFICATION AND DESCRIPTION OF ELEMENTS AT RISK (BASED ON FIELD SURVEYS, JULY 2005)

Buildings/land-use class	Building description	
Residential (single–apartment complex) Educational (primary–secondary–high) Commercial	Construction materials	Bricks Bricks and concrete Ignimbrite Makeshift* Other (etc.)
Institutional Lifeline utilities control or distribution center	Construction quality	Structural design Absence of structural design
	No. stories	
	Roof type	Flat Pitched
	No. people	Adults (men–women) Children Elderly
Infrastructure		
	Roads	Material type Length, width
	Bridges	Material type Length, width
	Lifeline utilities	Type Length

*Makeshift indicates mixture of poor-quality construction materials such as wood, bricks, and ignimbrites (absence of structural design).

TABLE 3. HOUSING AND CONSTRUCTION MATERIALS IN THE RÍO CHILI AND IN THE QUEBRADA HUARANGAL PILOT AREAS (MODIFIED FROM LE HOUEDEC, 2005)

	Residential buildings						
	No. stories	Percentage (avg)		Value U.S.$/$m^2$		Value house U.S.$	
Construction material		Qda. Huarangal	Río Chili	Qda. Huarangal	Río Chili	Qda. Huarangal/ 80 m^2	Río Chili/ 120 m^2
Class 1	1	4	5	123	150	9816	18,000
Bricks and concrete	2	33	50				
Class 2	1	40	5	78	100	6207	12,000
Bricks	2	20	5				
Class 3	1	3	5	53	75	4272	9000
Bricks, sillar	2	0	30				

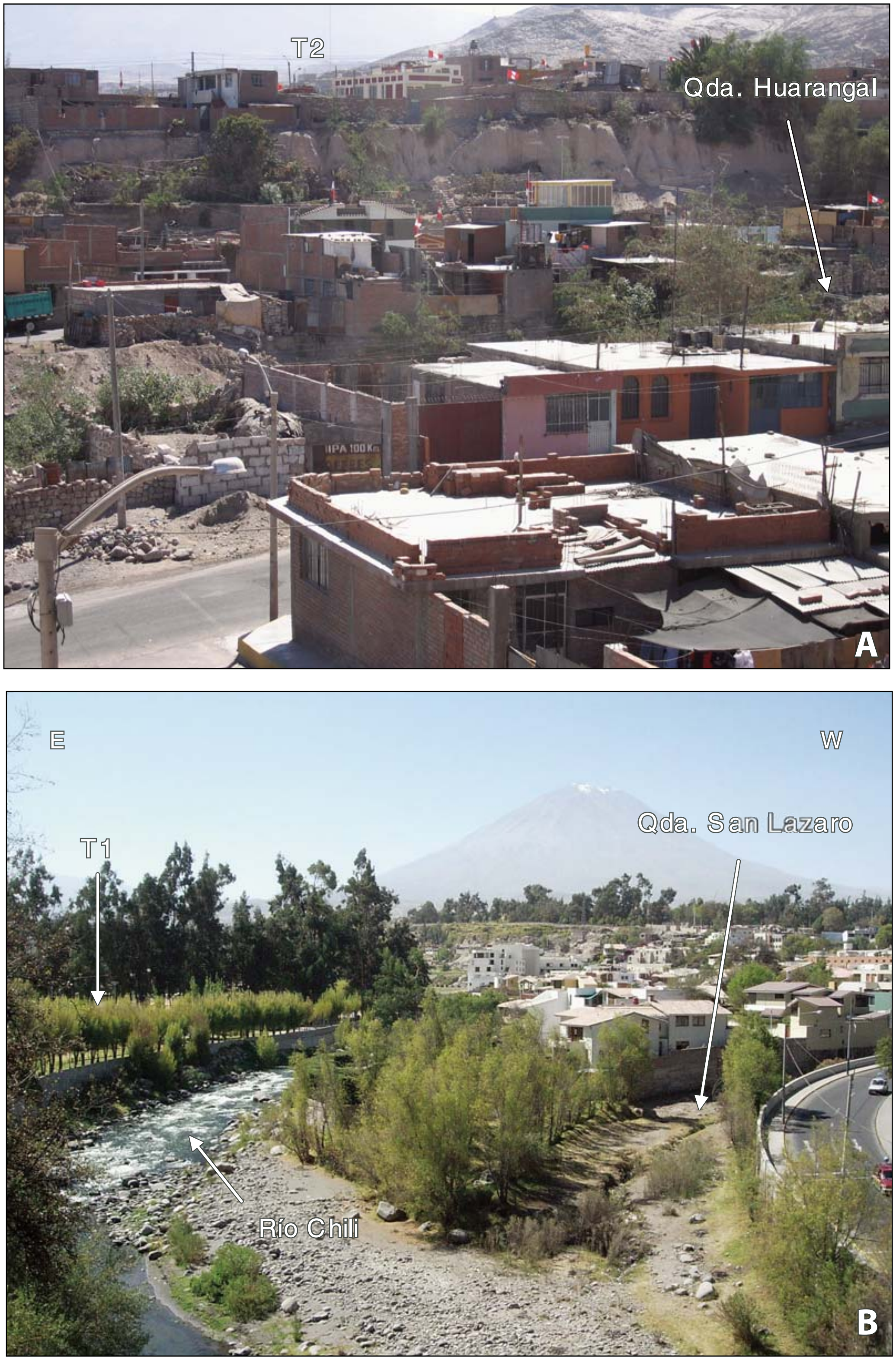


Figure 8. (A) Residential 1–2 story buildings in the Huarangal pilot area. Foreground: flood-prone surface of the volcaniclastic fan. In the back (T2), high terrace and scarp confining the channel. (B) Río Chili pilot area: residential areas located at the confluence of two lahar-prone streams: Río Chili and Quebrada San Lázaro. T1—lower terrace. The Quebrada San Lázaro cuts several meters into the volcaniclastic fan, and the channel has been paved.

Figure 9. Huarangal pilot area: Infrastructure (roads and bridges). This bridge (Paucarpata–Mariano Melgar) along the Avenida Castilla is not only vulnerable to lahars because it is too low, but it could also increase hazard levels in surrounding areas by blocking the flow and creating overflow. Constant dumping of debris does not help either.

city houses located in the center of the channel would be wiped out (either erased or completely buried) except for minor lahars or flash floods. On the margins of the channel (i.e., low terraces), destruction and burial would be less significant; structures of the houses would be affected, but housing would survive. Burial would be partial. On the higher terraces, there would be some damage inflicted to open areas (windows, doors, external structures), but the bulk of the housing would survive. The risk scenario, expressed as expected economic loss, was calculated using available data on the average number of houses per city block and their price per square meter. The risk scenario is complemented by indicating the number and type of essential facilities and relevant infrastructure elements within the affected area.

Table 4 shows the differences in the type and number of urban elements (at city block level) that would be affected by each of the selected lahar volumes (1.5 and 4 million m^3) and according to the two different simulation codes in the Río Chili and Qda. Huarangal pilot areas. In the case of LAHARZ, mainly residential areas would be affected along the Qda. Huarangal. The situation along the Río Chili is more critical: besides residential areas, the drinking water and electricity supplies would be severely disrupted for several weeks to months. This would create serious sanitary problems, and the agricultural and commercial sector would also be affected, with serious implications for the local economy. Note that in the case of the TITAN2D hazard scenario, only the largest lahar (11 × 10^6 m^3 lahar) in the Qda.

TABLE 4. QUEBRADA HUARANGAL AND RÍO CHILI PILOT AREAS POTENTIALLY AFFECTED BY LAHAR VOLUMES OF 1.5 AND 4 MILLION m^3

Risk scenario for the Qda. Huarangal valley					Risk scenario for the Río Chili valley				
	Lahar volume					Lahar volume			
	1.5 × 10^6 m^3		4 × 10^6 m^3			1.5 × 10^6 m^3		4 × 10^6 m^3	
Land use (area affected, in km^2)	LAHARZ	TITAN2D	LAHARZ	TITAN2D	Land use(area affected, in km^2)	LAHARZ	TITAN2D	LAHARZ	TITAN2D
Residential	0.382	0	1.093	0	Agricultural	3.139	0	3.579	0
Educational	0.009	0	0.069	0	Residential	0.271	0	0.616	0
Industrial	0.007	0	0.016	0	Commercial	0.032	0	0.165	0
Institutional	0.002	0	0.013	0	Public services	0.021	0	0.022	0
Public services	0	0	0.013	0	Industrial	0.020	0	0.063	0
Commercial	0	0	0.007	0	Institutional	0.010	0	0.022	0
Health services	0	0	0.004	0	Educational	0	0	0.033	0

Huarangal reaches the fan apex where a few poor-quality houses are located. All the other TITAN2D simulated lahars would not affect the city directly, and therefore these would not pose any risk, except in the case of the Río Chili canyon, where even a small lahar would disrupt the city's water and electricity supplies (see artificial dammed lakes of Aguada Blanca and El Frayle, as well as Charcani power plants in Fig. 2).

Table 4 shows a detailed description of the type of residential buildings located in the Río Chili and Huarangal pilot areas. Table 5 shows the difference in risk (expressed in economic terms) for the 1.5 and 4 million m^3 lahars, respectively, according to the LAHARZ simulation.

DISCUSSION

Stinton et al. (2004) already pointed out that, in the case of El Misti volcano, results obtained by the LAHARZ and TITAN2D simulations differ substantially (Fig. 7). Even the largest volume flows as simulated by TITAN2D (11.0×10^6 m^3) do not reach much further than the smallest volume of a flow (1.5×10^6 m^3) modeled by LAHARZ. However, TITAN2D simulations of the behavior of debris-flow features seem to be more realistic than those obtained from LAHARZ (Stinton et al., 2004; Delaite et al., 2005). Therefore, it would be reasonable to use TITAN2D simulation results as the basis on which to draw the boundaries for the lahar inundation zones.

On the other hand, a comparison of the LAHARZ simulations with the deposits of past lahar and hyperconcentrated flows shows a fair correlation, indicating that the LAHARZ simulations might represent more closely the spatial distribution and extension of past deposits (Delaite et al., 2005) than those provided by TITAN2D. The answer to the question of which of the methods should be used to draw the limits of the area expected to be flooded by lahars has serious implications in terms of risk mitigation planning. If the LAHARZ simulations were accepted as realistic for the case of the 1.5 and 4 m^3 million lahars (Fig. 7), the expected losses (risk scenario considering only direct effects) would include: (1) damages to the urban infrastructure along the Río Chili and Qda. Huarangal roughly estimated at ~40–100 million U.S. dollars; and (2) disruption of the water and electricity supplies (power stations and reservoirs along the Río Chili) with serious sanitary, economic, and social consequences. If TITAN2D simulation runs for the same expected lahars are used, economic losses would mostly be due to the disruption of the water supply and damage to the hydroelectric power stations along the Río Chili (Charcani five dams and irrigated agricultural area down valley). According to TITAN2D simulations, the moderate-volume lahars (1.5–4.0 million m^3) would not reach the urban areas in the Qda. Huarangal and the Río Chili.

LAHARZ and TITAN2D represent completely different approaches to modeling lahar inundation zones. Differences observed when computing the hazard scenarios derived from these codes (i.e., length of lahars being longer for LAHARZ runs than for TITAN2D runs) can be attributed to three critical issues. (1) These programs represent distinct type of codes. LAHARZ is a statistical and semi-empirical code, whereas TITAN2D is a computer program based upon a depth-averaged model for an incompressible Coulomb continuum, a "shallow-water" granular flow. TITAN2D conservation equations for mass and momentum are solved with a Coulomb-type friction term for the interactions between the grains of the media and between the granular material and the basal surface. (2) Distinct parameters are used as inputs. For LAHARZ, the inputs consist of the H/L ratio and channel cross sections perpendicular to a channel. For TITAN2D, the inputs are: two internal and basal friction angles in flow mass in motion (which are quite variable at Misti); starting pile dimensions (height × width × length) and thus starting volume; and location of the starting pile. (3) The goals of the codes are distinct. LAHARZ is intended to delineate lahar-prone areas in first approximation, whereas TITAN2D is intended to understand the relationship between the modeled topography as a DEM and the physics of flows being simulated.

LAHARZ has been used more extensively than TITAN2D. Reports indicate that LAHARZ works better in confined channels than in fan-like topographies such as the Qda. Huarangal volcaniclastic deposits (Canuti et al., 2002). On the other hand,

TABLE 5. VALUE OF RESIDENTIAL BUILDINGS WITHIN THE SIMULATED AREAS INUNDATED BY THE 1.5 AND 4 MILLION m^3 LAHARS (USING LAHARZ)

	Estimated number of houses and corresponding value excluding content								
Inundated area/lahar volume	Class	Class 1		Class 2		Class 3		Value U.S.$	People*
	No. stories	1	2	1	2	1	2		
	Approximate number of houses								
Río Chili 1.5×10^6 m^3	1000	50	500	50	50	300	50	24,320,000	4000
Río Chili 4×10^6 m^3	2200	110	1100	110	110	660	110	53,460,000	9200
Qda. Huarangal 1.5×10^6 m^3	1400	56	462	560	280	42	0	16,626,800	4500
Qda. Huarangal 4×10^6 m^3	4000	160	1320	1600	800	120	0	47,859,840	13,100

*The number of people was calculated using data on population density from the 2002–2015 strategic development plan (Municipalidad de Arequipa, 2002).

TITAN2D is still under development. The large difference in results indicates that caution is required when deciding which one is more appropriate. Canuti et al. (2002) compared LAHARZ and FLO-2D simulations and also found similar substantial differences. This implies that the results of the simulations need to be viewed with great care, especially if they are being considered for making decisions by local officials.

CONCLUSIONS

The lahar risk assessment for the city of Arequipa is based on the assumption that in the case of an eruption, even a small one, the entire Río Chili valley and the drainage systems originating at the upper slopes of the volcano will become lahar channels. Holocene and historical lahar deposits (and actual flash floods and hyperconcentrated flows that occurred in 1992 and 1997) confirm that the lahar threat is real. In the case of the Río Chili valley, conditions favor lahar generation and include: a large drainage area with a permanent source of water, loose material readily available in the river channel and volcano slopes, a deep narrow gorge with constrictions and five man-made dams, and direct supply of debris from the highly unstable WNW flank of El Misti. However, the probability of lahar generation at the upper slopes of the volcano is more difficult to forcast because their occurrence depends not only on the eruption but especially on the availability of water at the time of the eruption. Usually rainstorms only occur during the period from December to March, and the snow cover at El Misti is not permanent, although the snowfield can be as large as 7 km^2 in August or between December and May.

The use of simulation codes such as LAHARZ and TITAN2D could be very useful to provide a more realistic scenario in case of future lahars. If LAHARZ results were closer to the possible scenario, the lahars would certainly represent a very serious hazard for the entire city. However, if TITAN2D results were to be accepted, then hazard levels would be much lower. In this case, only urban areas located in the upper part of the Qda. Haurangal would be affected. Therefore, the procedure chosen for delimiting hazard zones will have serious implications for the planning and implementation of risk mitigation measures.

Lahar risk mitigation planning requires reliable information upon which to base decision making. Lahar hazard scenarios derived from the use of simulation codes could provide the required information. Although geomorphological evidence is overwhelming, decision makers might not take action unless unambiguous and convincing hazard and risk scenarios are prepared. Clearly, more research is required in order to provide the authorities with a reliable lahar hazard map.

Based on the previous analysis, future research should focus on two aspects, namely: (1) evaluation of the lahar initiation mechanisms, defining more accurately volume of expected flows, and (2) new simulations to improve the quality of the hazard and corresponding risk map. Vulnerability to volcanic hazards in the city of Arequipa is steadily growing, not only because the urban development is creeping up the slopes of the volcano, but more importantly because local authorities seem to ignore the magnitude of the threat. The strategic plan for the development of Arequipa for the period 2002–2015 briefly acknowledges the problem but does not include any specific risk mitigation project. The July 2005 conference on El Misti and related hazards organized by the Instituto Geológico Minero y Metalúrgico del Perú (INGEMMET) and hosted by the local university authorities showed positive signs and certain willingness to change this situation. In fact, in 2007 INGEMMET prepared an updated hazard map that has been discussed with the local authorities before final printing and distribution.

Figure 6 shows some important infrastructure assets that would be affected according to the different volcanic scenarios (dams and power supply plants in The Río Chili valley, airport, city center, town of Chiguata, and suburbs at the apex of the populated volcaniclastic fans of Qda. San Lázaro and Qda. Huarangal).

Recommendations in terms of contingency and mitigation planning should be prepared at two different scales. (1) At a local scale (Fig. 6), suburbs that would be most directly affected are located along both Río Chili and Qda. Huarangal. The option of creating a buffer zone free of dwellings, buildings, or infrastructure utilities along and on both sides of the river beds should be considered. Definition of the buffer zone extension would require a more detailed terrain model. (2) At the regional scale (Fig. 2), shelters should be constructed in Yarabamba and Quequeña toward the SE of the oasis. These shelters would be required in case of moderate eruption. In addition, roads should be enlarged or newly constructed to allow massive evacuation in the case of sub-Plinian eruption (Panamericana road, road to the east toward Puquina, and road to the SE toward Chapi and Rio Tambo; Fig. 2).

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