Characteristics and management of the 2006–2008 volcanic crisis at the Ubinas volcano (Peru)

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ABSTRACT

Ubinas volcano is located 75 km East of Arequipa and ca. 5000 people are living within 12 km from the summit. This composite cone is considered the most active volcano in southern Peru owing to its 24 low to moderate magnitude (VEI 1–3) eruptions in the past 500 years. The onset of the most recent eruptive episode occurred on 27 March 2006, following 8 months of heightened fumarolic activity. Vulcanian explosions occurred between 14 April 2006 and September 2007, at a time ejecting blocks up to 40 cm in diameter to distances of 2 km. Ash columns commonly rose to 3.5 km above the caldera rim and dispersed fine ash and aerosols to distances of 80 km between April 2006 and April 2007. Until April 2007, the total volume of ash was estimated at 0.004 km3, suggesting that the volume of fresh magma was small. Ash fallout has affected residents, livestock, water supplies, and crop cultivation within an area of ca. 100 km2 around the volcano. Continuous degassing and intermittent mild volcanic explosions lasted until the end of 2008. Shortly after the initial explosions on mid April 2006 that spread ash fallout within 7 km of the volcano, an integrated Scientific Committee including three Peruvian institutes affiliated to the Regional Committee of Civil Defense for Moquegua, aided by members of the international cooperation, worked together to: i) elaborate and publish volcanic hazard maps; ii) inform and educate the population; and iii) advise regional authorities in regard to the management of the volcanic crisis and the preparation of contingency plans. Although the 2006–2008 volcanic crisis has been moderate, its management has been a difficult task even though less than 5000 people now live around the Ubinas volcano. However, the successful management has provided experience and skills to the scientific community. This volcanic crisis was not the first one that Peru has experienced but the 2006–2008 experience is the first long-lasting crisis that the Peruvian civil authorities have had to cope with, including attempts to utilize a new alert-level scheme and communications system, and the successful evacuation of 1150 people. Lessons learned can be applied to future volcanic crises in southern Peru, particularly in the case of a reawakening of El Misti volcano nearby Arequipa.

1. Introduction

Ubinas volcano (16° 22′ S, 70° 54′ W; 5672 masl) is located in the Western Cordillera of the Andes 75 km East of Arequipa (Fig. 1). Approximately 5000 people live within 12 km of the summit, most of them in the valley of Río Ubinas at the foot of the southern flank of the volcano (Fig. 2). The composite cone looms 1400 m above surrounding ground, covers an area of 65 km2 and has an approximate volume of 56 km3, the largest proportion of rocks being lavas. The stratovolcano with a slight SE–NW elongation (Fig. 3) sits on the edge of a high plateau made up of Late Miocene–Early Pleistocene ignimbrites and lavas (Marocco and del Pino, 1966). This asymmetric edifice overlooks the valleys of Río Ubinas and Río Para towards the South and East, respectively. An elliptical summit caldera (5380 m a.s.l.) has a maximum axis of 1.4 km in the N–S direction. The hydrothermally altered lavas of the caldera floor underlie a 22 m thick sequence of ash and lapilli deposits. The SE sector of the caldera contains a crater, 300 m wide and 300 m deep, in an ash cone surrounded by a 50-m-high ring.

Ubinas is considered the most active volcano in southern Peru with an average recurrence of 6 to 7 eruptions per century (Rivera et al., 1998; Thouret et al., 2005). Twenty-three reported historical periods of unrest, most of them fumarolic or strong degassing episodes, occurred at Ubinas between 1550 and 1996 (Bullard, 1962; Hanks and Parodi, 1966; GVN, 1969, 1996; Simkin and Siebert, 1994; Valdivia, 1995; Rivera et al., 1998). Historical archives and geologic data for the past 500 years indicate that Ubinas has experienced long...
lasting periods of intense degassing interspersed with vulcanian and phreatomagmatic episodes, which resulted each in small-volume deposits $<0.01\, \text{km}^3$ (Hantke and Parodi, 1966; Rivera et al., 1998; Thouret et al., 2005). However, the AD 1667 largest historical explosive eruption (VEI 3, Simkin and Siebert, 1994) produced about 0.1 $\text{km}^3$ of scoria falls and flows. On some occasions, volcanic activity caused significant damage in eight villages near the volcano (Fig. 1): between 1936 and 1969 ten people and numerous cattle died due to intoxication from consumption of water, vegetables, and/or fruits contaminated by ash (El Pueblo newspaper, 1936, 1937, 1951, 1969; Valdivia, 1995). Ash fallout from the afore-mentioned eruptions frequently damaged crops and mixed with rain water to generate destructive lahars that travelled $\sim15\, \text{km}$ down the valley of Río Ubinas towards the canyon of Río Tambo (e.g., 1923, 1951, and 1969: El Pueblo newspaper, 1951, 1969; Valdivia, 1995). Before 2006, the last episode of degassing and seismic activity occurred between December 1995 and the end of 1996 (GVN, 1996). Before 2006, the last episode of degassing and seismic activity occurred between December 1995 and the end of 1996 (GVN, 1996). During this episode, fumaroles located in the summit crater generally rose to between 100 and 600 m above the summit. The persistence of degassing ($440\, ^\circ\text{C}$ in July 1998) indicated an active hydrothermal system beneath the volcano (Thouret et al., 2005).

At the onset of eruptive activity, representatives from INDECI, National Institute for Civil Defense held an emergency meeting on 30 March 2006 that brought together representatives from several institutions pertaining to the Peruvian ministries of health, education, agriculture, transportation, energy, and mining. At this meeting, a Scientific Committee of Science and Technology was formed within the Regional Committee of Civil Defense for Moquegua (CRDCM). The Scientific Committee included experts from three Peruvian scientific institutions: INGEMMET, IGP, and IG-UNSA (Geophysical Institute of the San Agustin University in Arequipa). This scientific committee immediately began to install equipment to monitor the volcano with support...
from the French Institut de Recherche pour le Développement (IRD), Laboratoire Magmas et Volcans, Université Blaise Pascal (LMV-UBP) and Université de Savoie, and the Canadian Multinational Andean Project (MAP-GAC). The objective of the volcano monitoring was to detect signs of escalating activity that might augur a larger, much destructive eruption that would affect the population centers within the Ubinas valley. Additionally, the committee worked to: i) elaborate and publish volcanic hazard maps; ii) inform and educate the population; and iii) advise regional authorities and CRDCM regarding the management of the volcanic crisis and the preparation of contingency plans.

This paper describes the 2006–2008 volcanic activity, the procedures of prevention and risk management, the scientific and social responses, lessons learned, and difficulties in managing this small crisis.


2.1. Chronology of events

Three eruptive phases (Table 1) were recognized by the INGEM-MET team since March 2006. Measurements and observations were carried out from a campsite located at 4497 masl, 4 km SW of the volcano (Fig. 1). First phase: after a small gas cloud rose above Ubinas summit at 5670 masl in August 1995, degassing increased on 27 March 2006 and the volcano produced fine gray ash to heights <1000 m above the summit. During 14–18 April 2006, two large explosions ejected blocks of weathered lava as large as 70 cm in diameter 400 m away from the crater. Second phase: on 19 April 2006, a plug of incandescent lava was discernable for the first time inside the crater. Between 14 and 27 April (and more sporadically later), increased explosive activity hurled ballistic, juvenile andesitic lava blocks up to 40–50 cm within 1 km of the crater. Impact craters up to 2 m in diameter strew the floor of the caldera: an exit velocity of ~170 m/s was calculated using “Eject! 1.1” software (Mastin, 2001). These explosions typically lasted <8 seconds. Significant ash-laden eruption columns rose up to 3000 m in height above the caldera rim (Fig. 4). Table 1 includes >30 noteworthy eruption columns averaging 800 to 4000 m in height between May 2006 and May 2007. Third phase: since 24 May 2007 to December 2008, gas and ash columns commonly rose to between 400 to 600 m, rarely to 1400 m. Although the volume of ash fallout was small (c. 0.0041 km³), the fine ash and aerosols carried aloft by the winds drifted to distances >60 km around the volcano, mainly to the southeast, north and northeast during the period April 2006 to April 2008 (Fig. 5).
Samples collected in medial areas (between 5 and 8 km around volcano) contain a large proportion of 100–50 μm size and less abundant fine ash. Scanning Electron Microscopy photographs show that the gray ash emitted in March and April 2006 contains a large amount (70%) of very fine material (<20 μm) and a minor amount (30%) of large particles (>200 μm). The large particles are mostly shards of andesitic composition (56–57 wt.% SiO2), approximately 40% of which contain crystals of plagioclase (20%), and lesser pyroxenes (~7%). Smaller grains form diffuse or dense clots that correspond to particle aggregates. The fact that at large distance exist larger particles can be due to particle aggregation.

The content and percentage of the lithological components of ash has varied only slightly throughout the eruptive process. Since May 2006 the percentage of shards of andesitic composition (>50%) increased with respect to the other components but the non-juvenile components show characteristics typical of hydrothermal systems. The small (<5 μm across) grains are gypsum, pyrite, and aluminium sulphate, all scoured from the summit hydrothermal system, and shards of plagioclase, pyroxene, magnetite, and silica (30%). The silica shows either massive fragments with no internal structure or clots (up to 300 micros across) of micron-sub-micron sized particles. The juvenile scoriae and ballistic quenched lava blocks ejected during the first phase of the eruption between April and October 2006 show a remarkably homogeneous, subalkaline andesitic composition (56.5–57.5 wt.% SiO2 and >6 wt.% Na2O + K2O: Fig. 6), which is similar to that of other historical magmas of Ubinas, but less mafic than the AD 1677 scoriae (55.3 wt.% SiO2).

2.2. Subsequent non-eruptive events during the episode

During December 2006 and early January 2007, with precipitation the volcano’s summit became covered by snow down to an elevation of 4900 masl. On 17 January 2007, at approximately 2:15 pm (local time), a lahar travelled on the south and southeast flank of the volcano and was channeled in the quebrada (ravine) Volcanmayo and Río Ubinas, and eventually reached the Río Tambo, 14 km SE of the volcano. About 15 minutes earlier, people living in the Ubinas valley heard loud noises from the volcano and observed that the snow started to disappear at the same time. A debris flow began to flow at 2:30 pm in the Río Ubinas. Blocks 4 m in diameter were transported 6 km down-valley from the volcano. People living in the Ubinas valley were alarmed and climbed to the high, safer parts of the valley. One hour later at 3:30 pm, the debris flow arrived at the lowest point of the valley 9 km SE from the volcano (nearby San Miguel and Huatagua villages). In this area, debris flow deposits were characterized by subangular to subrounded blocks up to 1 m in diameter surrounded by an indurated matrix of mud and sand. Along its course, the debris flow caused damage to the road and bridge linking Huarina to Arequipa and also to agricultural lands. The lahar stopped at about 5:00 pm. The day before the debris flow and on 17 of January, neither explosions nor rainfall was recorded, in fact it was sunny. Melting of snow and/or rockfall from the top of the volcano probably triggered the debris flow.

The lahar happened almost 10 months after the onset of the volcanic activity. The estimated volume of ash fallout did not exceed 0.004 km³ in January 2007 and most of the fine ash was dispersed in different directions around the volcano. Consequently, the flow did not reach a significant volume. The channel gradient of the Río Ubinas is 6–8% in the upper course but decreases to 5% and 2% downstream, thus the velocity in the upper reaches may have exceeded 3 ms⁻¹ but decreased to as little as 2 ms⁻¹ in the lower reaches. When considering a cross section of 20 m² with debris, and the 13-km-long course of the Volcanmayo and Ubinas Rivers the volume of the total sediment moved by the debris flow was about 260,000 m³. The 17 January 2007 lahar deposits are similar to historical lahar deposits which crop out in the Ubinas valley.
Table 1
Chronology of the eruptive activity at Ubinas volcano, 2005–2008, and its hazardous impacts. The “Comments” column also summarizes actions taken by scientists and civil authorities in the management of the volcanic crisis.

<table>
<thead>
<tr>
<th>Date</th>
<th>Height of the volcanic plume above the volcano summit (m)</th>
<th>Direction and distance of fumaroles (degassing) and fine ash fallout</th>
<th>Comments (chronology: all local time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From August 2005 to March 2006</td>
<td>200–400</td>
<td>Not recorded</td>
<td>Ubinas shows a slight increase in fumarolic activity.</td>
</tr>
<tr>
<td>27 March to 13 April 2006</td>
<td>200–700</td>
<td>Between 5 and 9 km to the NE, W and SW of the volcano.</td>
<td>Ash fell on the village of Querapi, located 4 km SE of the crater. Degassing was mild and almost constant.</td>
</tr>
<tr>
<td>14 April 2006</td>
<td>800</td>
<td>&gt;5 km South of volcano.</td>
<td>A moderate explosion produced fine ash fallout on the villages of Querapi and Ubinas. Plumes of ash and degassing were generated during three days.</td>
</tr>
<tr>
<td>15 April 2006</td>
<td>800–1500</td>
<td>6–9 km to the NE, S and W.</td>
<td></td>
</tr>
<tr>
<td>Phase II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 April 2006</td>
<td>600–300</td>
<td>&gt;10 km to the NW, W, and SW.</td>
<td>A body of lava ~60 m in diameter and 2 m high was observed on the crater floor for the first time.</td>
</tr>
<tr>
<td>20 April 2006</td>
<td>1200</td>
<td>&gt;18 km to the E and NE.</td>
<td>10:50 am: a plume of ash and gas rose to ~3000 m above top of volcano (Fig. 5). Then ash fell on the villages of Moche and Logen, located 7 and 10 km west of Ubinas, respectively. Plume reached 60 km from volcano; traces of fine ash reached the Arequipa airport.</td>
</tr>
<tr>
<td>10 May 2006</td>
<td>1400</td>
<td>15 km to the NE, N, NW, and SE.</td>
<td>Weak white fumaroles. On 26 April (8:00 am), the eruptive column reached 2000 m in height. 18:30 pm: a loud explosion, which hurled away incandescent ballistic projectiles 800 m away from the crater, was heard in the town of Ubinas.</td>
</tr>
<tr>
<td>11 to 21 May 2006</td>
<td>3000</td>
<td>&gt;20 km to the E, SE, and NE.</td>
<td>The activity was mild to moderate during this week, except for 14 May when an explosion occurred (4:48 pm), followed by the formation of a cauliflower-shaped volcanic plume &gt;2000 m high.</td>
</tr>
<tr>
<td>22 May 2006</td>
<td>3000</td>
<td>&gt;14 km to the S and SE.</td>
<td>4:30 am: an explosion ejected incandescent blocks that reached 2 km above the crater, followed by degassing and ash emissions.</td>
</tr>
<tr>
<td>23 to 28 May 2006</td>
<td>200–1200</td>
<td>&gt;15 km to the NE, N, NW, and SE.</td>
<td>The activity was mild to moderate during this week, except for 24 May when a volcanic plume 1200 m high travelled ~15 km to the NE.</td>
</tr>
<tr>
<td>29 May 2006</td>
<td>4000</td>
<td>&gt;40 km mainly to the NW.</td>
<td>A plume of gas and ash in the form of cauliflower was generated. Fine ash fell on Sacohaya, Tonohaya, Escacha, San Miguel and Ubinas.</td>
</tr>
<tr>
<td>1 June 2006</td>
<td>4000</td>
<td>&gt;8 km to the N, NE, S and SE.</td>
<td>18:08 pm: a moderate explosion triggered an ash column 4000 m in height. That day the committee recommended SIDERECI – Moquegua to change the alert level from yellow to orange, which implied, according to the “Evacuation Plan”, the evacuation of all people from the towns of Ubinas, Tonohaya, San Miguel, Huatagua and Escacha to the area of Chachchagen (Fig. 14). The evacuation was conducted between 9 and 11 June 2006.</td>
</tr>
<tr>
<td>2 June 2006</td>
<td>4000</td>
<td>&gt;14 km to the E and SE.</td>
<td>On 3 June, degassing and ash column rose to 1800 m. Mild ash emissions occurred during the following days. On 13 June, steady cauliflower-shaped ash plumes formed and fine ash subsequently fell on the villages of Para, Yalagua and Elosque 20 km to the E and NE (Fig. 1). 1:10 and 5:55 am: two explosions occurred. The second explosion triggered incandescent blocks that fell ~1000 m SE of the crater. Immediately, gray ash plumes rose up to 3600 m for about two hours, and then fine ash fell on the town of Moche and Laguna Salinas 24 km to the W of Ubinas summit.</td>
</tr>
<tr>
<td>3 to 13 June 2006</td>
<td>400–1800</td>
<td>&gt;40 km to the E and SE.</td>
<td></td>
</tr>
<tr>
<td>10 June 2006</td>
<td>4000</td>
<td>&gt;20 km to the W</td>
<td>Emission of ash that was later dispersed by the wind.</td>
</tr>
<tr>
<td>19 to 23 June 2006</td>
<td>1000</td>
<td>&gt;14 km to the E and SE.</td>
<td>2:21 am: a strong explosion expelled incandescent rocks as far as ~1.2 km to the NE of the crater. For about three hours onward, degassing and ash plumes were generated and later ash fell in the valley of Ubinas.</td>
</tr>
<tr>
<td>24 June 2006</td>
<td>3000</td>
<td>&gt;20 km to the E and SW.</td>
<td>7:54 am: an explosion triggered incandescent blocks to the NW of Ubinas, then a plume of volcanic ash and gas was generated.</td>
</tr>
<tr>
<td>30 June 2006</td>
<td>3000</td>
<td>&gt;20 km to the S, SE and SW.</td>
<td>4:30 am: a moderate explosion triggered emissions of gray ash and gas. Constant but weak emission of fumaroles and grayish-white ash.</td>
</tr>
<tr>
<td>1 to 9 July 2006</td>
<td>700–1000</td>
<td>&gt;8 km to the NE and SE.</td>
<td>11:49 am and 12:06 pm: moderate explosions. The last one was followed by ash plumes that reached approximately 3000 m in height.</td>
</tr>
<tr>
<td>10 July 2006</td>
<td>200–1200</td>
<td>&gt;15 km to the SE and East.</td>
<td></td>
</tr>
<tr>
<td>11 to 16 July 2006</td>
<td>2500</td>
<td>&gt;20 km to the NW, E and SW.</td>
<td>Moderate emissions of ash that later fell on the towns of San Juan de Tarucani, Moche, Laguna Salinas, Saint Lucia and Tite.</td>
</tr>
<tr>
<td>17 and 18 July 2006</td>
<td>1000–2000</td>
<td>&gt;60 km to the NW and W.</td>
<td>Moderate degassing and ash emissions.</td>
</tr>
<tr>
<td>19 July 2006</td>
<td>3000–3500</td>
<td>&gt;70 km to the W and SW including the city of Arequipa.</td>
<td>8:29 am: an explosion hurled incandescent blocks ~1 km above the crater, and an ash plume was immediately produced. That day fine ash fell in the city of Arequipa.</td>
</tr>
<tr>
<td>22 July 2006</td>
<td>3000</td>
<td>&gt;6 km to the SE.</td>
<td>6:40 am: an explosion expelled ballistic blocks 1 km from the crater, followed by emission of ash and gas.</td>
</tr>
<tr>
<td>23 to 26 July 2006</td>
<td>200–1000</td>
<td>&gt;15 km to the SE.</td>
<td>Constant emission of fumaroles and dark gray ash that fell in the valley of Ubinas and on the towns of Matalaque and Chachchagen.</td>
</tr>
<tr>
<td>27 July 2006</td>
<td>1500</td>
<td>&gt;15 km mainly to the SE.</td>
<td>2:24 am: an explosion expelled ballistic blocks followed by degassing and sustained gray ash plumes.</td>
</tr>
</tbody>
</table>

(continued on next page)
Sampling of ash fall was conducted throughout the 2006–2007 activity, permitting the construction of an isopach map (Fig. 7). This map shows thickness of ash deposited through April 2007, e.g. 1-cm isopach including the village of Ubinas 6 km from the crater and 2-cm isopach encompassing the hamlet of Querapi. In April 2007, the volume of erupted ash was estimated to be ca. 0.004 km³. Ash dispersal has changed according to variable wind direction and velocity (Table 2). The greatest impact on people, tilled lands, and on

Note: Days that are not reported in the table are days with a very low volcanic activity when degassing and/or ash emission did not exceed 400 m above the top of the volcano.
sources of drinkable water was due to ash fallout at least 1 cm in thickness within a radius of 6 km around Ubinas. Within this area, as many as seven small villages totaling ~5000 people, who are engaged in agriculture and livestock, were affected by tephra fallout (Fig. 8). Fine ash (<500 μm) has caused problems to respiratory and visual systems, and stomach disorders of people, mostly children. People

**Fig. 4.** Diagram showing the maximum height of the eruption columns between April 2006 and December 2008, measured above the summit of the volcano (5670 masl, i.e. 400 m above the vent). Measurements made by INGEMMET team from the observation post 4 km SW of the volcano. Three eruption phases and alert levels are indicated with a bar.

**Fig. 5.** GOES image acquired on 1 April 2007 showing a plume of fine ash and aerosols spreading 95 km to the SE of Ubinas volcano. The yellow-line oval indicates the ash fallout area downwind from the volcano. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
have constantly been recommended to avoid contact with ash by using masks, safety glasses, and to remain inside their home or workplace. In addition, ash has adversely affected agriculture and livestock, contaminated water sources, fruit plantations and pastures, and caused people and cattle diarrheas. Occasionally, fine ash dust and aerosols were blown away more than 60 km from the volcano to the South, and eventually to the West, affecting more remote villages such as Yalagua 18 km to the NE, and Omate 30 km to the South. As a result, the majority of residents, whose main economic activity is agriculture and livestock, were unable to work during the crisis, creating a significant financial loss exceeding 1,000,000 $US (Regional Government of Moquegua, R. Berolatti, pers. comm., 2009). Unfortunately, since the onset of the volcanic activity, farmers decided to sell their livestock for lower prices than normal, creating further deficit in the region. Farmers feared that cattle would die when grazing ash-
covered fields and drinking contaminated water from the clogged drainage. They were also eager to leave, without the cattle, towards the cities of Arequipa and Moquegua in the case of an imminent eruption.

We now focus on the response to the eruptive crisis in order to understand how scientists, civil authorities, and threatened people have coped with its effects and aftermath.

3. Prevention and risk management

3.1. Formation of the scientific committee and communications released

In Peru the central body of the National System of Civil Defense (SINADECI) is the National Institute of Civil Defense (INDECI), which promotes policies and programs of prevention and disaster relief at the national level (Fig. 8). The SINADECI is composed of two main bodies: (1) Regional Systems of Civil Defense, consisting of 12 Regional Governments in all Peru, the Regional Committee, the Provincial and district Civil Defense; and (2) Regional Offices and Offices of Civil Defense of the Local Governments. The Civil Defense Committees, organized at the national level, execute the actions of Civil Defense of SINADECI, and as such, bear the responsibility to implement measures to minimize damage to life and property that can be caused by natural disasters. These committees are supported by the INDECI through their Regional Bureaus of Civil Defense. Depending on the size of a disaster, a Centre of Emergency Operations (COER) led by the highest authority in the area, will provide the SINADECI with information on the magnitude of the damage and on requirements to coordinate and meet emergencies.

On 30 March 2006, a few days after the onset of eruptive activity at Ubinas and ash fallout in Querapi, an official Scientific Committee was formed. The committee, which included members of INGEMMET, IGP, and IG-UNSA, had three objectives: 1) to carry out volcano monitoring; 2) to mitigate the effects of a large eruption on people in the Ubinas valley, and 3) to develop a contingency plan that regional and local authorities (i.e. the Regional Government of Moquegua and CRDCM) use in decision making. As early as 23 April 2006, the CRDCM had six fully active committees and established the COER, taking on a permanent role during the crisis. The CRDCM was in charge of disseminating hazards information to the public and media. Since the beginning of the activity until the day of this writing (December 2009), 24 official communications were issued (http://www.ingemmet.gob.pe/webubinas/02-comunicados.htm). Among the most important of these was communication #03 on 20 April that recommended the CRDCM to raise the alert level to orange due to the gradual increase in eruption activity and the observation of incandescent lava at the bottom of the crater. The events of 20 and 22 April, which produced plumes up to 3000 m high, prompted the precautionary evacuation of Querapi, only 4 km south of the crater, on 23 April 2006. Another important communication #08 was released on 3 June, due to the increase in the amount of ash and gas, frequency of explosions, and seismic activity. For the second time the committee recommended the CRDCM to raise the level of alert from yellow to orange. This communication implemented the contingency plan to evacuate five villages in Ubinas valley, as planned earlier. The decision to evacuate also was prompted by uncertainty due to the paucity of monitoring data.

Following the onset of activity at Ubinas, the news media generated messages that produced panic and confusion among the population. The press releases did not include official statements made by the CRDCM. The press interviewed people not knowledgeable in volcanology but who gave their opinion and even forecasted future activity, creating confusion among the population and civil authorities. As a consequence, during April and May 2006, many dwellers of the Ubinas valley, whose economic activity is chiefly based on agriculture and stockbreeding, became frightened by the substantial increase in the volcanic activity, sold their cattle at very low cost, abandoned their housing, and moved out to the cities of Arequipa and Moquegua. During its first meetings, the scientific committee concluded that any public announcements regarding Ubinas activity and forecasts of future risks would be first agreed upon within the scientific committee and that any announcement with potential to cause alarm would be made public only by the CRDCM. Nevertheless, at the same time, alarming communications and statements were
attributed misleadingly by the press to members of the scientific committee, adding to confusion.

3.2. Volcano monitoring

At the onset of the 2006 crisis, no adequate volcanic monitoring system was in place at Ubinas. Sporadic seismic, deformation, and fluid chemistry data on the Ubinas volcano had been collected over the previous few years; however, such incomplete and limited data were not suitable for real-time evaluation or monitoring of the evolution of the 2006–2008 crisis. Active volcanoes with villages nearby in some developing countries (e.g., Ecuador, Colombia, Costa Rica) and in most developed countries like Japan, Italy, and the USA are equipped with a complete seismic network and additional geophysical and geochemical equipment that monitor precursory volcanic activity. In some circumstances, scientists could anticipate an eruption based on precursory signals recorded from such a network, e.g., at Mount St. Helens in 1980–1982 (Swanson et al., 1983) and at Mt. Pinatubo in 1991 (Harlow et al., 1996).

The Scientific Committee, supported by several international specialists, was tasked to monitor the volcanic activity. INGEMMET, assisted by Institut de Recherche pour le Développement (France) and Laboratoire Magnas et Volcans (Clermont-Ferrand, France) implemented the following tasks: i) daily visual observation from a camp that was established at 4560 masl 4 km west of the volcano (Fig. 1); ii) deformation measurement particularly on the unstable southern flank using InSAR images (12 April 2004, 13 May 2006, 7 September 2006), performed jointly with the Peruvian National Committee for Aerospace Research and Development (CONIDA), and iii) monitoring the temperature and chemistry of hot springs associated with the volcanic hydrothermal system beneath Ubinas (Fig. 7). The results of InSAR analyses were actually available to the scientific team on site in

Fig. 9. Hazard-zone map of Ubinas volcano (completed in April–May 2006). This map displays three distinct areas based on three hazard levels: high, moderate, and low, around Ubinas volcano: 1) Summit cone and unstable south flank (in red); and 2) Principal river or stream channels that can carry debris flows, pyroclastic flows, and/or debris avalanches (in orange); 3) Areas (in yellow) likely to be covered by ashfalls to the west, east, and southeast according to column heights and wind patterns prevailing towards N-NE in dry season and towards S-SW in wet season; 4) Summit caldera, area of prohibited access; 5) Most vulnerable roads; 6) Dirt roads; 7) Towns. According to the outlined hazard zonation, population living inside high hazardous areas (red) and moderate hazardous areas (orange) should be relocated outside the Ubinas region. The construction of important infrastructure and lifelines (roads, water tanks, irrigation channels, etc.) should be avoided inside these areas. This map, based on geologic information available on the Ubinas volcano from previous studies, has ranked hazard areas in case of moderate to relatively large magnitude eruptions (vulcanian, phreatomagmatic, and Saint-Vincent type), during which an eruptive column could raise between 5 and 15 km in height. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
May 2006 (http://www.ingemmet.gob.pe/webubinas/01-vigilancia.htm). In hindsight however, the analysis of InSAR interferograms revealed no significant deformation and the geothermal system did not show significant changes during the crisis. We attribute this lack of changes to the small volume of magma that intruded the shallow hydrothermal system at the volcano summit and to the fact that any given aquifer near the summit caldera level was emptied after almost three years of explosive activity. Throughout 2009, degassing and other eruptive phenomena show a constant decline that supports this eruption scenario (see below). Given the limited resources in southern Peru, the scientific committee did not have access, at the beginning of the crisis, to real-time recorded seismic activity that would have made possible a better assessment of the level of volcanic activity, although this is considered as one of the principle techniques used to forecast an eminent eruption (e.g., Scarpa and Tilling, 1996; Tilling, 2005). The lack of previous information on the background seismic activity at Ubinas, as well as during the crisis, was one of the factors that influenced the decision to evacuate the inhabitants of Ubinas valley to shelters. On 24 May 2006, IGP with the help of other institutions installed a digital telemetered seismic station, which is still operational in January 2010. In 2007, INGEMMET therefore decided to acquire digital broadband seismometers, GPS and EDM equipment, which would enable its scientists to systematically monitor Ubinas in near-real time as well as other active volcanoes in southern Peru.

3.3. Elaboration of the hazard-zone map

Hazard-zone maps have become a fundamental means of communicating volcanic hazard and risk assessment to the public. They are used to explain and display the distribution of hazards, areas at risk either likely to be affected or to which access may be denied in time of heightened crisis. Maps also form an integral part of emergency plans and response in which they are considered vital for the coordination of preventive, protective and rescue evacuations (Dymon and Winter, 1993; Nourbakhsh et al., 2006).

Prior to the crisis of Ubinas, an official map of volcanic hazard was not available at an adequate scale and in simple language that could guide the effective management of a crisis by the authorities and people. Thus, geologists from INGEMMET, IRD and Laboratoire Magmas et Volcans (France) immediately proceeded to collect and integrate all available geological and volcanological information to evaluate the types of volcanic hazards. Based primarily on information in Rivera et al. (1998) and Thouret et al. (2005), the scientific team quickly produced a volcanic hazard-zone map (Fig. 9) during April–May 2006. The hazard-zone map has two primary purposes: (1) to delineate the areas likely to be affected in case of an imminent eruption; and (2) to outline the areas that are apparently out of danger, which can serve as safety zones in case of eruption. The delineation of areas related to different types of hazard was based on interpretation of 1:65,000-scale aerial photographs and on fieldwork during which ten stratigraphic sections were analyzed. Deposits and their distribution as well as types of eruption were identified. The eruptive history of the Ubinas volcano over the past 250 ka was reconstructed based on this information and on data in previous publications.

The maximum distance that eruptive products can reach as well as the probable magnitude and frequency of the events was determined (Table 3). We use a data set of information stemming from the most frequent explosive activity that occurred over the past 1500 years (Thouret et al., 2005), the types of observed events since the onset of crisis until April 2006, the types of tephras and lavas, and the chemical composition of magma (andesite 56–57 wt. % SiO2, Fig. 6). Based on this information and on our previous experience in southern Peru since 1990, we depicted hazard-prone areas according to the occurrence of two principal types of eruptive behavior: a moderate but long-lasting volcanic and/or phreatic to phreatomagmatic eruptive episode (e.g., Nevado Sabancaya, 1990–1998) and, in case of increase in activity, a relatively large ‘Saint-Vincent’ type eruption (e.g., 1979 at the Caribbean Island of St. Vincent). On the one hand, a moderate volcanic eruption consists of short-lived (second to minutes), violent outbursts that eject relatively small volumes of magma (<0.01 km³). This type of explosive activity can produce volcanic plumes that can reach up to several km in height for a single eruption and produce moderately dispersed deposits (Morrissey and Mastin, 2000). Our examples are based on the first phase of the Nevado Sabancaya eruption in 1990–1998 (Gerbe and Thouret, 2004) and on the behavior of Sakurajima in Japan in 1955 (Morrissey and Mastin, 2000). Volcanic eruptions may generate scoria or block-and-ash flows, thin distal ash falls, and near-vent ballistic blocks (e.g., Morrissey and Mastin, 2000). On other hand, a ‘Saint-Vincent’ type eruption can produce mainly ash fall and scoria flows (Hay, 1959; Bourdier et al., 1985) with <1 km³ total volume that can travel distances five times the height of 4 or 5 km that they drop from the

Table 3

Types and frequency of prehistoric and historical eruptions at the Ubinas volcano.

<table>
<thead>
<tr>
<th>Event type</th>
<th>Type of deposit</th>
<th>Area (km²)</th>
<th>Volume (km³)</th>
<th>VEI</th>
<th>Reported or estimated frequency</th>
<th>Dated Ubinas deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate and minor eruptions:</td>
<td>Ash fall</td>
<td>120</td>
<td>0.0002</td>
<td>1–3</td>
<td>Small-volume ash falls every 15 yr on average.</td>
<td>24 recorded events since AD 1550</td>
</tr>
<tr>
<td>Vulcanian, Phreatomagmatic, Phreatic Saint-Vincent’ (moderate eruption, open vent, mafic magma)</td>
<td>Scoria flow</td>
<td>~32</td>
<td>~0.0001</td>
<td>3</td>
<td></td>
<td>Scoria fall and flow deposits in AD 1667²</td>
</tr>
<tr>
<td>Plinian and Subplinian</td>
<td>Lahars</td>
<td>38</td>
<td>0</td>
<td>3–5</td>
<td>(Sub) Plinian pumice falls 3000 to 6000 yr.</td>
<td>980 ± 60 yr³</td>
</tr>
<tr>
<td></td>
<td>Pumice fall</td>
<td>180</td>
<td>0.01</td>
<td></td>
<td></td>
<td>7480 ± 40 yr³</td>
</tr>
<tr>
<td></td>
<td>Pumice fall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9700 ± 190 yr³</td>
</tr>
<tr>
<td></td>
<td>Pumice fall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14690 ± 200 yr²</td>
</tr>
<tr>
<td></td>
<td>Pumice and ash flow Lahars</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Between 120 and 25 ka².</td>
</tr>
<tr>
<td>Dome growth and collapses</td>
<td>Block-and-ash flow</td>
<td>40</td>
<td>&lt; 0.05</td>
<td>3–5</td>
<td>Block-and-ash flows 40,000 to 80,000 yr.</td>
<td>150 ka²</td>
</tr>
<tr>
<td>Medium-size gravitational collapse</td>
<td>Debris avalanche 1</td>
<td>25</td>
<td>0</td>
<td></td>
<td>Debris avalanches 5000 to 20,000 yr.</td>
<td>3670 ± 60 yr²</td>
</tr>
<tr>
<td>Large-size gravitational or explosively-driven collapse</td>
<td>Debris avalanche 2</td>
<td>50</td>
<td>&lt; 0.02</td>
<td></td>
<td></td>
<td>Between 370 and 250 ka</td>
</tr>
<tr>
<td>Effusive eruption</td>
<td>Lava flow</td>
<td>36</td>
<td>0.02</td>
<td>3–6</td>
<td>Lava flows every 25,000 to 100,000 yr</td>
<td>142 ± 3 ka²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>168 ± 30 ka²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>261 ± 10 ka²</td>
</tr>
</tbody>
</table>

Rivera et al. (1998)¹; Thouret et al. (2005)².
eruption column. The extent and the trajectories of the products of the Saint-Vincent type eruption are based on the andesite scoria fall and flow deposits that previously occurred in Ubinas in 1667 AD (VEI 3: Simkin and Siebert, 1994; Rivera et al., 1998; Thouret et al., 2005) and on the effects of similar eruptions such as Ngauruhoe in New Zealand in 1974 (Self et al., 1979).

The hazard-zone map shows three distinct areas based on three degrees, high, moderate and low, of hazard. According to the frequency of hazardous events, the main volcanic hazards are ash fall, lahars, pyroclastic flows, failure of the south flank and subsequent debris avalanche, and lava flows. In addition, hazard zonation is influenced strongly by the geomorphological characteristics of the area surrounding the volcano. In the case of Ubinas, its lower flanks are relatively gentle to the north and west, whereas deep, steep valleys are found to the east and south. To elaborate the hazard-zone map, boundaries were drawn using the maximum range of erupted deposits from past eruptions and based on energy line calculations (Malin and Sheridan, 1982), on LAHARZ code for inundation areas (Iverson et al., 1998), and on TITANZD code for pyroclastic flows (Sheridan and Patra, 2005). We also took into account heights, directions and velocity of prevailing winds in wet and dry seasons and at distinct elevations over the region of the Ubinas volcano, provided by SENAMHI (National Institute of Meteorology and Hydrology). At the onset of the volcanic crisis, SENAMHI launched balloons in the atmosphere 4 km west of the Ubinas volcano (2891705 S, 8187620 W, 4660 masl, Table 3). The area of high hazard (red color) covers a roughly circular area 3 km in radius around the crater. All types of eruptions can affect the high-hazard area, including those of low magnitude. The area of moderate hazard (orange color) extends from 3.0 km away from the crater to a maximum distance of 12 km down the southern flank. This area may be affected by ash fall, pyroclastic flows, lahars, and/or debris avalanches in case of medium to large magnitude eruptions. The area has been outlined on the basis of two debris-avalanche deposits from the Ubinas south flank, which crop out between 4 km and 14 km from the summit. The low hazard zone (yellow color) extends between 12 km and more than 30 km around the summit. This area may be affected by tephra fall, lahars, and exceptional pyroclastic flows. This is based on the occurrence of moderate to high magnitude eruptions (VEI 3–4), as indicated by six plinian and subplinian eruptions between ca. 25,000 years and 980 years BP. (Rivera et al., 1998; Thouret et al., 2005).

As often happens during the high-stress situation of a volcanic crisis, the map was constructed within a very short time (two weeks) in April 2006. This map was intended to be used immediately as a management tool during the present volcanic crisis by the authorities of CRDCM and by Regional Governments in Arequipa and Moquegua and District Municipalities. The hazard-zone map was also intended to be disseminated in educational institutions and amongst the population living nearby the Ubinas volcano. Subsequently, by the end of 2007, national institutions and NGOs as Caritas Moquegua, PREDES, Oxfam America as well as the Regional Government of Moquegua, the Municipality of Ubinas and INGEMMET, undertook the dissemination of the several hundred copies of the map in all the villages in the framework of the project ‘Living at risk, the eruption of Ubinas volcano’. Currently, the hazard-zone map is strategically displayed in many public places, such as city halls, local communities, educational centers, and health facilities. The successful dissemination of the map has allowed the villagers to have easy access to available information, to know better the environment and what to do in case of increase in volcanic activity.

3.4. Elaboration of the contingency map and alert level scheme

At the start of the crisis, the local and regional authorities requested evacuation routes be designated and shelter sites be planned in case of increased activity, which would allow to evacuate the affected population to safe areas. Based on the hazard-zone map, volcanologists of INGEMMET, IRD, and Laboratoire Magmas et Volcans (France), and technicians of Regional Government of Moquegua drew a contingency map designating evacuation routes and sites for refuge (Fig. 10), guided by methods used for Sakurajima and other volcanoes in Japan (Fujita, 2009). A number of issues were addressed and included in the preparation of the contingency map: the geomorphic context of the Ubinas valley, the eruptive activity of Ubinas over the past 1500 years, and three eruption scenarios that could occur within the upcoming weeks to months. The group of experts also determined the amount of time required to evacuate the population of five villages (Ubinas, Tonohaya, Escacha, San Miguel, Huatagua) that are located in hazardous parts deep in the Ubinas valley, to areas outside the first danger zone.

The contingency map, also called administrative map (Fig. 10), was drawn with simple color codes and symbols that can be easily interpreted by the threatened population and by the civil authorities. In this map, we distinguish four potentially affected areas based on degrees of risk: (i) zone 1 (purple color), corresponds to prohibited access to the caldera and summit of the volcano within a 2 km radius; (ii) zone 2 (red color) corresponds to restricted access and high risk; (iii) zone 3 (orange color) is at moderate risk but access is guaranteed only with caution; and (iv) zone 4 (yellow color) corresponds to free access in daytime although risk is not nil. On the other hand, two areas of refuge are designated: shelter I is located in the low risk yellow area in the village of Anascapa on the right side of the Ubinas valley while shelter II lies outside risk zones in an uninhabited area called Chacchagen, 1.5 km from Matalaque (Fig. 11).

In addition to this map, three phases of evacuation have been recommended and planned in the contingency map, which would be implemented according to the intensity of the eruptive activity. During the first meetings deliberating crisis management, the CRDCM, with advice from ONGs and INGEMMET, agreed to establish three levels of alert and three phases in the case of an increase in activity: yellow alert (mild activity characterized by degassing), orange alert (moderate activity characterized by strong degassing and ash fallout), and red alert (imminent large eruption). This alert level scheme has no national basis but it is applied at regional scale by the Regional Governments such as COER (Centre for Emergency Operations) in Moquegua. Phase I, when the alert goes from green to yellow, required the evacuation of the village of Querapi to shelter I (Fig. 11). Phase II, when the alert level rises from yellow to orange (volcano unrest), would involve the evacuation of five villages (Tonohaya, Escacha, San Miguel, Huatagua, and Ubinas) to shelter II (Fig. 11). Phase III, once the explosive activity becomes critical (red alert) just before an imminent large eruption, would trigger the evacuation of the populations of the villages of Huarina, Anascapa, and Sacohaya from shelter I to shelter II. In retrospect, this map did help the civil authorities and decision makers to effectively manage the volcanic crisis and to carry out needed evacuations in Spring 2006. This map was widely disseminated and posted in key public areas, facilitating its wide use by civil authorities and population for evacuation and emergency procedures.

3.5. Precautionary evacuations

On 24 April, the CRDCM proceeded to develop a “Contingency plan in case of increase in activity of the Ubinas volcano” (Fig. 8), whose aim was to establish tasks and coordination procedures for alerts and evacuations during the volcanic crisis. This plan involved five phases: (1) preparation for evacuation, (2) evacuation and establishment of shelters, (3) permanent social support in shelters, (4) final relocation, and (5) deployment of human resources and material to the area and re-evaluation of the situation. The contingency plan also included a plan for dissemination of emergency information. Its formulation also took into account proposals made by community leaders and
authorities not only in 9 villages located in the Ubinas valley (Querapi, Tonohaya, Sacohaya, Anascapa, Escacha, San Miguel, Huatagua, Huarina, and Ubinas) but also in communities located >15 km West and North of the volcano such as San Carlos de Tite, Santa Rosa de Para, Santa Lucia de Salinas, Salinas, Cancosani, and San Juan de Tarucani (Fig. 1). The “Contingency plan” (CPIAUV) was approved on 31 May 2006 during a meeting of representatives of all committees of Ubinas and Matalaque led by CRDCM.

A month earlier (20 April 2006), as no contingency plan existed, civil authorities received the recommendation of the scientific committee for precautionary evacuation of people from the hamlet of Querapi. Since the start of the crisis, Querapi was the locality most affected by ashfalls and volcanic gases due to its close proximity to the volcano. Approximately 45 families living in Querapi (COER-Moquegua, 2006) and their livestock were taken to a refuge located in the village of Anascapa, which is within the low hazard area, and which was equipped with tents, food rations, and shelter. Following a week of increasing eruptive and seismic activity, the scientific committee recommended on 3 June 2006, that the CRDCM raise the alert level from “yellow” to “orange”. According to the CPIAUV, this procedure involved the evacuation of 5 villages of Ubinas, Tonohaya, Escacha, San Miguel, and Huatagua to shelter II in Chacchagen. In total, 991 people were evacuated to Chacchagen, which lies in a low risk area 20 km to the SE of Ubinas on the right bank of the valley of Río Tambo. The area of Chacchagen was chosen as a shelter by the scientific committee on the basis of the following advantages: (i) This low risk area can only be affected by large events (plinian eruptions); (ii) The distance between the Ubinas valley and Chacchagen is such that

Fig. 10. The contingency map (completed in May 2006) shows and identifies four types of color-coded risk-prone areas: Zone 1 (purple), prohibited access; Zone 2 (red), restricted access and high risk; Zone 3 (orange), moderate risk; and Zone 4 (yellow), free access in daytime although risk is not nil. This map is based on a series of criteria: hazardous areas, elements at risk, location of 8 threatened villages, pattern of evacuation routes, distance to shelters in case of medium- to large sized eruptions. In addition to people, elements at risk include housing, roads, bridges, lifelines, crop and livestock. This map showing evacuation routes and shelter areas in case of a possible eruption of Ubinas is designed to be used by authorities of the National Civil Defense, regional and local entities and population of Ubinas valley. 1) Summit caldera of volcano; 2) Area likely to be affected by pyroclastic flows and surges, lahars, debris avalanches, lava flows, and 10 cm thick ash fall; 3) Area likely to be moderately affected by pyroclastic flows and surges, lahars, lava flows and <5 cm thick ash fall; 4) Area that can be affected by light ash fall according to prevailing wind direction: towards the N-NE in dry season and towards S-SW in wet season; 5) vulnerable villages; 6) Temporary shelter; 7) vulnerable roads and dirt paths; 8) Dirt roads; 9) Dirt paths outside hazard; 10) Escape dirt paths. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
temperatures between 6 and 25 °C during most of the year (May–November); (v) There is abundant water for human consumption, and; (vi) A dirt road links Matalaque and Anascapa to Ubinas and Arequipa.

The shelter area covering approximately 5 ha was prepared by heavy machinery provided by the Regional Government of Moquegua (RGM). The design of the shelter included areas of bathrooms, kitchens, dining, warehouses, health care, and education, etc. The shelter area adequately accommodated the families of the five villages and could provide additional room for the inhabitants of Sacohaya, Huarina, and Anascapa in case of an abnormal increase in eruptive activity. After having spent more than eight months in Chacchagen, the people evacuated during the months of February to April 2007 decided to return to their villages of origin. This was due to the living conditions, which were harsh, and also to a loss of production and purchasing capacity among the population. The modules of temporary housing and essential services still remain, but now there are no dwellers in the shelter area.

During 2008, the RGM is promoting the permanent relocation of the entire population of the valley of Ubinas away from the region of active volcanoes; having carried out an evaluation of the residents affected, the RGM is building a water canal towards a vast arid area on the coast, so-called “Pampas of Jahuay, Moquegua”, where the inhabitants of Ubinas could be eventually relocated. This integrated project intends to provide social and economic integration of dwellers in this new environment. If the above-mentioned actions are not suspended, the relocation project would be completed within four years.

4. Discussion

The fact that the current crisis lasted two years and half but eruptive activity has not ceased prompts the following questions. What are the potential eruption scenarios in the future for Ubinas? Why is a minor crisis caused by relatively weak but sustained eruptive activity difficult to manage? What lessons can we gain from this crisis that can be applied to possible larger future eruptions of Ubinas, or to reactivation of other active volcanoes in southern Peru?

4.1. Potential eruption scenarios in the future

We highlight three possible likely eruption scenarios if the current crisis persists beyond 2009:

1. The first scenario projects the eruptive activity of Ubinas to continue with degassing and weak to moderate Vulcanian or phreatomagmatic, sometimes small phreatomagmatic, events, and then subside within a few years. This scenario assumes that the magma intrusion to date probably represents only a small volume, given the lack of measurable deformation of the summit and south flank, and on the overall decline in volcanic seismic activity. The activity shows a declining trend since May 2008: degassing plumes are less than 800 m high and ash fall is nearly absent.

2. Should explosive activity increase, two additional eruptions can be envisaged. After passage of time, another injection of fresh magma occurs and may produce an increase in eruptive output, involving a mafic andesite composition and a high content of volatiles. Such an event could lead to an explosive Vulcanian or Saint-Vincent type eruption. On the one hand, a Vulcanian eruption (e.g., Nevada Sabancaya, 1990–1998) can generate eruptive columns that would reach at least 5 km in height with proximal ballistic blocks and widespread ashfall. Column collapse also may occur and generate small- to moderate-sized block-and-ash flows that may be channeled in the ravine network all around the volcano flanks. On the other hand, a Saint-Vincent-type eruption (e.g., Soufrière of Saint-Vincent Island, 1979) can generate higher eruptive columns that would exceed 9 km in height and produce considerable proximal volume of ash and distal ash falls. Column collapse may generate moderate to large scoria flows that may be channeled in the ravines network farther downvalley. These mobile scoria flows may cause damage in villages located 6 to 12 km in the Ubinas valley.

3. Within several months or even years, a larger volume of mafic andesite can be intruded in the magma chamber. Lava flows can fill the crater and pour out on the caldera floor. This eruptive behavior produced relatively thick lava flows before the Holocene times (>14 ka), which formed the caldera floor at the Ubinas summit.

4.2. Lessons learned

The management of minor to moderate volcanic crises can be complex and difficult for long-duration eruptive activity, even if
relatively minor. A particular concern is the uncertainty of future volcanic events, thereby causing confusion and anxiety amongst the dwellers, the community leaders, and local authorities. Furthermore, despite the historical record of the eruptive activity of Ubinas, no complete, real-time monitoring network was installed and no contingency plan existed prior to 2006 that might have provided an improved basis for hazard mitigation and emergency planning. The 2006–2008 crisis has been relatively minor so far, but weak activity continues at Ubinas, still warranting a yellow level of alert. This volcanic crisis was not the first one that Peru has experienced but the 2006–2008 experience is the first long-lasting crisis that the Peruvian civil authorities have had to cope with, including attempts to utilize a new alert-level scheme and communications system, and successful evacuation of 1150 people. Teams led by INGEMMET with foreign help succeeded in offering advice to INDECI, namely by quickly preparing a hazard-zone map and a contingency map now used in the Ubinas valley, and by explaining the implications of the volcano-monitoring data. Throughout the 2006–2008 crisis, the scientific committee maintained open communications with the authorities in the affected region, providing advice and information regarding hazard-zone maps. The scientific committee also focused on providing information and increasing awareness of volcano hazards among teachers, students and the population in general by means of workshops and conferences. Finally, the scientific committee has recommended the authorities that people located in six villages in zones of high and moderate hazard be permanently resettled within a few years near the city of Moquegua (80 km away from the volcano). The Moquegua Regional Government has planned to re-locate people of the threatened villages to an area c. 5 ha near the coast, where free area and basic services would be provided. This area 100 km West of the volcano has been selected because no safe and free area is available to host 5000 people in the vicinity of the volcano. The altiplano north and east of the volcano is too cold for permanent settlements above 4000 masl. The narrow Rio Tambo Valley, 15 km south of the volcano, can be affected by slope mass movements and floods. The population of Ubinas Valley is still waiting (in 2010) for safe relocation away from the volcano.

5. Conclusion: challenges for the future

In the most recent active episode, the onset of explosive behavior occurred on 27 March 2006, following 8 months of heightened gas emissions. The 2006–2008 crisis has been moderate so far but the eruptive activity continues with a yellow level in 2009. Ongoing activity is manifested as continuous degassing with a minor amount of ash fallout. Fine ash continues to affect residents, livestock, water supply, and crop cultivation within an area of ~100 km2 around the volcano. Although the population around the Ubinas volcano is less than 5000 people, the mild eruptive activity has created a series of difficulties in crisis management. In particular the relocation of evacuated people remains a tough issue, as social and economic consequences are too difficult to be supported by the regional government alone.

This should prompt us to be better prepared for possible reactivation of the active Misti volcano (currently fumarolic) in a much more densely populated and developed region in southern Peru. There are several lines of evidence for Misti’s future reactivation based on relatively frequent historical and Holocene eruptions (Legros, 2001; Thouret et al., 2001; Delaite et al., 2005), the presence of a fumarolic plug and an active hydrothermal system at the summit, and occasional weak, short-lived volcano-tectonic seismicity. However, there is no contingency plan established to reduce future volcano risks in the city of Arequipa and its environs. INGEMMET in cooperation with IRD, LMV, and the Multinational Andean Project of Canada, has published a modern hazard-zone map in 2007 (Mariano et al., 2007). The hazard-zone map of El Misti volcano is already incorporated by civil authorities in the management of the territory and urban planning of the city of Arequipa. However, the dissemination of the map and the education of the people require a greater effort than that for the sparsely populated area around Ubinas for several reasons: (1) Arequipa has approximately 900,000 inhabitants, a figure much higher than the 5000 inhabitants of the Ubinas valley; and (2) as El Misti is currently weakly fumarolic, it generates little interest or urgency among the population and civil authorities of Arequipa to the subject; (3) because of complacency, the housing and development have mushroomed on the flanks of the volcano within 9 km from the summit. It is a high priority of INGEMMET to design and implement an effective program for disseminating the hazard-zone map and increasing awareness of its implications. In that respect, INGEMMET is carrying out the following actions: (a) coordination with the Director of Education of the Regional Government of Arequipa, so that a simplified hazard-zone map can be used in local schools; (b) printing a great number of hazard-zone maps for mass distribution, with the collaboration of private enterprises, local institutions, and ONGs; (c) a training program targeting teachers of all educational institutions to be expanded (Macedo et al., 2008), and; (d) an exercise of evacuation in case of a volcanic crisis was held in 16 May 2009 with the district of Alto Selva Alegre (Arequipa) as a pilot place (Macedo et al., 2009). This evacuation simulation is a landmark in the management of volcanic hazards in the second most important city of Peru. Active participation of private and public institutions demonstrated significant progress in preparing an effective response to another volcanic eruption in southern Peru.

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