MMA Memo 251

MMA Site East of San Pedro De Atacama
North Chile

Volcanic Hazards Assessment
and Geologic Setting

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CONCLUSIONS

- The MAA site is located in the western foothills of the Western Cordillera de los Andes, in the limit with the Altiplano, at *ca.* 5,000 above sea level. The site sits on welded pyroclastic rocks or ignimbrites that show extensive, nearly flat surfaces, smoothed by glacial erosion. It is surrounded by volcanic cones of various sizes and ages, none of the closer ones active.

- Welded ignimbrites are solid rocks that ahow good mechanical behavior and are often used as building stone due to their strength and insulating characteristic.

- A major NS regional fault that extends close to the MMA site apparently has had no movements for more than 1 million year (Ma), as suggested by the lack of displacement of 1.3 Ma old ignimbrites.

- Three volcanoes currently identified as active are in a radious of less than 100 km from the site Putana, Sairecabur and Lascar. Lascar is the most active, with an important eruptive activity in historic and recent times (1993). Putana is in a fumarolic state and Sairecabur shows evidences of recent fumarolic activity. Putana and Sairecabur have no records of historic activity and the chance they erupt in a near future is low, while for Lascar is appears high.

- Due to its considerable distance from active volcanoes, lava flows, pyroclastic flows, volcanic landslides and lahars do not pose a direct hazard to the site. Hazards from volcanic gases and acid rain are very low as downwind gas concentration becomes diluted by air.

- The more relevant volcanic hazard posed to the MAA site is the fall of fine-grained pyroclatic material (ash) during explosive eruptions of one of the three active volcanoes. Due to the regional prevailing E-SE winds, the hazard is larger in terms of size and thickness of material in case Putana or Sairecabur erupt but, the probability of occurrance is lower. If Lascar renues its eruptive and explosive activity, there is a true probability that ash falls on the site, as occurred during the 1993 eruption. Due to the 40 km that separate the MMA site from Lascar, and the lower transport capacity shown by volcanic plumes when shifted from their main dispersion trend, the fallout would most probably be small-volume and fine-grained.

INTRODUCTION

The present report was requested by the Associated Universities, Inc.. Corresponds to a volcanic hazards assessment of the site where the Associated Universities, Inc., on behalf of the National Radio Astronomy Observatory (NRAO), proposes to build **The Millimeter Array**. The site, located in the foothills of the Andes in the northern Atacama desert in Chile, is surrounded by volcanic edifices and relatively close to the intensively active Lascar volcano.

The report includes:

- a brief description of the geographical and geological setting of the site,
- a characterization of the Central Andes volcanic chain in general, with more detailed references to the site surroundings and the nearby active volcanoes
- a description of the different types of volcanic activity that might be expected in this part of the Central Andes and the hazards that, in general, they pose.
- an assessment of the hazards that these volcanic processes pose to the site in case one of the nearby active volcanoes erupts.

GEOGRAPHIC SETTING

Location

The site area is located in northern Chile, in the western foothills of the Altiplano of Antofagasta, about 40 km SW in strait line of San Pedro de Atacama, the closest village (Fig.1). The site itself is located in a relatively flat area, on a N-S-trending ridge which locally divides the water shed, at an altitude of nearly 5,000 m. It is close to an old track for four-wheel-drive vehicles that leads to the Alitar sulfur mine, currently inactive. A new international road to Argentina (Paso Jama), not included in Fig.1, was built a few years ago that passes north of the Purico hill.

Morphology

The **Main or Western Cordillera de los Andes** consists of volcanic cones built up on the non-volcanic basement of the Altiplano. This corresponds to the area immediately east of the intermontane basins of the Río Loa and Salar de Atacama. In the study area it forms a gently westward dipping slope (3-5°) of ignimbrites and pyroclastic flows associated with cones located mainly on its eastern border and large calderas located on the Altiplano. A group of volcanic edifices that rise above 5,000 m and include, from north to south, Licancabur (5,916 m), Purico (5,604 m), Cerro Negro (5,025 m), the active Láscar (5,592 m), Tumisa (5,614 m), Lejía (5,793 m), Miscanti (5,622 m), Miñiques (5,910 m) and Púlar-Pajonales (6,233 m) volcanoes define the western volcanic front in this part of the Central Andes. Inmedialety east and with a not well defined limit is the **Altiplano** or **Puna**, one of the world's largest plateaus. It is *ca.* 200 km wide, with a basal elevation of *ca.* 3,800 m, and lies between the Western and Eastern Cordilleras. This plateau consist of Upper Cenozoic volcanic cones that rise to well over 5,500 m and extensive ignimbrite shields built up on a non volcanic basement of Palaeozoic to Tertiary age. Large calderas or volcano-tectonic depressions control internal drainage basins, most of which include a salt pan or saline

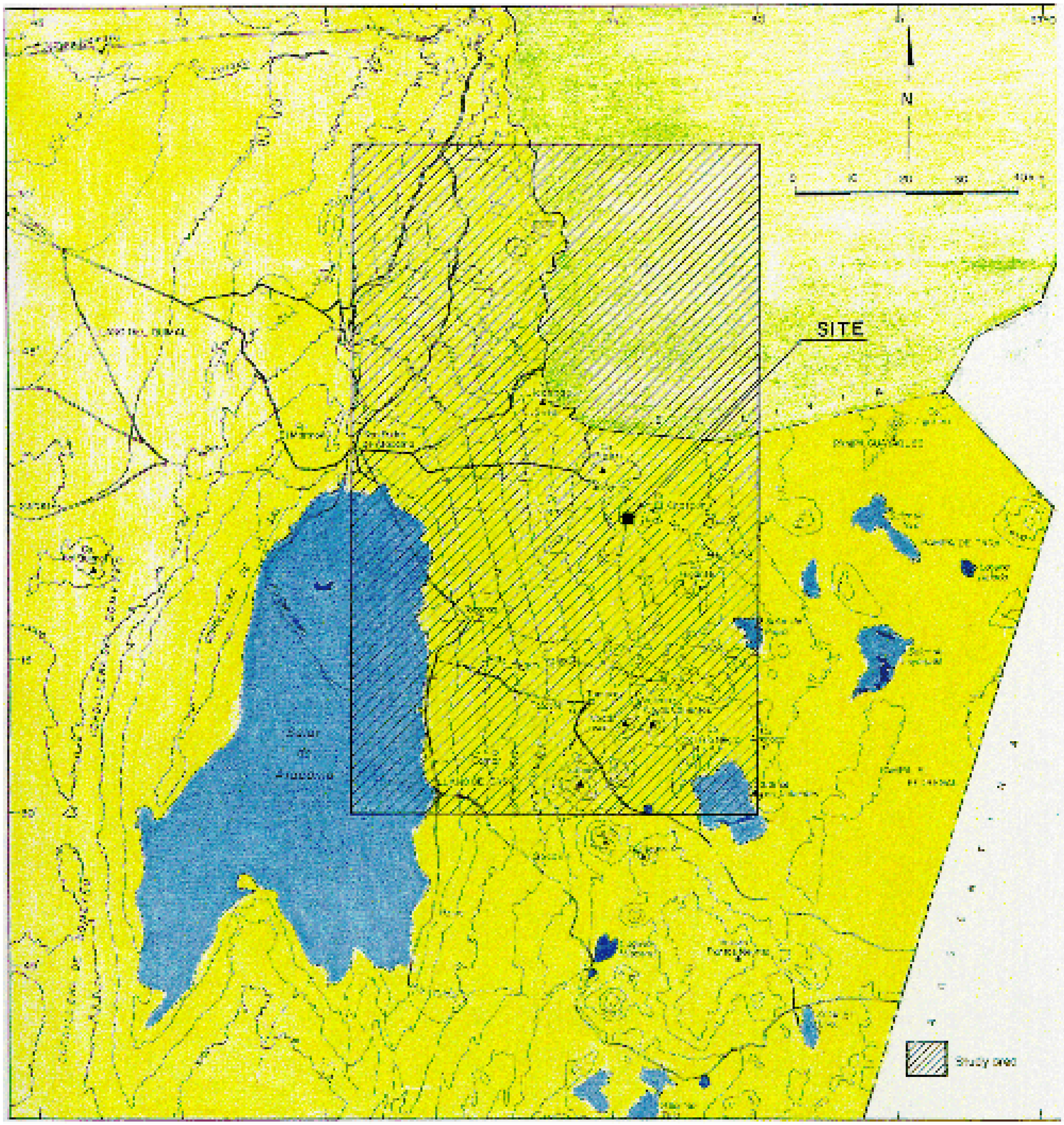

Fig. 1 - Location of map of the MMA site. Access roads, villages, and well known volcanic centers are shown. The stippled zone shows the area comprised by the simplified geologic map of Fig. 2.

pond in the lowest portion. The eastern flank of the **Altiplano** is also a gently eastward dipping slope (1-4°) mainly formed by ignimbrite sheets that abut against hills of Palaeozoic sedimentary rock from the Sub-Andean Ranges close to the Argentinian border.

Climate and Vegetation

The study area is part of the Atacama Desert, the driest desert in the world. Rainfall is controlled by elevation and there is slightly more rain at higher altitudes were the site is located. Sporadic rainstorms do occur but the time interval is long (1-5 years). Such rainstorms generate mudflows in the quebradas[1] that drain towards the Salar de Atacama from both the Cordillera de los Andes and the Cordillera de Domeyko. At a similar altitude as the site, but 150 km south rainfall records over 12 years (1970-1981; Gallinski *et al.*., 1984) give average values of rainfall of 18 mm/annum (between December-March) and estimate the rate of snowfall as 75 mm/annum mostly during winter (southern hemisphere). Meltwater from the snowfall drains chiefly as underground water.

Due to the extreme aridity of the area, vegetation is sparce. In the Cordillera de Domeyko where the climate is that of a normal desert, with low humidity and strong day-to-night temperature variations, scarce vegetation is only found following the short and sporadic summer rainfalls. In the Salar de Atacama basin shrubs and tough grass are found close to the ponds and in the moist crusts. Experimental growth of Tamarugal trees (a variety of mesquite) in the eastern margin of the salar has been carried out with some success. This basin shows an annual average temperature of 14.1°C, 54.7% of relative humidity and a high evaporation rate of 11.1 l/m_2 (Ide, 1978). In the Western Cordillera, characterized by a high marginal desert climate, below 3,000 m, the vegetation is confined to quebradas. The fresh water streams

[1] **Quebradas:** Deep, narrow, commonly dry valleys with almost vertical walls that often reveal ignimbrites in cross section. East of the Salar de Atacama basin a few of these quebradas carry fresh water streams.

found in some of these quebradas is extensively used for growing crops and fruit trees in the villages of Toconao, Cámar, Talabre, Socaire and Peine (fIG.1). Above 3,000 m snow melt and summer rainfalls support a vegetation of tough grass, shrubs, short flower-bushes and a variety of cactus which are used by pastoral communities to feed their llama and sheep flocks.

Strong winds blowing from the west, usually in the afternoon, that reach up to 120 km/h, are characteristic of this area. They produce a varnished surface of the lava blocks ("desert varnish") and raise strong sand storms and dust vortices ("dust devils") up to 100 m high, mainly in the Salar de Atacama basin.

GEOLOGICAL SETTING

The geology of the MMA site is summarized in the Calama (Marinovic and Lahsen, 1984) and Toconao (Ramírez and Gardeweg, 1982) sheets published by the Chilean Geological Survey (Servicio Nacional de Geología y Minería). A simplified map is presented in Figure 2 and a general description that emphazises the local geology follows.

The MMA site is located south of the Quaternary Purico Volcanic Complex and inmediately west of the Quaternary Chascón dome (5,703 m) and an older altered group of lavas, the C° Agua Amarga (5.058 m) (Fig.2 and 3). The limit between the Agua Amarga and Chascón hills is the Quebrada Agua Amarga (Bitter Water Creek), a stream with permanent supply of water, but which is not drinkable (Fig.4). The site is directly on the Cajón Ignimbrite, a 1.3 Ma (million years) welded ash-flow-tuff deposit related to the Purico Complex, which in its term overly an older extensive ignimbrites (Atana Ignimbrite, 4.1 Ma) erupted from a large collapse caldera (La Pacana, 60x35 km; Figs. 2 and 3).

The Cajón Ignimbrite is an extensive deposit (surface area of nearly 800 km^2) of pyroclastic volcanic rocks related to early explosive eruptions of the Purico Complex. These eruptions originated various pyroclastic flow units that spread mainly westward, following the main slope of this part of the Andes and reached 35-40 km from its vent (Fig.3). The eruption and deposition of the ignimbrites was followed by the construction of the Toco volcano (5,604 m) formed by stubby weakly dipping thick dacitic lavas. The southeastern flank of the cone is eroded, showing an altered core with the Purico sulphur mine. An 0.8-Ma-old dacitic dome was the final eruption of this complex. The normally rugged surface of the Cajón Ignimbrite has been smoothed by glacial erosion. Glacial activity in this area is evidenced by the extensive morainic deposits related to volcanic cones (Hollingworth and Guest, 1967), occurring as low as 4,200 m and dated in about 27,000 years B.P.

The site is located in the north prolongation of a mayor regional structure: the Callejón de Varela Fault or Miscanti lineament (Fig.2). This is 180-km-long N-S-trending fault recognized southward which controls the location of large Quaternary volcanoes, including the active Lascar, the location of older domes and of small lakes. This fault is apparently older than the Purico Ignimbrite ($\sim$1.3 Ma) as younger displacements have been observed.

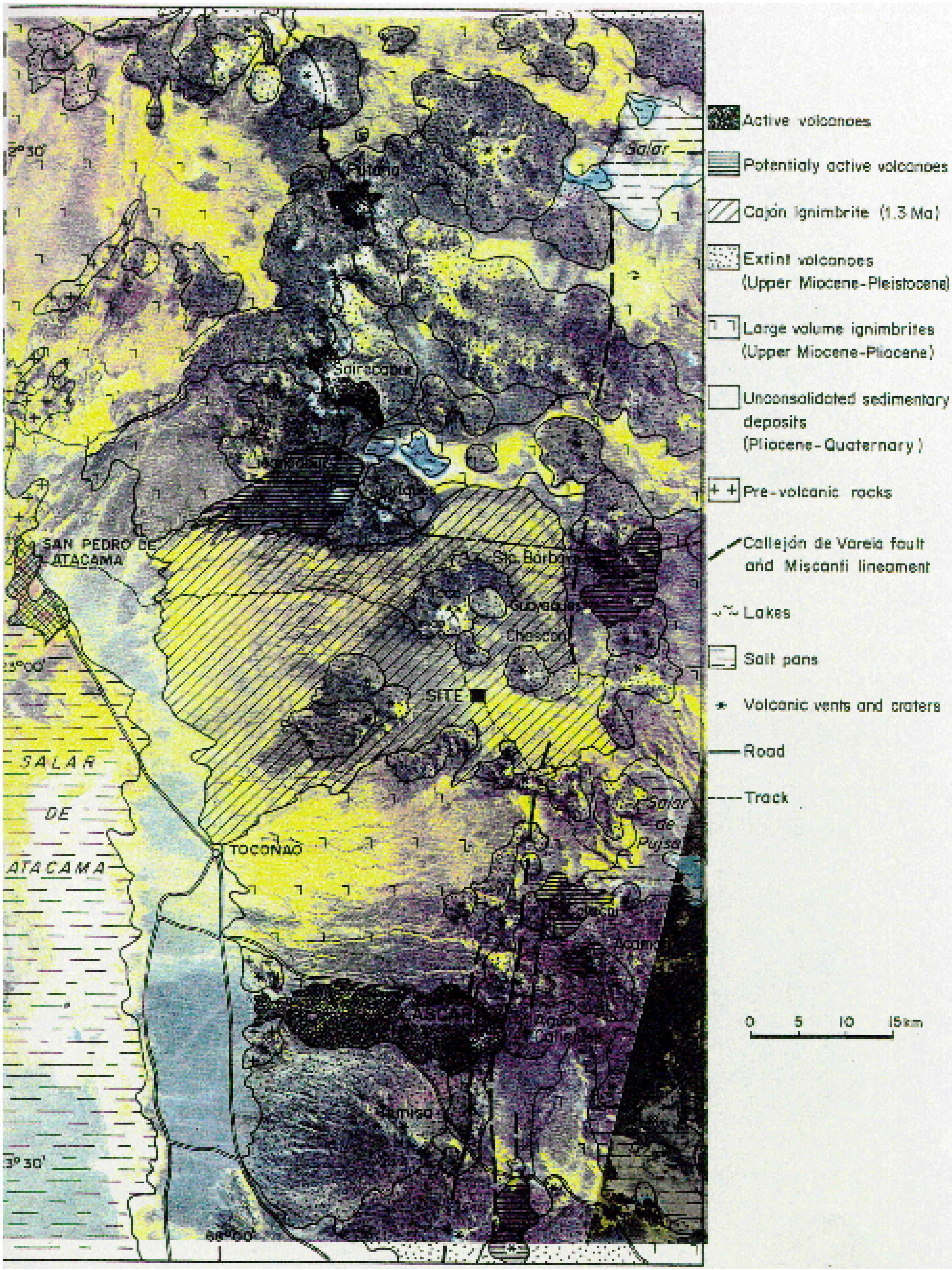

Fig 2. - Simplified geological map of the site area over a 1:500.000 scale satellite image. Based on Marinovic and Lahsen (1984) and Ramfrez and Gardeweg (1982).

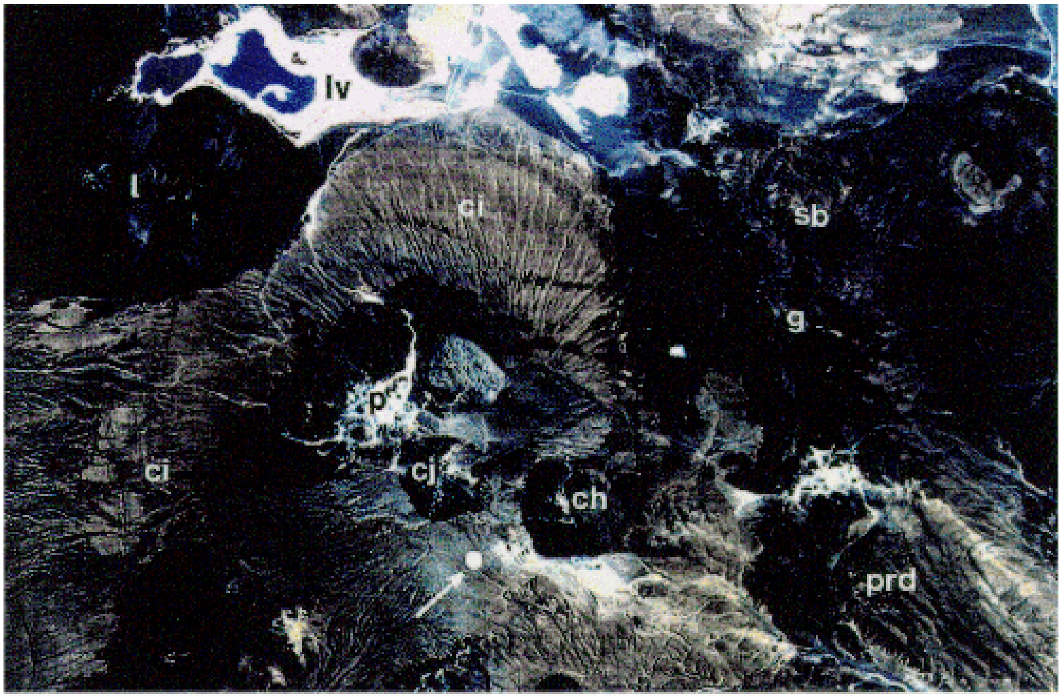

Fig. 3. - Satellite image of the MMA site (white arrow). Shown are the Chascón dome (ch), Chajnantor dome (cj) and Purico complex (p). The Cajón ignimbrite (ci) extends radially from the Purico complex and is covered by the lavas of the volcanoes Licancabur (l), Guayaques (g), and Santa Bárbara (sb). The north end of the La Pacana caldera resurgent dome (prd), source of the Atana Ignimbrite, is also observed as are the salty lakes of Laguna Verde (lv) in Bolivia.

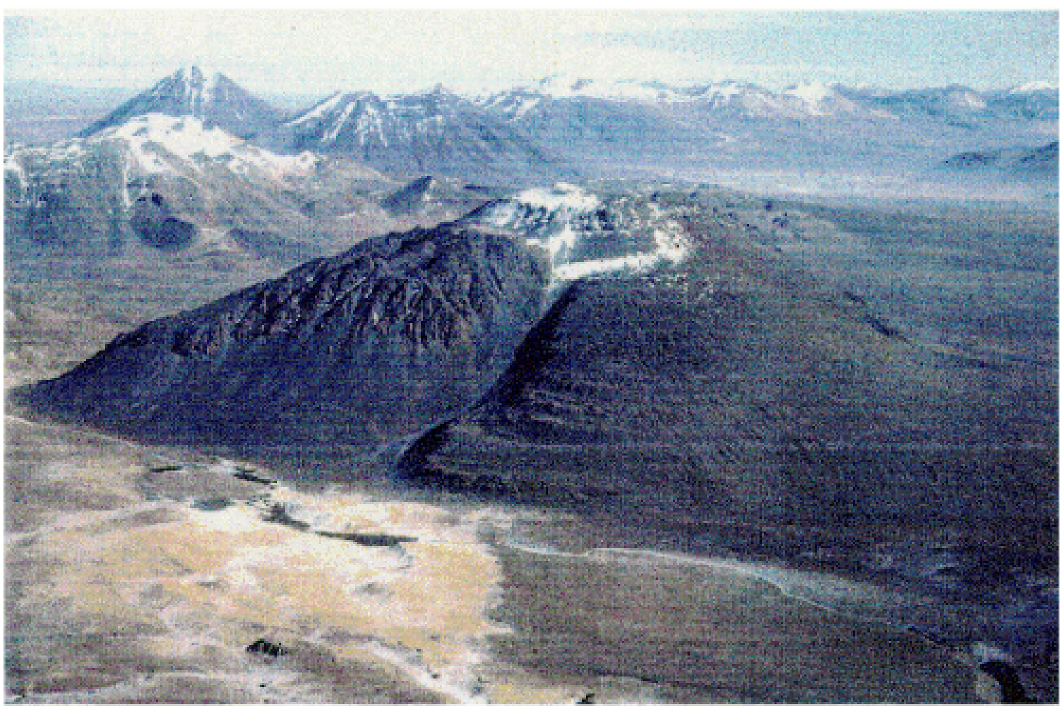
Fig. 4. - Chascón dome and the Agua Amarga creek, immediately east of the MMA site. View northward; in rear the Chajnantor dome, Juriques and Licancabur volcanoes and a NS linear group of volcanoes in the border with Bolivia.

THE CENTRAL ANDES VOLCANIC ZONE

The Central Andes, where the MMA is proposed, is the intermediate of three discrete segments with recent volcanism along the Pacific Margin of South America (northern zone: 5°N-2°S; central zone: 15-28°S; southern zone: 31-52°S).

The Central Volcanic Zone of the Andes is one of the most extensive volcanic provinces of the world. It is also a major ignimbrite province where voluminous dacitic to rhyolitic ash-flow sheets of Early Miocene (22 Ma; Lahsen, 1982) to Quaternary age related to caldera structures are extensively exposed. They are interbedded with the products of large dacite-andesite composite cones and dome complexes many of which exceed 6,000 m in height above see level (*ca.* 2,000 m above the Altiplano) and include most of the highest volcanoes of the world. These cones are formed by lava flows, some pyroclastic deposits and debris avalanche deposits. Less common are small monogenetic andesitic-basaltic to andesitic extrusions (cinder cones and lava flows) and high-SiO_2 dacitic and rhyolitic flows that commonly form flat domes ("tortas").

Close to the potential site for the MMA there are an important number of large-size volcanoes, only a few of which are active[2]. They all form part of the Quaternary volcanic arc that besides this active volcanoes include a large number of extint volcanic edifices, most of which are old and show various degrees of erosion (Fig.5). A few of these volcanoes are young or recent and potentially active.

North of San Pedro de Atacama (about 23°S) the Quaternary volcanic arc lie 320 to 360 km east of the Chile-Perú trench, between 110 to 125 km above the Benioff zone

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[2] **Active volcanoes:** a volcano is considered to be active if it has erupted in historic times. In Chile this is quite misleading as being a young country, historic records involve only the last 400-500 years. The scarcity of historic records is particularly notorious in northern Chile where the population density is minimal. In fact the reports of volcanic activity have increased in number and quality in the last decade due to a larger mining activity in the Salar de Atacama area. Therefore, in Northern Chile are also considered active volcanoes those that show permanent fumarolic activity, although not recording eruptions in historic times.

and largely defines the Chilean-Bolivian border (Fig.5). Southward, between 23-24°S, the Quaternary arc shows an eastward deflection and lie 360 to 390 km east of the Chile-Perú trench, between 120 to 140 km above the Benioff zone (Fig.5). In this area, most of the volcanoes are located east of the major regional structure Callejón de Varela fault or Miscanti Lineament (Gardeweg and Ramírez, 1984, 1987), although a few are located to the west (Fig.2). Among the latter are the Tumisa and Lejía volcanoes, while the active Lascar volcano is built directly along the fault.

The density of active volcanoes in this part of the Andes is lower than in southern Chile. It is thus that in a radious of 100 Km around the the site there are only three volcanoes currently identified as active: **Putana** (55 km NW), **Negro del Sairecabur** (37 km NW) and **Lascar** (40 Km S) (Fig.2). On the other hand, there are a number of other volcanoes with youthfull features, that show no evidences of glacial erosion (post 27,000 years) and are potentially active (Fig.2). This include **Licancabur, Santa Bárbara-Guayaques** (Fig.3), **Colachi, Acamarachi, Aguas Calientes** (Fig.6), **Chiliques, Cordón Punta Negra, Punta Negra** and **Cordón Chalviri.**

Follows a brief description of the geology of the three active volcanoes and a summary of their known eruptive activity, essential data needed for an adequate hazards assessment. In the case of Lascar the stratigraphy, nature, distribution, volume, and chemical composition of the eruptive products are well known as is the record of historic eruptions (Petit-Breuil in Gardeweg *et al.*, 1994). For Putana and Sairecabur data is scarce and preliminar (Lahsen and Marinovic, 1984; de Silva and Francis, 1991), as no detailed studies of their geology or potential hazards have been carried out.

Putana

The main edifice of **Putana** consists of an accumulation of several postglacial lava flows of mainly dacitic composition. These flows are typically short and stubby, rarely more than 3 km in length, while older lavas of the complex are longer. de Silva and Francis (1991) note that there is no evidence for significant pyroclastic eruptions during the construction of the Putana complex.

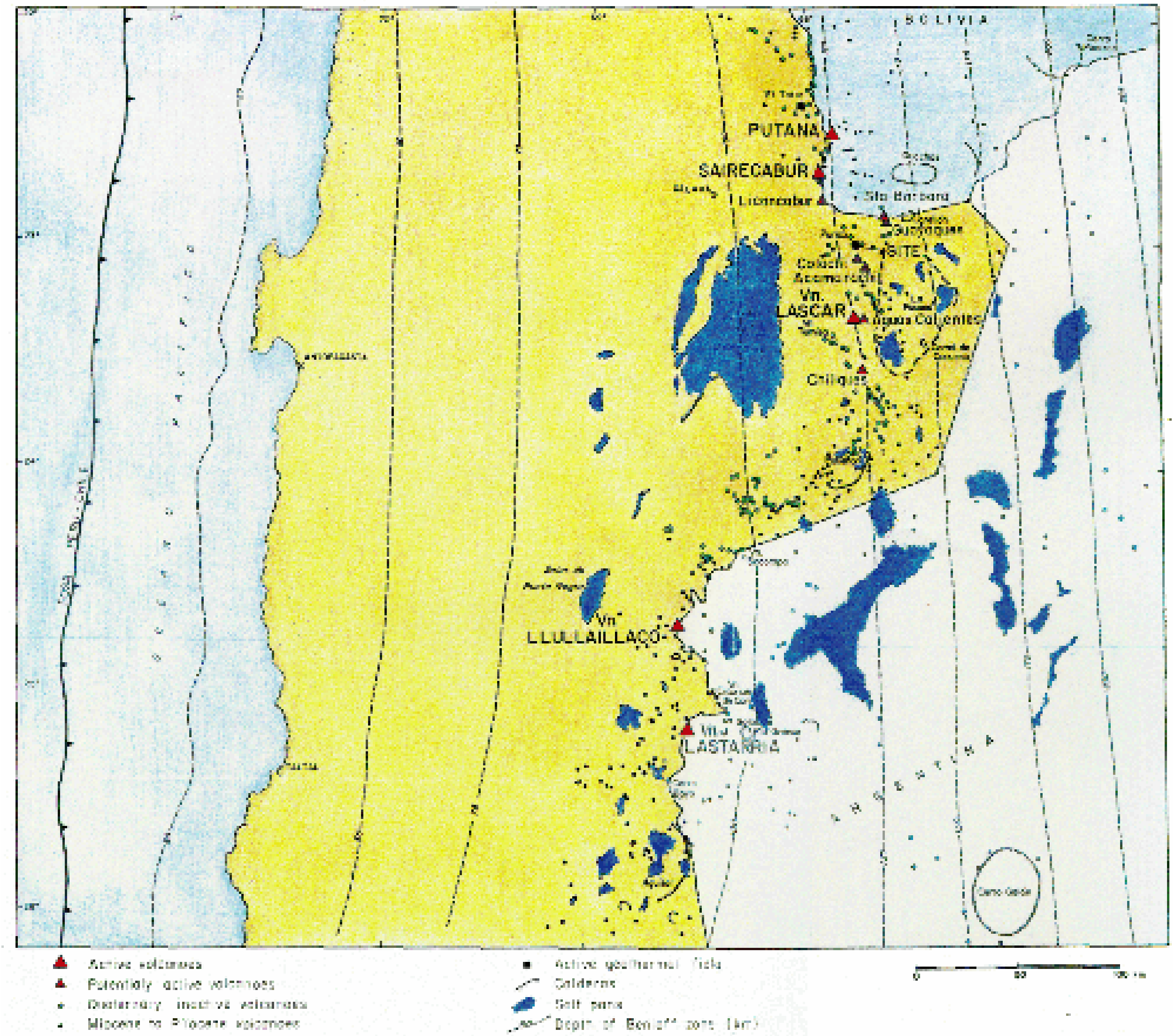


Fig 5. - Distribution of volcanic vents (active, potentially active and extint) and calderas in the study and surrounding areas. Contours to depth of the scenter of the Wadati-Benioff zone and the Peŕu-Chile trench are shown

Currently Putana is in a solfataric stage, with extensive fumarolic activity observed from the end of the 19th century that persists to the present day.

Sairecabur

Corresponds to the southernmost center of a a linear complex assemblage of volcanoes starting with Putana in the north, formed by at Least 10 distinct, potentially active postglacial centers. Sairecabur is formed by several short young lava flows capped by pristine, dark lava flows about 2.5 km long (de Silva and Francis, 1991). As in the case of Putana, there is no evidence for significant pyroclastic eruptions during the construction of the complex. The lavas are andesitic in composition (59-60 % SiO,; Marinovic and Lahsen, 1984; Harmon et *al.,* 1964).

No current activity at present day is known; appears to be dormant, although extensive earlier fumarolic activity is indicated by the presence of altered material.

Fig. 6. - Aguas Calientes and Acamarachi volcanoes, two potentially active centers. A view northward from Laguna Lejía.

Lascar

Compound composite edifice formed by two truncated cones lined EW that host in the summit 5 nested craters, the central one currently active. The edifice is formed by the superposition of pyroclastic flow deposits (up to 30 km from vent), their related tephra fall deposits, all showing an E-SE dispersion, and interbedded lava flows. The larger of the Lascar tephra fall deposits can be trace 60 km SE, and probably extends far beyond into NW Argentina. The lava flows vary in length from 17 km the oldest and lower in silica, to less than 5 km long in a midle stage and to 8 km the youngest erupted 7000-8000 years ago. The products from Lascar range from basic andesites (56-58 % SiO_2) to dacites (up to 67 % SiO_2). Lavas are mainly andesitic with a few higher in silica of dacitic composition, in typically short and stubby flows. The pyroclastic flows range from andesitic to dacitic. The most extensive deposit originated in the most explosive eruption of the geological history of Lascar, and shows the higher silica contents.

Lascar is the most active volcano of this part of the Central Andes (Fig.7). Its historic activity has been traced back to 1848 since when the evidences indicate a near continous fumarolic activity with a few more subtancial vulcanian eruptions, notably in 1933. Since 1984 Lascar entered a new period of vigorous activity characterized by strong fumarolic activity with sporadic vulcanian eruptions (1986, 1990, 1992) that culminated with a major explosive eruption in April 1993. Since 1993 the strong fumarolic activity has persisted, generating a sustained plume above the volcano and occasional minor explosions.

The largest historical eruption of Lascar took place on 19-20 April 1993 (Gardeweg and Medina, 1994). The eruption was preceded by two substantial vulcanian eruptions on 18 April 1993. From the dawn of the 19th an eruption column was mantained for nearly 36 hours between 5,000 and 25,000 m above the volcano with discrete mayor events with column collapse generating pyroclastic flows to the NW, NE and SE of the volcano extending up to 10 km (Figs. 8, 9 and 10). Tephra fall occurred over a large area of Argentina, Paraguay, Uruguay and Brasil, including Porto

Alegre, 1,800 km to the E. Due to the prevailing E-SE winds it did not affect the nearby villages of Talabre (17 km W), Toconao (35 km W-NW) nor San Pedro de Atacama (70 km NW), although the plume was observed temporary headed northward, reaching far beyond the Purico hill, passing over the MMA site.

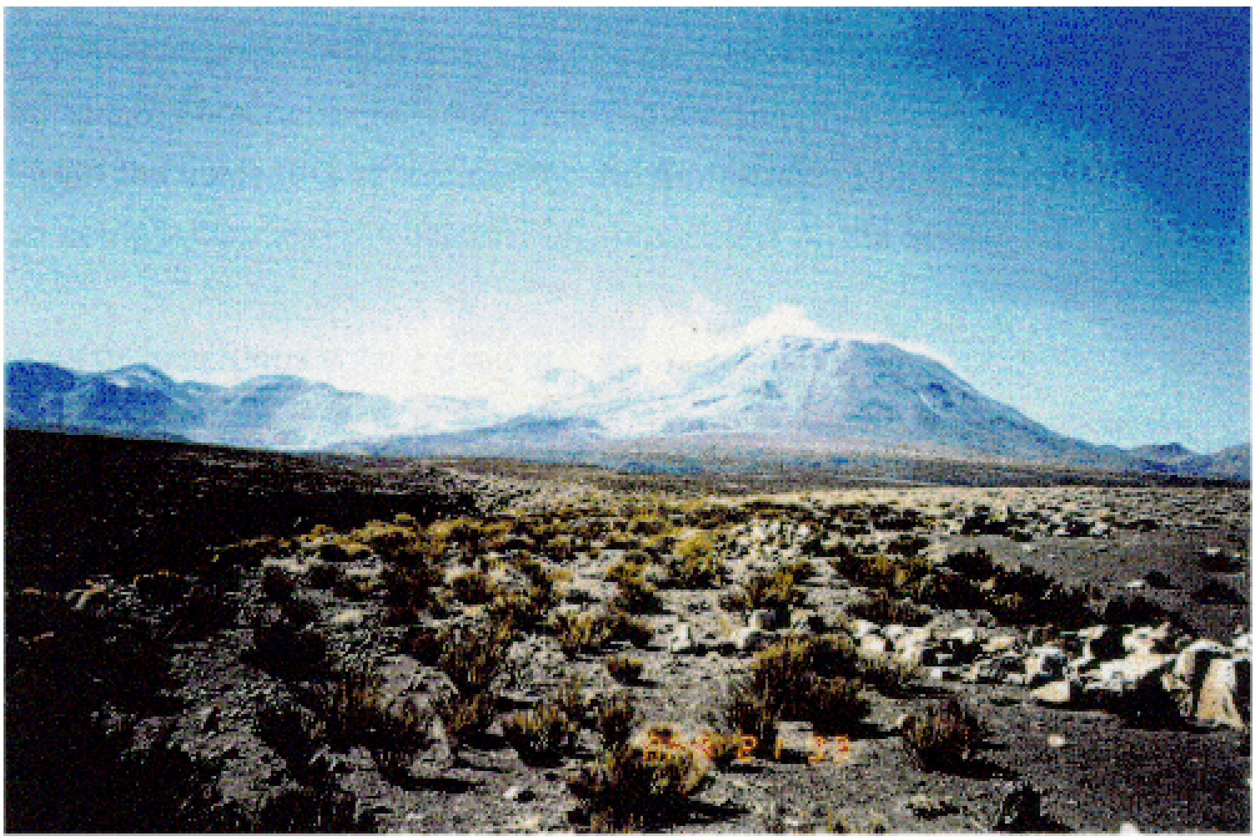


Fig. 7 - Laser volcano showing its characteristic persistent fumarolic activity. A view east from the road to Talabre. In the northwest flank, the pale material corresponds to the piroclastic-flow deposit of the 1993 eruption. Fine ash was being resuspended a few days after the eruption.

POTENTIAL VOLCANIC PROCESSES AND RELATED HAZARDS

To asses the volcanic hazard that might face the site area in the case one of these volcanoes erupt, it is necessary to know the different types of volcanic activity that might be expected. It is also required to establish how these different types of activity present a hazard over different areas.

A brief description of these hazardous events follows based on the notes of the American Geophysical Union (AGU) short course on Volcanic Hazards edited by R. Tilling in 1989 and in personal experience. Included are only those events that might be expected from the volcanoes of this part of the Andes taking under consideration their chemical composition and the climatic characteristics of the area.

Two main types of hazardous volcanic events can be recognized:
- those directly related with eruptions, which are the most relevant, like lava flows, pyroclastic flows, pyroclastic airfalls, and gas emissions
- other dangerous processes directly or indirectly related with the eruptions like volcanic landslides (debris avalanches), volcanic debris flows (lahars), earthquakes, electric storms, and acid rain.

Lava flows and domes

Lava flows and domes are generated by the efusive extrusion of molten rock (magma[3]) that pours or oozes onto the Earth's surface. The mayor hazard from lava flows is damage or total destruction by burying, crushing, or burning everything in their paths. Lava flows can also melt snow and ice that can produce floods and debris flows, reason why efusive eruptions that generate lava flows are always more

[3] **Magma:** molten rock that contains disolved gas and minerals. When magma reaches the surface it is called lava.

dangerous in winter time. For that reason, predicting the extent of lava flows and their likely paths is escential to mitigate their effects.

Predicting the final extent of a lava flow is a difficult task as its morphology (length, width, thicknes and surface features) is determined by a various facts as rate of effusion, the slope of the surface onto which it is erupted, and the viscosity and chemical composition of the lava. In general, the higher a lava's silica content, the more viscous it becomes. Low-silica basalt lava (< 52 % SiO_2) can form fast-moving (15-50 km/hr) narrow lava streams or spread out in broad sheets up to several kilometers wide. Basaltic magmas are very scarce in the Central Andes, and when present, characteristically small in volume. In contrast, higher-silica lavas (andesites and dacites; 56-70 % SiO_2) tend to be thick, move slowly, and travel short distances from a vent. Dacites and andesites are the most abundante lava-type in this part of the Andes. The flows seldom exceed a length of 15 km. Notable exceptions are observed in lavas chaneled in narrow quebradas that have reached up to 30 km in length. More silicic lavas (dacitic and rhyolitic; 65-75 % SiO_2) often form mound-shaped features called domes which are abundant in this part of the Andes but rarely exceed 5 km in diameter.

Taking in account that lava flows follow valleys and depressions, once potential or actual vents of lavas are identified, their likely path can be predicted based on the surrounding topography.

Eruption Columns and Plumes, and Pyroclastic Airfalls

Volcanic eruptions commonly eject into the atmosphere fragments of molten lava and rocks (**pyroclasts or tephra**) that fall back onto the Earth's surface. An explosive eruption can blast this fragments into the air with tremendous force. The largest fragments (**blocks and bombs**) fall back to the ground near the vent, usually within 5 km (ballistic projectiles). The smaller rock fragments (**lapilli and ash**) continue rising into the air, forming a huge, bilowing **eruption column** (Fig.8).

Fig. 8. - The 25 km-high eruptive column of the April 1993 eruption of Lascar volcano. The denser basal portion of the column can be observed collapsing to form pyroclasytic flows.

Eruption columns can be enormous in size and grow rapidly, reaching more than 20 km above a volcano in less than 30 minutes (Fig.8). They consist of a lower gas-thrust region and an upper convective region. A column will continue to rise convectively until its density is equal to that of the surrounding atmosphere. When reaching the tropopause it will then expand laterally but will also continue upward due to its momentum to form a broad umbrella cloud (Fig.9). Once in the air, the ash and gases of the eruption column are dispersed by the prevailing winds to form an eruption cloud or plume. The strength and direction of the wind, along with the height of the column, exert the principal controls on the transport and final deposition (fallout) of the tephra.

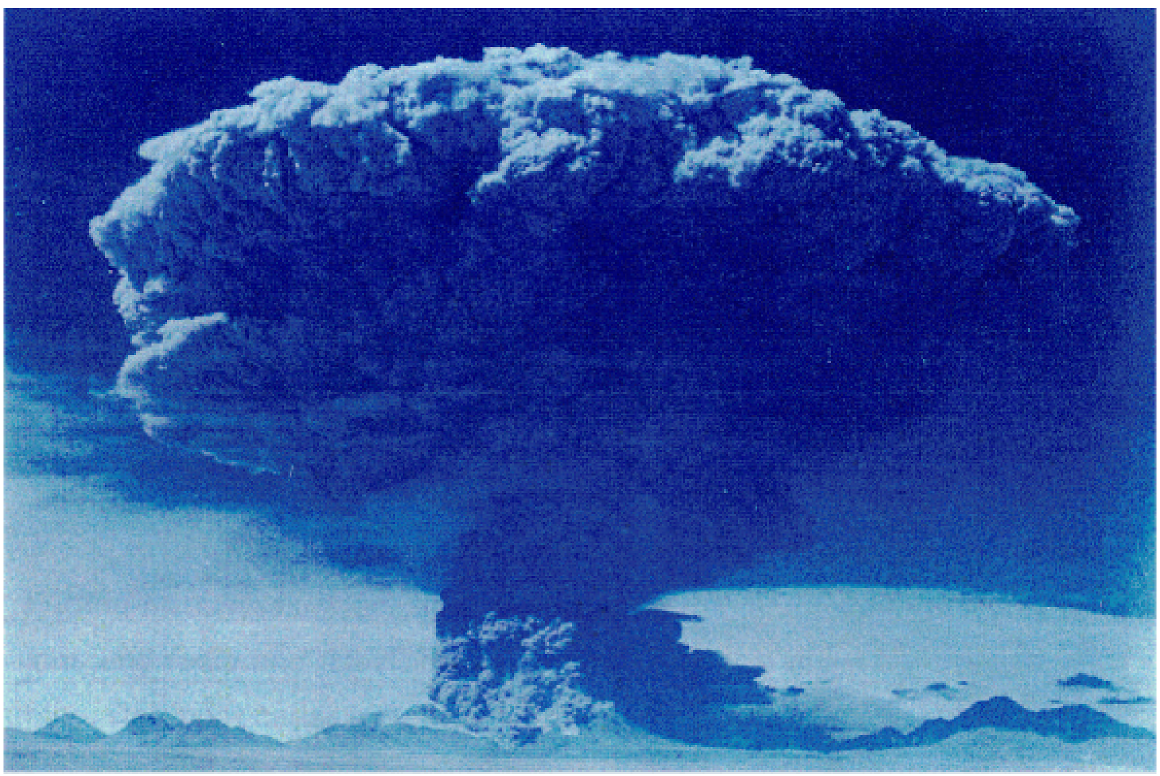


Fig. 9. - The same eruptive column as in Fig. 8, a few minutes later. Picture of the approximately 30 km wide umbrella developed when the the column reached the tropopause and expand laterally. Observers reported lightening under the umbrella. Pyroclastic flows can be seen advancing on the N and NW flanks of the volcano and covering the whole summit area.

Tephra fall poses the widest-ranging direct hazard from volcanic eruptions. Vast areas (10.000-100.000 km^2) have been covered by more than 10 cm of tephra during some large eruptions while fine ash can be carried over areas of continental size. Recent examples in Chile are the eruptions of Lascar (April 19-20, 1993) and Hudson volcanoes (August 8-15, 1991), where ashfall was reported over the Atlantic coast (in Puerto Alegre, Brasil, 1800 km from Lascar and in Las Malvinas islands, 1700 km from Hudson). Tephra typically becomes finer-grained and formes finer deposits as distance from the vent increases.

Tephra fall and ballistic projectiles endanger life and property by:

1) the force of impact of falling fragments
2) burial
3) producing a suspension of fine-grained particles in the air
4) carrying noxious gases, acids, salts, and, close to the vent, heat.

The hazard from **impact of large fragments** is greatest close to the vent and decreases with increasin distance. People and property can survive falls of small bombs with minimal shelter, however, falls of larger bombs can be devastating even in substantial shelters. **Burial by tephra** can collapse roofs of buildings, break power and communication lines, and damage or kill vegetation. The **suspension of fine-grained particles in air** affects visibility and health (especially for people with respiratry problems), and can damage unprotected machinery (especially internal-combustion engines). Air and road traffic are especially vulnerable. Fine ash can also cause short circuits in electric-transmission facilities, and affect communications by damage to telephone lines and radio and television transmitters, and by electrical disturbances due to lightning. Darkness cause by tephra falls during daylight hours can persist from a few hours to several days, and compound other problems. The resuspension of fine-grained tephra by wind, especially in dry climates, can prolong these problems.

Tephra falls can also cause fires, both by lightning generated in eruption clouds and by hot fragments. Fragments large enough to retain sufficient heat to tart fires typically fall within a few kilometers of vent.

Some of the hazardous effects of tephra falls can be mitigated with proper planning and preparation, in contrast to the hazards posed by other volcanic events. Some of this include designing roof orientation and pitch to discourage thick buildups of fallen ash, strengthening roofs and walls to withstand loading and projectile impacts and designing filters for machinery.

Pyroclastic Flows

Pyroclastic flows are masses of hot (300-800°C), dry, pyroclastic debris and gases that move rapidly along the ground surface at velocities ranging from 10 to several hundred meters per second. A flow is composed typically of two parts: (1) a ground-hugging, dense basal flow that is the pyroclastic flow proper, and (2) a preceeding or overriding turbulent ash-cloud surge of ash elutriated from the flow that can also originate convective clouds of ash and tephra-fall deposits (Fig. 10).

Fig. 10. - A pyroclastic flow during the April 1993 eruption of Lascar volcano showing the typical ground-hugging, dense basal flow, an overriding turbulent ash-cloud of ash elutriated from the flow and a preceding ash-surge formed ahead of the flow that affected areas well beyond the limits of the pyroclastic flow.

This high-speed hot avalanches form in several ways, beeing two of them the most common:

1) during explosive eruptions due to the gravitational collapse of the lower, dense part of high vertical eruption columns (Figs. 6 and 8)

2) break apart and collapse of the steep edge of a dome or thick lava flow, collapse that can be driven simply by gravity or by the explosive disruption of the dome or lava.

Pyroclastic flows are common at many andesitic and dacitic composite volcanoes and at silicic calderas, which are the predomnant volcanic edifices in the Central Andes. These deposits vary widely in composition, temperature, volume, and eruption rate, which is reflected in their great range in extent. Flows composed mostly of dense to slightly vesicular lithic fragments are of lower volume, less mobile, typically restricted to within a few tens of kilometers of vents and, controlled by topography so they tend to follow valleys. In contrast, large pumiceous flows composed mostly of ash can extend up to 200 km from vents and cover thousands to of tens of thousands of square kilometers.

Closely related to the pyroclastic flows are the **pyroclastic surges**, turbulent, low-particle-concentration, gas-solid dispersions that flow above the ground surface at high velocities. The most common are hot pyroclasstic surge which are generated by the same processes that form pyroclastic flows. They may be formed ahead of a pyroclastic flow, by colapse of an eruption column that may or may not also be spawning pyroclastic flows, or by the overriding ash cloud that is formed by a pyroclastic flow (Fig.10). In comparison with pyroclastic flows that can be topographycally controlled, surges are much more mobile and may affect areas well beyond the limits of the pyroclastic flow. Therefore, whereas pyroclastic flows are likely to be restricted to valley floors, accompanying pyroclastic surges could affect areas high on valley walls and even in adjacent valleys.

Owing to their mass, high temperature, high velocity, and potentially great mobility, pyroclastic flows and surges pose grave hazards from asphyxiation, burial, incineration and impact. They are very effective in melting large volumes of snow and form lahars and floods that can extend far beyond the limits of a flow. Owing to their high velocities and great mobility, escape is impossible once pyroclastic currents are generated. Preventing human settlements or evacuation prior to eruptions from areas likely to be affected by pyroclastic flows and/or surges is the only effective method of mitigation.

Volcanic Gases

Magma contains dissolved gases that are released to the atmosphere both during eruptions and while magma lies close to the surface (fumarolic activity[4]). The volume and concentration of a volcanic gas is directly related to the composition of magmas and the size of an eruption, although the relative proportions are highly variable even within a single eruption. By far the most abundant volcanic gas is water vapor (90%); other important gases, in decreasing abundance include carbon dioxide, carbon monoxide, sulfur oxides, hydrogen sulfide, chlorine, and fluorine. These gases are transported away from vents as acid aerosols, as compounds adsorbed on tephra, and as microscopic salt particles.

Sulfur dioxide gas can react with water droplets in the in the atmosphere downwind and fall as acid rain, causing corrosion and damaging fabrics and metals, and adversely affecting vegetation. Carbon dioxide is heavier than air and tends to collect in depressions, where on occasion it can accumulate in lethal concentrations and cause people and animals to suffocate. Sometimes, toxic concentrations of fluorine are adsorbed onto ash and ingested by livestock or leached into fresh water supplies.

The effects of a volcanic gas are directly related to its concentration, which generally decreases downwind from its source vent as the gas becomes diluted by air. Harmull efects are usually restricted to within 10 km of vents. However, explosive large-

[4] **Fumarolic activity:** volcanic gas emissions, including water vapor, vent to the surface through cracks in the ground in a volcano that is not erupting.

volume eruptions inject sulfur dioxide gas into the stratosphere, where it combines with water to form an aerosol of sulfuric acid. By reflecting solar radiation, the sulfur aerosols can lower Earth's average surface temperature by a few degrees.

Volcanic Landslides

Volcanoes are susceptible to structural collapse and the formation of various types of landslides (rapid downslope movement of rock, snow, and ice) owing to steep slopes, faults, weak materials (layers of weak, fragmented volcanic rocks that tower above the surrounding terrane), internal deformation caused by intrusions, and other factors. Sudden failures such as rockfalls, rockslides, and debris avalanches constitute a great hazard because they can be triggered suddenly and move very rapidly. Gradual collapse of large sectors of volcanoes is a less catastrophic process, but also has associated hazards.

Among the volcanic landslides, **debris avalanches deposits** are the most commonly recorded in the Central Andes. In the world, debris falls, slides and avalanches on volcanoes range from relatively small events to some of the most voluminous mass movements of Quaternary age. Intrusions, hydrothermal alteration, erosion, and other processes aid in the progressive weakening of a volcanic edifice by developing shear surfaces that can act as bounding surfaces for detachments. Eventhough this progressive weakening can lead to failure, more likely a failure will be triggered by a volcanic eruption (explosion) or an earthquake.

Known debris avalanches extend up to 85 km from their sources and cover tens to more than 1000 km^2. Their momentum allows them to run up slopes and to cross divides up to several hundred meters high. Debris avalanches bury and destroy everything in their paths. They occur predominantly in composite volcanoes of dacitic and andesitic composition. The generation of debris avalanches is an essential part of the history of many volcanic edifices in the Central Andes. Outstanding are the large-volume debris avalanche deposits of the Socompa (Ramírez, 1988) and Llullaillaco (Francis and Wells, 1988; Gardeweg *et al.*, 1993) volcanoes.

Volcanic Earthquakes

Most volcanic eruptions are preceeded by local seismic activity of varios magnitude and intensity, which may continue during and after the eruption.

Earthquakes in volcanic areas can be generated by:
1) the movement of magma and crack formation
2) volcanic explosions
3) large-scale mass movements
4) tectonic forces

Earthquakes of the first two categories are directly related to volcanic activity and are typically shallow, of small to moderate magnitude and seldom cause damage far from the source volcano. Shocks generated by large mass movements (Eg. structural collapse) or tectonic forces are much stronger than those directly related to eruptions.

The damaging effects of volcanic earthquakes are typically restricted to proximal areas, and are the result of ground shaking, and perhaps ground breakage. Earthquakes can also trigger mass movements that can lead to other hazardous events as debris avalanches.

Acid Rain

Acid rain can fall from eruption columns and volcanic plumes when:
1) the water vapor emitted by the volcano condenses forming water droplets that react with acid components like H_2S or HCl and fall as chowers
2) normal rain fall through the column or plume generating a similar reaction

Acid rain is highly corrosive and affect mainly vegetation and metals (roofs, machinery, etc.). They alter dramaticaly surface waters and the composition of soils.

Electric Storms

Electric storms that include spectacular lightening commonly form under the umbrella of eruptive columns. Electric charge formes because of the collision of the volcanic particles violently ejected. Electric storms may interfere with radio, telephone and TV transmissions, and can also set up fires.

ASSESSMENT OF VOLCANIC HAZARDS AT THE MMA SITE FROM FUTURE ACTIVITY OF THE ACTIVE VOLCANOES EAST OF SAN PEDRO DE ATACAMA

Hazard assessments are usually premised on the assumption that the same general areas on a volcano are likely to be affected by future eruptive events of the same kinds, at about the same average frequency as in the past (Tilling, 1989). However, volcanoes not always follow past behaviour, thus even the best hazard assessment is not perfect.

For the MAA site I will discuss the probability of this given area being affected by the potentially destructive volcanic processes or products described above, in case one of the three nearby active volcanoes erupt (Lascar, Putana or Sairecabur). Predicting if they might erupt or when can not be achieved with our present knowledge of these volcanoes, specially Putana and Sairecabur, however, some considerations will be made based on general assunptions. In the case of Lascar the recent geological and volcanic hazards studies carried out by the Chilean Geological Survey (Gardeweg *et al.*, 1994) enables a better aproximation to a long-term forecast, but the lack of proper monitoring does not allow short-term forecasts. To date, Lascar is only monitored visually from Talabre, where the school teacher fills up a chart with his daily observations. Even this rudimentary monitoring is often interrupted when the school teacher is out of town.

For assessing the volcanic hazards pose to the MMA site its distantce to the active volcanoes is highly relevant:

- **Putana:**	55 km NW
- **Negro del Sairecabur:**	37 km NW
- **Lascar:**	40 Km S

Also relevant is the volcanic style and chemical composition of its products, both of which were described above.

Future eruption of lava flows and domes

The distance of the site to the three active volcanoes, the length of the flows (<30 km), and the rough topography of the foothills surrounding the volcanic edifices indicates that in case any of them erupts lava flows or domes, they would be chaneled by the local quebradas, far from the MMA site. In consequence, the site is not under the hazard of lava flows, not even in the case that one of the nearby potentially active volcanoes erupt (Licancabur, Guayaques, Santa Bárbara). However, as most eruptions of lava flows and domes are accompanied by explosive active with the violent emmission of tephra easily windblown, lava and dome eruptions would colaterally pose the site to the hazard of tephra fall (see below).

Future eruption of pyroclastic flows

As with the lava flows, the distance of the site to the three active volcanoes, the known length of the flows related to andesitic and dacitic stratovolcanoes in this part of the Andes (<30 km), and their tendency to follow valleys suggest that in case any of the nearby active volcanoes erupts lava flows or domes, they would not affect the MMA site. However, as pyroclastic flows include an overriding turbulent ash-cloud commonly windblown (Fig.10), consequently they can affect the site by tephra fall (see below).

Future explosive eruptions and pyroclastic airfalls

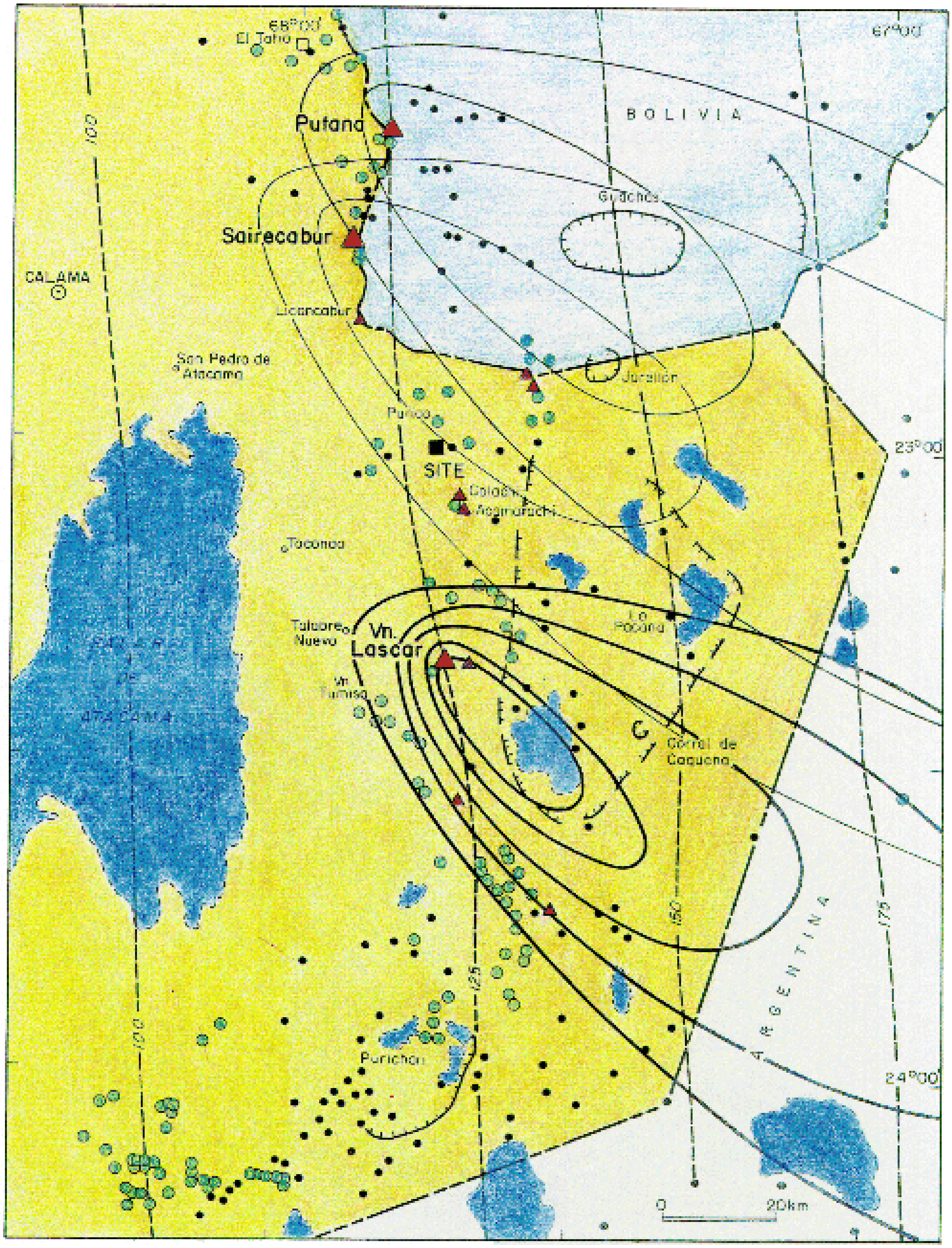
As previously described, pyroclastic airfall material or tephra includes the large fragments (blocks and bombs) that fall back to the ground near the vent and, the smaller rock fragments (lapilli and ash) that continue rising into the air to form an eruption column, and are dispersed by the prevailing winds as a plume. Considering that the ballistic projectiles usually fall within 5 km of the vent, the MMA site is not under their hazard. As for the hazard posed by the fine-grain tephra is has to be assessed considering its strong dependance of the prevailing winds. General observations and more detailed studies carried in Lascar (Gardeweg *et al.*, 1994) and of varios eruptions along Chile indicate that tephra is predominantly (95%) dispersed eastward or slightly southeast. When changes to this tendency have been observed during historic eruptions, it has been for short periods and typically has involved smaller volumes of tephra fall. Recent examples are the erupption of Lonquimay (1989-1990) and Hudson (1991) volcanoes in southern Chile. In Lonquimay, during the 13 months that the eruption lasted, in about 5 oportunities ash fell westward for a few hours, at more that 100 km from the vent (Moreno and Gardeweg, 1989). In the Hudson eruption, during the first event that lasted two days, the plume extended northward and tephra fell as far as 250 km from the vent (Naranjo *et al.*, 1993). Close to the MMA site the only volcano that has erupted historically is Lascar. According to the Historic Eruptive Chronology (Petit-Breuihl in Gardeweg *et al.*, 1994), in only one eruption in 1967, ash fell west of the volcano during the nights of three days, in the old village of Talabre (Figs. 1 and 2). A thin layer of fine ash ("dust") covered the town every night, and S and SE during the following day (Gardeweg *et al.*, 1990). There are no historic reports of ash-fall in Toconao nor in San Pedro de Atacama, the largest and better documented village of the area. During the 1993 eruption no ashfall was reported in the villages west or northwest of the volcano, but photographic records and field observations show that eventhough the plume and ashfall dispersion was predominantly E-SE, in some moments is was dispersed northward, clearly over the MMA site (Fig.11).

Tephra fall is the most serious volcanic hazard pose to the MMA site, specially for the damage that fine ash can cause to unprotected machinery (especially internal-combustion engines), the short circuits in electric-transmission facilities, and its negative effects to communications by damaging telephone lines and radio and television transmitters.

Figure 12 ilustrates the preferencial dispersion tendency of tephra fall material in case one of the three nearby active volcanoes erupts explosively. For Lascar, the curves

correspond to isoplets that show the worst scenario for future tephra fall (from Gardeweg et *al*., 1994). For Putana and Sairecabur I reproduced the dispersion historically observed in Lascar, which is similar to the tendency shown by all the volcanoes in Chile. It is clear that explosive eruptions of Putana or Sairecabur pose serious hazard of tephra fall to the MMA site as in case that the potentially active volcanoes Licancabur, Acamarachi or Colcachi erupt (Fig. 12). However, the chances that any of this volcanoes erupt on a near future is low, based on their lack of eruptions in historic times and the assumption that a volcano is likely to erupt at about the same frequency as in the past. For Lascar the scenario is quite different. Beeing a strongly active volcano, the chances it will erupt in a near future (years) are high. On the other hand, the possibilities that large volumes of tephra fall from Lascar affects the MMA site are low, as shown by the isoplet curves in Fig.1 1. As temporary changes of wind direction can always be expected, and the plume shiftes northward as in 1993 (Fig. 11) it is possible that the site is affected by fine ash-fall in a future explosive eruption of Lascar.

Fig. 11 - A distinctive episode during the explosive eruption of April 1993 of Lascar. The plume is dispersed northward and passes over the MMM site (s). Picture by E. Medina from the Cordillera de la Sal, west of San Pedro de Atacama.



68°00
El Tatio
67°00
BOLIVIA
Putana
Sairecabur
CALAMA
Licancabur
San Pedro de Atacama
Jarellon
Purico
SITE
Colachi
Acamarachi
Toconao
23°00
La Pacana
Talabre Nuevo
Vn. Lascar
Vn. Tumisa
Corral de Coquena
100
125
150
175
ARGENTINA
Purichari
24°00
0
20km

Other hazards related to future eruptions

Considering the distance of the active volcanoes, volcanic landslides, lahars and volcanic electric storms do not pose hazards to the MMA site. Hazards from volcanic gases and acid rain are closely related to the dipersion of plumes and are usually restricted to within 10 km of vents so the chances they affect the site are low. Volcanic erthquakes pose little or no hazard to the MMA site due to its'dinstance from the active volcanoes. On the other hand, the intensity of volcanic earthquakes would be negligible in comparison with the tectonic earthquakes that also affect the area.

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