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Assessment of volcanic hazards in the area of Arequipa City, based on the eruptive history of the Misti Volcano, Southern Peru

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with 13 figures

Summary. About 700,000 people live at risk in Arequipa city whose center lies 17 km from the vent of the active Misti stratovolcano (Central Andean Volcanic Zone). Misti has been built on a volcanoclastic bedrock and ignimbrites of late Pliocene age, overlain by a series of lava flows and ignimbrites of Quaternary age. Misti encompasses two edifices: a 'modern' stratocone, to the E and SE, has been built up side by side with, and has overlapped in part on 'old' stratovolcano which is built of a series of lava flows of middle to late Pleistocene age, overlain by debris-avalanche deposits to the SW and S. These deposits, burying a piedmont in excess of 50 km^2 in area, record the destabilization of the stratovolcano some time before late Pleistocene. The ca. 30 km^3 and 5,825 m high 'modern' stratocone consists of stubby lava flows and pyroclastic debris piling up to 2 km in thickness. On top of the cone-shaped summit, the historical crater, 500 m across and 200 m deep including an andesitic plug, nests in another crater 900 m wide. Both vents are located within a summit explosive caldera 1.5 km across.

Based on fieldwork and interpretation of air-photos and one SPOT satellite image, seven groups of deposits record the late Pleistocene eruptive history, as follows: (1) lava flows, block-lava flows, and buried domes of the lower stratocone are overlain by a composite pyroclastic sequence interbedded in block-lava flows, which have built up the cone-shaped summit above 4,000 m; (2) thick deposits of breccias attributed to dome collapse and overlain by lithic-rich pyroclastic-flow deposits; (3) pyroclastic flows and nonwelded ignimbrites may bear witness to eruptions that formed the summit caldera around 47,000 yr B.P.; (4) scoria-flow deposits, pumice-rich pyroclastic-flow and fall deposits with interbedded deposits of glacial source can be placed within the last glacial period; (5) pumice- or ash-flow and tephra-fall deposits, rhyolitic in compositon, may reflect an explosive episode which led to the formation of, or enlarged the summit caldera around 34,000 yr B.P.; (6) thick block-and-ash and lithic-rich pyroclastic-flow deposits, including a few interbedded Plinian pumice-fall layers, record repeated dome growth and destruction towards the end of the last glaciation; (7) a pile of pumice lapilli and ashfall deposits, with interbedded pyroclastic-surge deposits, indicates that Misti has erupted explosively at least 8 times over the past ca. 14,000 years. Finally, several valley-confined pumice-flow deposits with a Plinian tephra-fall deposit were radiocarbon dated at 200 BC–200 AD. Historical data and at least one ashfall layer refer to some volcanic activity at A.D. 1440–1480, 1677, 1784 and 1787, while fumarolic activity persists at the crater plug.

Stratigraphy and sedimentology point to alternating, Plinian and ignimbrite-forming eruptions, and dome growth for at least the past 50,000 years. Thus, the most severe volcanic hazards for the 700,000 people of Arequipa are as follows: (1) low subplinian columns (4 to 9 km) may cause ashfall in the city; for higher Plinian columns (9 to 20 km), the thickness of the relevant layer could amount to 50 cm in the city; (2) block-and-ash-pyroclastic flows are expected towards the S, SW, and SE and might hit the NE suburbs of Arequipa and Chiguata town; more mobile pumice-, or scoria-rich pyroclastic flows might reach the city center; (3) lahars are to be expected in the upper suburbs, particularly during the rain and snow season (December to March); (4) flank failures can occur especially along the steep-sided W and S flanks of the volcano; the city might be reached even by low-energy debris avalanches.

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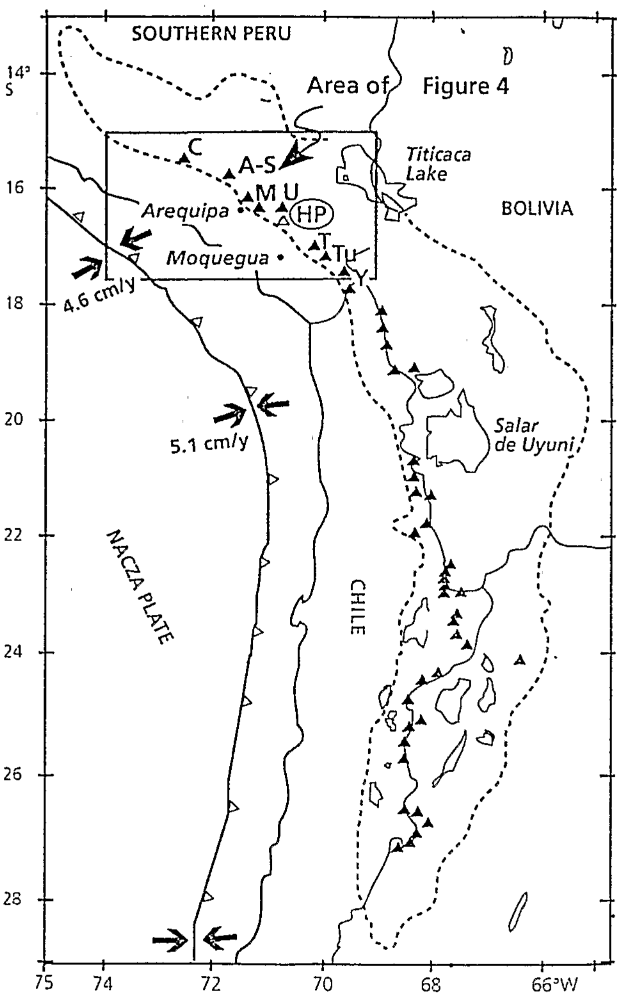
1 *Introduction*

Misti is one of the seven active volcanoes that form the northern volcanic range of the Central Andean Volcanic Zone in Southern Peru (Figs. 1 and 2). The volcanic range parallels the faulted NW-SE-trending boundary of the Western Cordillera, which consists of extensive plateaus of ignimbrites and lava flows of late Miocene to early Quaternary age, and of stratovolcanoes, calderas and lava domes of Pleistocne to Holocene age (DE SILVA & FRANCIS 1991, THOURET et al. 1995, 1996).

In the Arequipa area, Misti is the youngest edifice of a cluster of Quaternary stratovolcanoes which includes the dissected Chachani-La Orqueta lava domes to the W and the extinct Pichu Pichu complex to the E (THOURET et al. 1996; Fig. 3). It is located



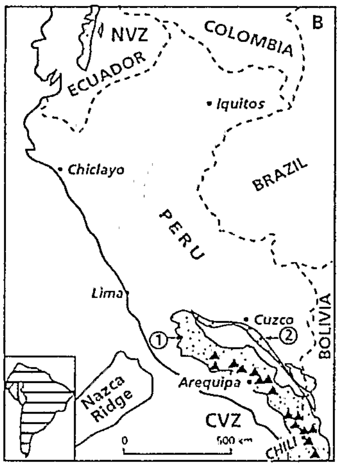


FIG.1 . The Central Andean Volcanic Zone showing the location of the present-day volcanic front (defined by the volcanoes) and its relation to the Peru-Chile trench (after De Silva and Francis, 1991).
Subduction vectors and rates taken from This Dynamic Planet World Map (Simkin et al., 1994).

Inset : Areas of Magmatic activity of late Pliocene and Quaternary age
1. Calc-alkaline rocks (black triangles = active or recent volcanoes)
2. Shoshonitic rocks (after Sébrier and Soler, 1991)

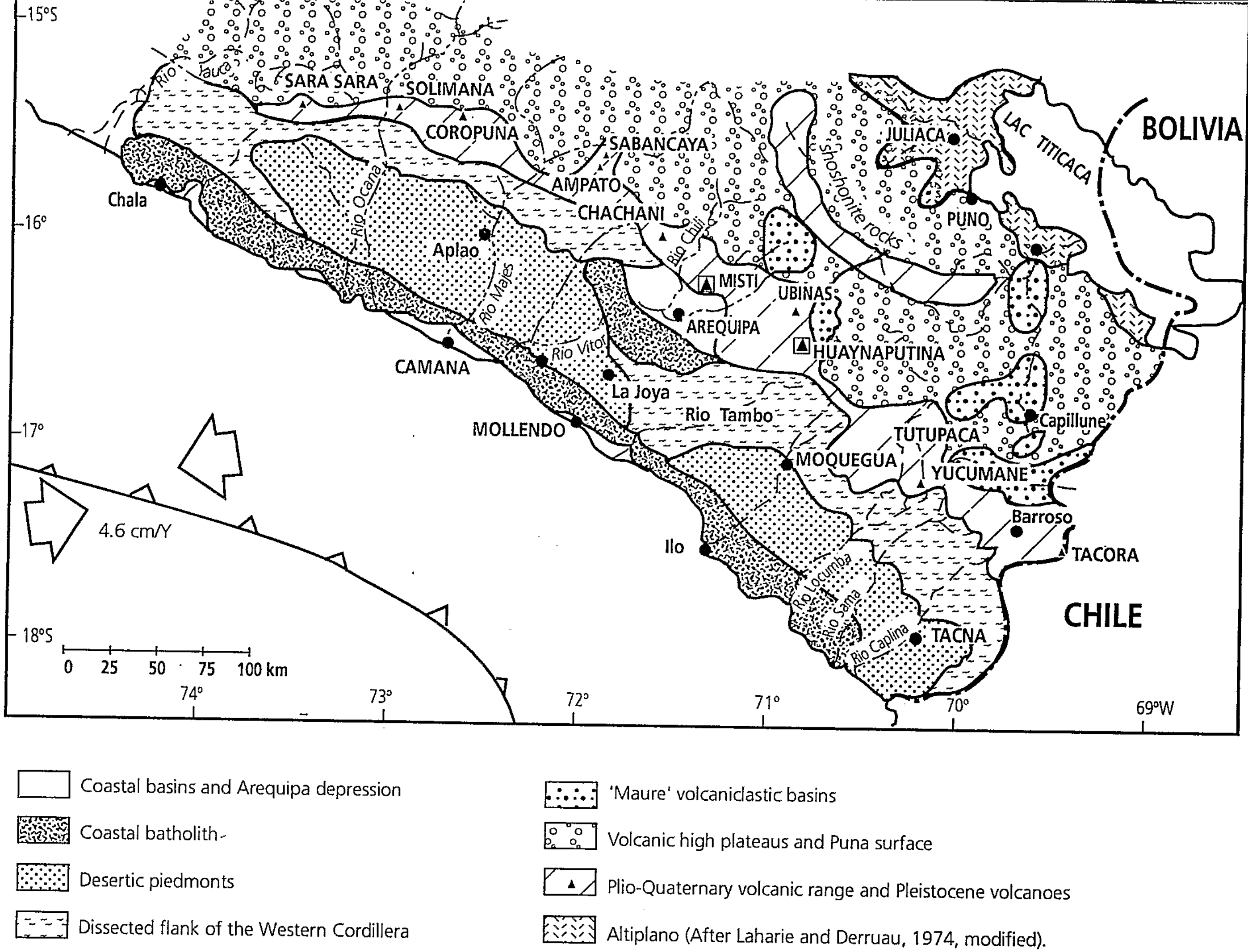


Fig. 2. Geological and geomorphological setting of the present volcanic range in Southern Peru (after LAHARIE & DERRUAU 1974, modified).

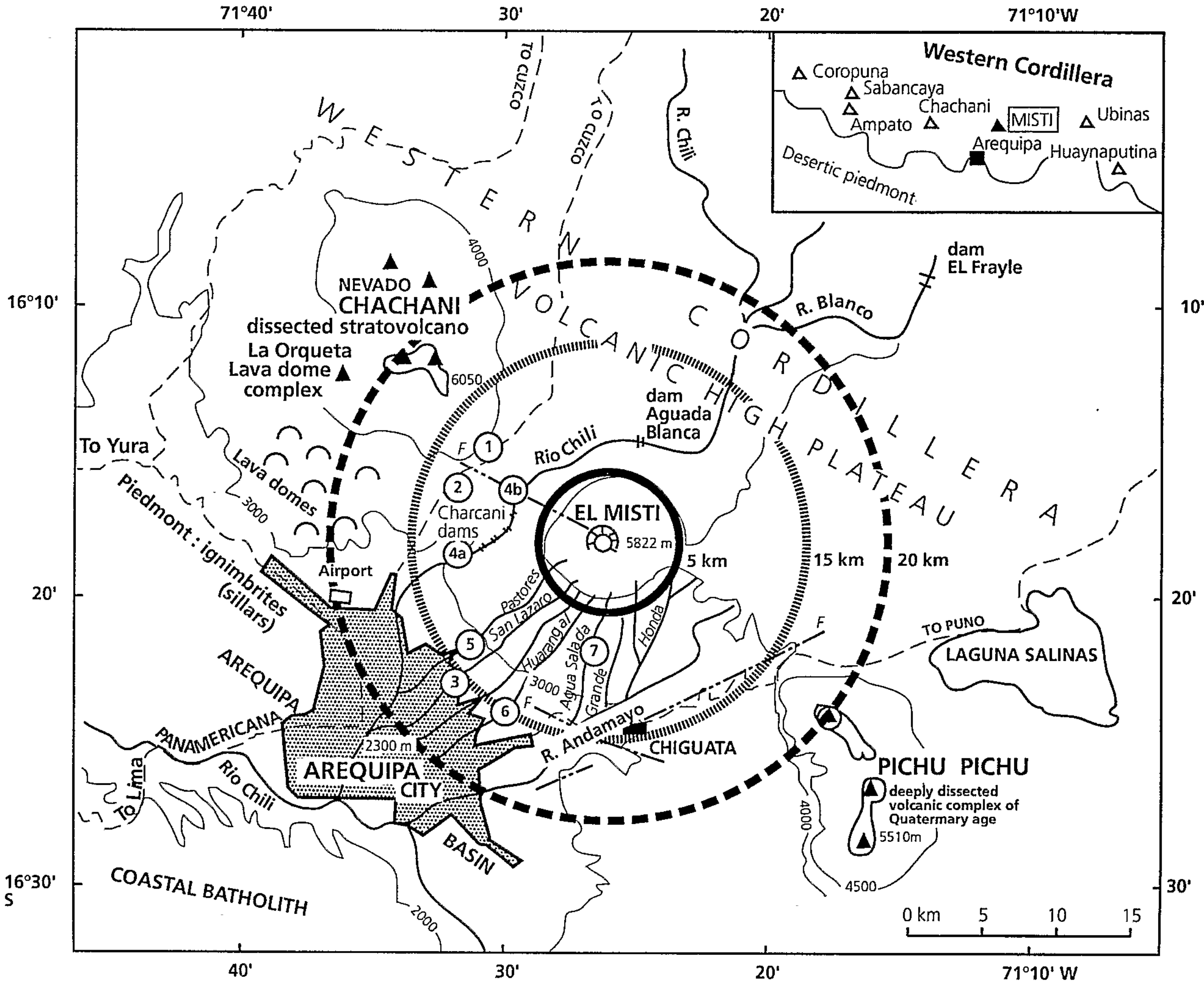


Fig. 3. Geographical and geological setting of the Misti stratovolcano and Arequipa city area. Circles of 5, 15, and 20 km radius around the Misti crater are shown. Numbers indicate sites of main stratigraphic sections.

along N45-trending fractures on the E bank of the Chili canyon. This drains the Altiplano towards the Arequipa basin, a tectonic depression at 2,300 m above sea-level, limited to the S by the coastal batholith (VARGAS 1970, GUEVARA 1969).

Eruptive activity at Misti represents an impending threat for about 700,000 people who live at risk in Arequipa, Peru's second largest city, whose center at 2,300 m asl. lies 17 km to the SW and 3.5 km lower in elevation than the vent at 5,800 m asl (Fig. 4A). Recently, the city has spread upstream along the deep valleys that drain the SW piedmont and the S flank of the volcano.

First, we present the geological and volcanic setting of the Misti volcano which encompasses two edifices: the 'old Misti' stratovolcano and the 'young Misti' strataocone. Second, we analyze the stratigraphy and the chronology of its eruptive activity, in particular over the past 100,000 years: seven compound groups of deposits record the late Pleistocene eruptive of the modern Misti stratocone. Third, we aim to assess the volcanic hazards of future eruptions at Misti, based on mapping, recent eruptive deposits, and models used on similar stratovolcanoes: 700,000 people in the Arequipa-Chiguata region are threatened by at least four types of volcanic hazards.

2 *Geological and volcanological setting*

Misti encompasses two edifices: a pristine 'modern' stratocone to the E and SE, which rises up to 5,800 m (Fig. 4B) and a dissected 'old' stratovolcano to the W and NW. The modern stratocone has been built up next to, and has overlapped in part, a dissected 'old' stratovolcano to the W and NW (Fig. 4C). Both edifices have been built on top of at least 5 welded and nonwelded dacitic-rhyolitic ignimbrites, termed 'sillars' (JENKS &

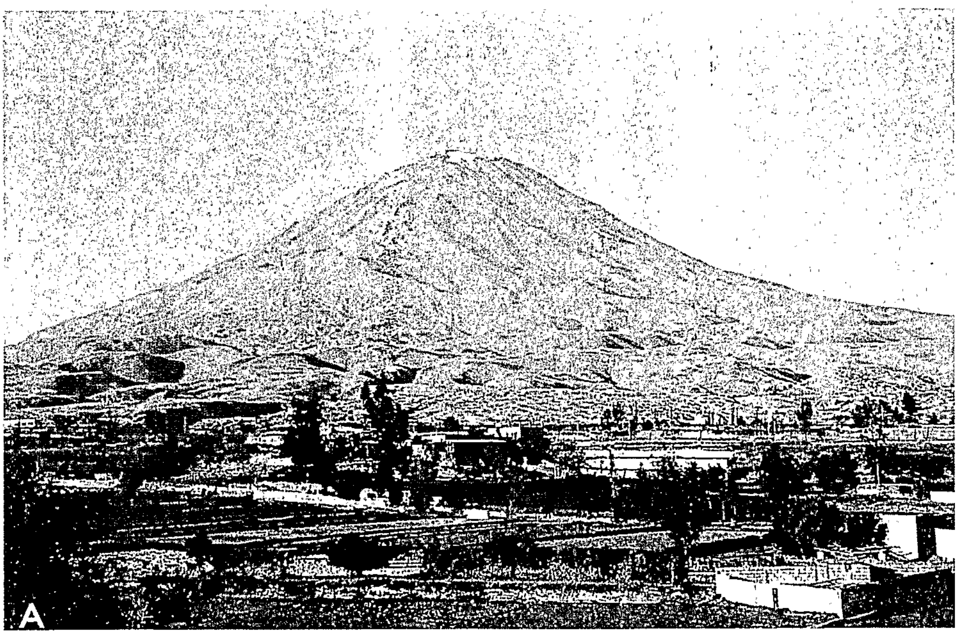


Fig. 4A. Misti volcano (5,820 m elevation) and Arequipa city (2,300 m altitude) looking NE. Distance between Misti summit and Arequipa center is 17 km.

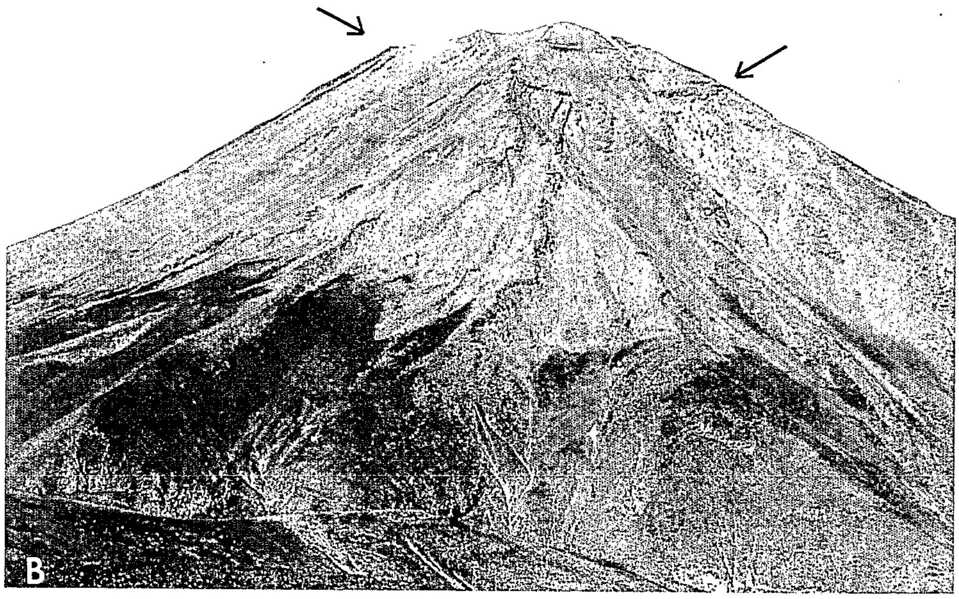


Fig. 4B. Dissected W flank of Misti above the Rio Chili canyon, looking ESE. Steep-sided lava flows dipping toward photographer belong to 'Old Misti', whereas lava flows dipping SW belong to the 'Modern Misti'. Arrows pinpoint the floor of the summit caldera buried by products of the 5,800-m-high cinder cone.

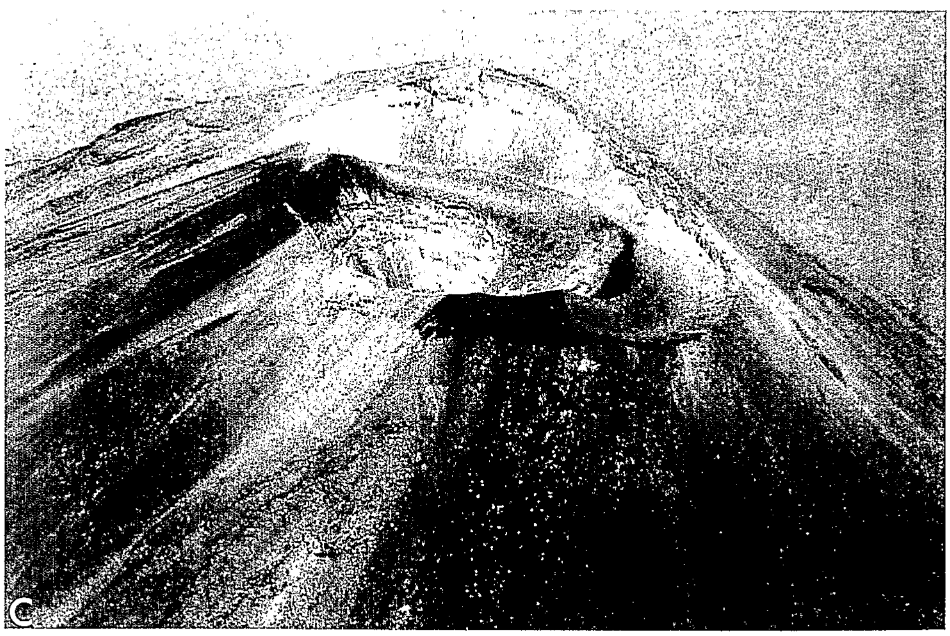


Fig. 4C. Nested craters on the Misti summit: the 950-m-wide crater about 2,000 yr old contains the historical, scoria-rimmed crater 550 m across, 200 m deep, which includes a fumarolic andesitic plug (not visible here).

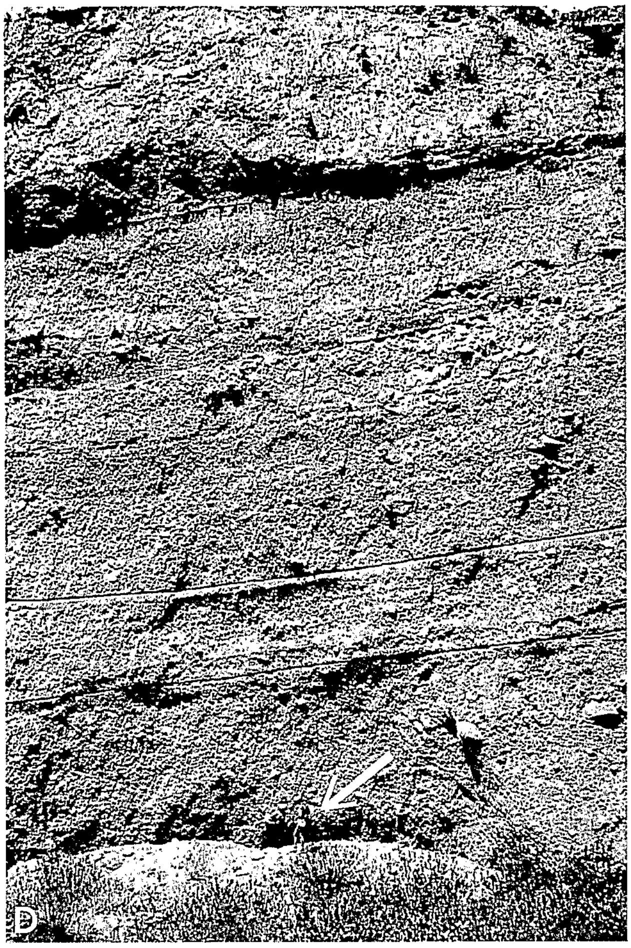


Fig. 4D. Group VI (Qda. Huarangal, Misti's S flank) about 18 m thick consists of block-and-ash pyroclastic-flow deposits including a few Plinian lapilli-fall layers (arrow pinpoints a person for scale). Group VI is overlain by a 6-m-thick, massive, pumice-rich pyroclastic-flow deposit ca. 2,000 yr old.

GOLDICH 1956; Figs. 5, 6). The sillars observed in Rio Chili exceed 300 m in thickness and belong to Late Pliocene (Fig. 6; VATIN-PÉRIGNON et al. 1996).

The 'old Misti' stratovolcano is Lower to Middle (?) Pleistocene in age and consists of at least 400 m thick and up to 6 km long andesite lava flows, interbedded volcaniclastic sediments, and thin, nonwelded ignimbrites. The base of the 'old Misti' volcano is overlain by debris-avalanche deposits at least 100 m thick towards the W and SW. Subdued hummocky deposits burying the S and SE piedmont in excess of 50 km^2 record the probable flank failure of the 'old' stratovolcano, which probably occurred before Late Pleistocene (Fig. 5). Similar debris-avalanche deposits outcrop on the steep-sided WNW flank of the volcano. Whether the two debris-avalanche deposits reflect only one destabilization is not yet known. In addition, the debris-avalanche deposits interwine with other similar deposits towards the SE of the Misti piedmont, which may reflect the destabilization of the extinct Pichu Pichu volcanic complex 35 km to the E of Arequipa (Figs. 3, 5).

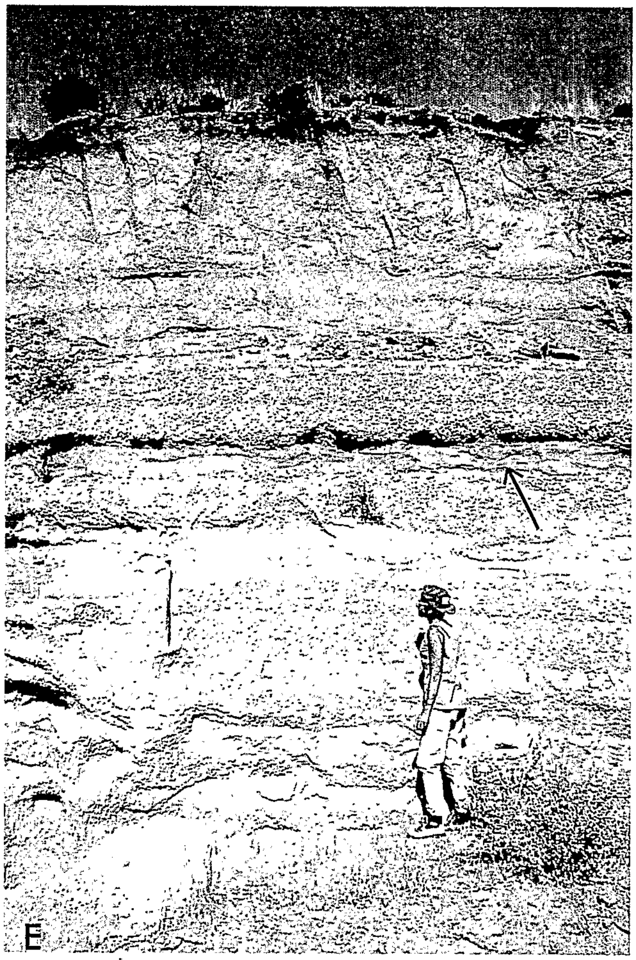


Fig. 4E. Group VII consists of Plinian pumice-fall deposits, ash-fall deposits, and a few soils in ash (Person for scale, and ice axe is 60 cm long). Arrow pinpoints a grey, ash-rich pyroclastic surge deposit beneath a 80-cm-thick Plinian pumice lapilli-fall deposit, 8 km due W of Misti's vent.

The 'modern Misti' stratocone (≥70 km^3) consists of stubby lava flows and pyroclastic debris piling up to 2 km in thickness (Fig. 6). Volcaniclastic sediments have formed an extensive piedmont and two large fan aprons (Figs. 5, 6) upon which the city has grown. A mass of lava domes and flows forms the base of the stratocone above 3,200 m: they have been emplaced through long periods of dome growth and lava extrusion. The cone-shaped summit above 4,500 m shows two concentric craters nested within a crescent-shaped lava and cinder cone (Fig. 4D). The walls of the 950 m-wide 'old' crater parallel N40 and N120-trending fractures. The youthful black scoria-rimmed crater 550 m across and 200 m deep has been intruded by an andesitic plug where persistent fumarolic activity is taking place. Both vents and the summit cone are located within a summit caldera 1.5 km across whose rims are partly buried by pyroclastic deposits and cut in a welded ignimbrite. About 100-m-thick pyroclastic-flow deposits and reworked debris that outcrop in the S piedmont (Agua Salada, Honda, and Grande valleys: Fig. 3) may witness to the caldera-forming eruption(s) whose age is not yet known.

3 *Eruptive history based on the late Pleistocene stratigraphy*

A collection of block-and-ash flows, scoria-rich pyroclastic flows, pumice and lithic-rich pyroclastic-flow deposits, and tephra-fall deposits form the piedmonts of Misti 250 km^2 in area, particularly to the SW, S and SE (Fig. 5; THOURET et al. 1997). Based on field mapping and photointerpretation, lithology and geochemistry, and on a few ^{14}C datings, nine measured composite sections suggest stratigraphical relationships. In sum, seven compound groups of deposits (Fig. 7, Groups I–VII), mostly pyroclastic in origin, record the late Pleistocene eruptive history of the modern Misti stratocone, as follows.

1) The first group consists of thick and stubby lava flows, block-lava flows, and lava domes at the base of the stratocone (3,200–4,000 m) towards the S, SW and NE (Figs. 5, 6). They were emplaced through long periods of lava and dome extrusion from about 0.3 Ma (0.27±0.08 Ma: this study) to about 0.1 Ma (0.78±0.035: KANEOKA & GUEVARA 1984). This is overlain by a composite pyroclastic sequence (block-and-ash flows, scoria-rich and pumice-rich pyroclastic-flow deposits) interbedded in block-lava flows which has built up the cone-shaped summit above 4,000 m (Fig. 7, Group I).
2) The second group comprises thick deposits of monolithologic, dense and vitreous breccias channeled as far as 10 km downvalley from the vent, attributed to dome collapse, pointing to the destruction of summit domes (Fig. 7, Group 2). They are overlain by lithic-rich pyroclastic-flow deposits, suggesting that violent explosive eruptions formed a summit caldera or a large crater.
3) A thick group of pyroclastic flows and nonwelded ignimbrites, including interbedded tephra-fall and volcaniclastic deposits, may bear witness to eruptions that formed the summit caldera. One of the pumice-rich pyroclastic flows yielded a radiocarbon age of 47,350±2,100/1,700 yr BP (Fig. 7, Group 3).
4) A 10-m-thick sequence of scoria-flow deposits, pumice-rich pyroclastic-flow and fall deposits mantles the flanks of the extinct Chachani stratovolcano to the W, and the N and NE of Misti's flanks (Figs. 5 and 7, Group IV). Interbedded deposits of glacial origin suggest that this sequence can be placed within the Last Glacial period after approximately 47,000 yr B.P.
5) A group of pumice- or ash-flow and tephra-fall deposits, rhyolitic in composition, may reflect an explosive eruption which led to the formation of, or enlarged the summit caldera (Figs. 6 and 7, Group V). Organic material on top of a brown soil within the upper part of these deposits (Pastores valley, Fig. 3) yielded a radiocarbon age of ca. 33,870±1800–1460 yr B.P. (GrN-21574).
6) A succession 30 to 50 m thick of block-and-ash and lithic-rich pyroclastic-flow deposits on the SW, S, and SE flanks include a few interbedded Plinian pumice-fall layers, e.g., 8 km away from the vent in San Lazaro, Huarangal, and Agua Salada valleys (Figs. 4E, 5 and 7, Group VI). The pyroclastic-flow deposits record repeated dome growth and destruction towards the end of the last glaciation.
7) A pile 4–6 m thick of pumice lapilli and ashfall deposits indicates that Misti has erupted explosively at least 8 times over the past ca. 14,000 years. Well stratified deposits probably emplaced in water bodies (near melting glaciers?) and debris-flow deposits underlying and interbedded in the lower part of the section (Fig. 7, Group VII), indicate that the tephra have been erupted close to the Late Glacial period. Soils are scarce or poorly developed in ash, suggesting that the explosive activity came to

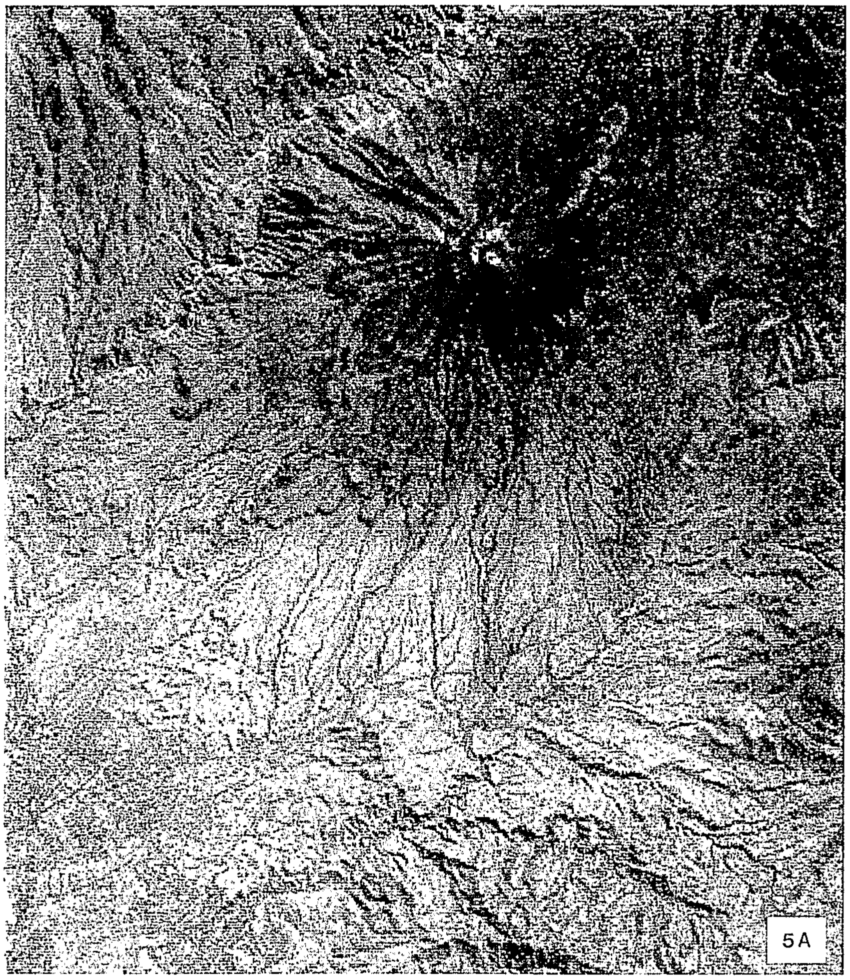


Fig. 5 A. Sketch map of volcanic deposits on Misti and in Arequipa area based on a SPOT satellite image, 1991.

rest for relatively short periods only or, alternatively, the poor development of soils may have been climatically controled. In addition, thin, ungraded grey ash-rich layers, including dune-like and cross-stratified deposits with tiny lithic fragments underlie Plinian pumice-fall deposits (Fig. 4F, Group VII) in proximal sections and pyroclastic-flow deposits as far as 15 km away in the city suburbs. They point to explosive eruptions that have probably emplaced pyroclastic-surge or blast deposits.

The last Plinian eruptions dated at Cal 200 BC–200 AD (based on five ^{14}C ages between 2090±40 yr B.P., GrN-22162 and 1920±200 yr B.P., Lv-2111; THOURET et al. 1995, 1996) delivered a pumice-fall deposit which was carried towards Arequipa by prevailing E winds. During that eruptive episode, nonwelded pumice-rich pyroclastic flows

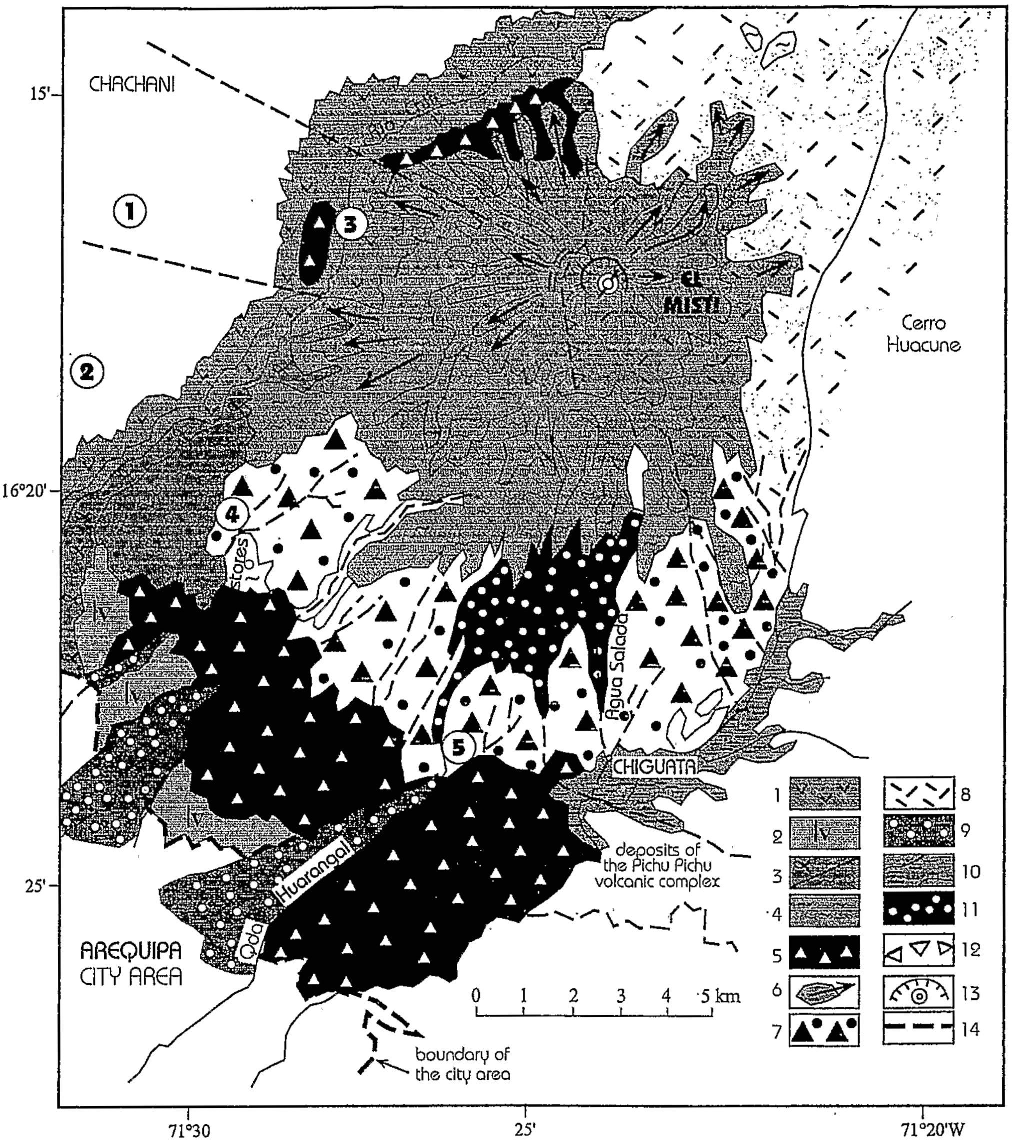


Fig. 5B. 1. Ignimbrites of upper Tertiary overlain by volcaniclastic sediments of Plio-Quaternary age. 2. Lava flows of Quaternary age (pre-Misti?). 3. 'Old' Misti stratovolcano (lower to middle?) Pleistocene in age: a) andesitic lava flows; b) block-lava flows. 4. Lava flows of the base of the 'modern' stratocone (middle to late?) Pleistocene in age. 5. Debris-avalanche deposits (end of middle Pleistocene?). 6. Stratocone of late Pleistocene to Holocene age. 7. Piedmonts built up of pyroclastic deposits (units II to V, Fig. 6). 8. Area mantled by black scoriae and ash deposits (related to the summit caldera-forming eruption?). 9. Fans of volcaniclastic deposits in the lower radial valleys. 10. Lacustrine deposits of the (Late Glacial?) Chiguata basin. 11. Pumice-rich pyroclastic-flow deposit 2,000 yr B.P. old. 12. Scar of the probable flank failure. 13. Nested craters and plug. 14. Main fracture.

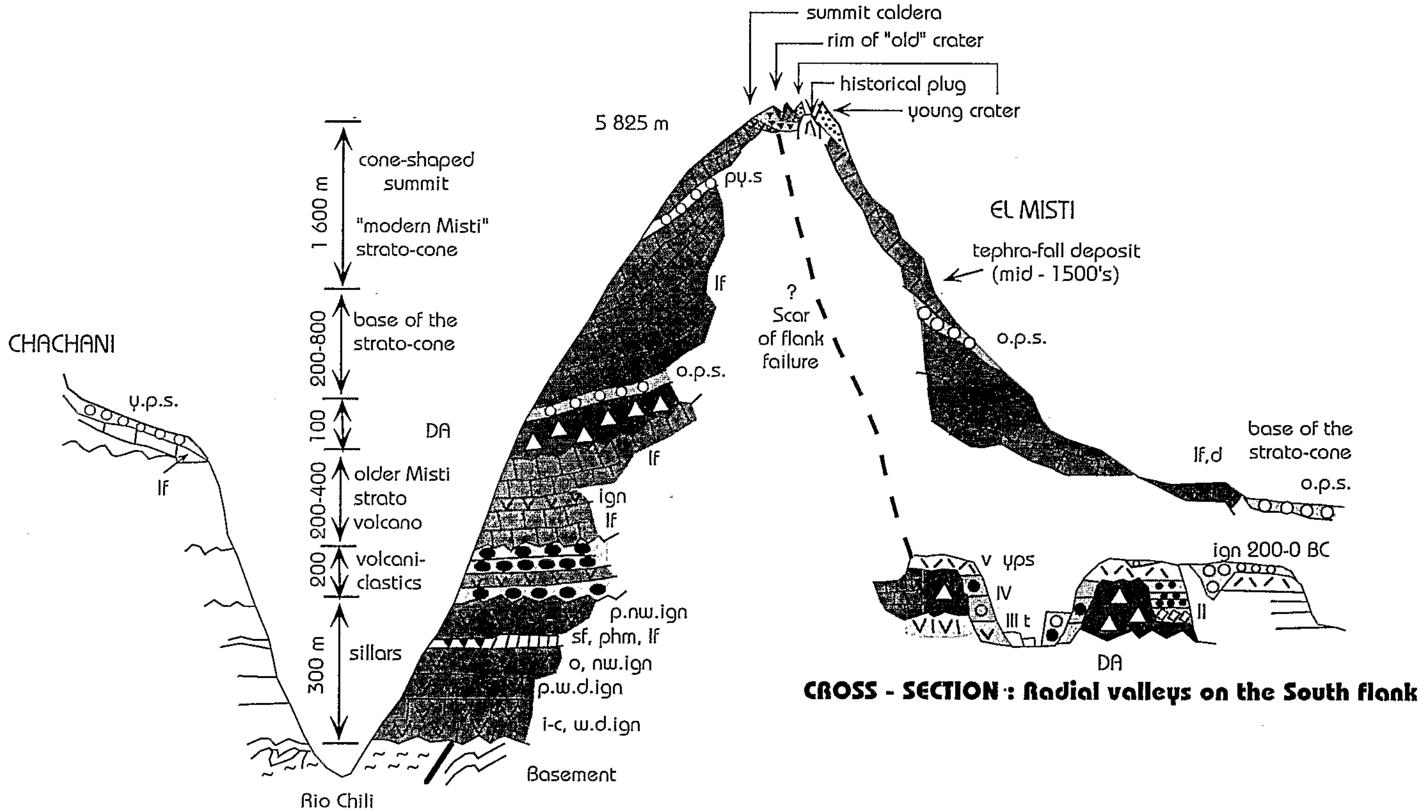


Fig. 6. Schematic cross-section of Misti stratovolcano (SWS-ENE). Basement: a) folded sedimentary rocks of Jurassic age, Yura Group; b) Precambrian gneiss. Pre-Misti: nonwelded and welded ignimbrites (sillars: recrystallized pumice-rich pyroclastic flow deposits) of Neogene age; 1-c = light-colored, p = pink, o = orange, pu = purple, w = welded, d = devitrified; sf.phm = scoria-rich pyroclastic-flow and phreatomagmatic deposits; volcaniclastic sediments of Plio-Quaternary age. 'Old' Misti stratovolcano: 1f = lava flows (LF when large-scale volume); d = dome; DAD = Debris-avalanche deposits of (middle?) Pleistocene age. Base of the 'Modern' Misti stratocone: andesite lava flows and 'old pyroclastic sequence' = Unit I. Deposit of dome collapse = Unit II. 'Modern' Misti stratocone: Units II to VII: b-a p-f = block-and-ash pyroclastic-flow deposit; sf = scoria-rich pyroclastic-flow deposit. pf = pyroclastic-flow deposit; ps = pyroclastic surge deposit; tf = pumice- or ashfall deposit. o.p.s./y.p.s. = old/young pyroclastic sequence. y.ign = young ignimbrite (from the summit caldera?). Inset, right-hand corner: schematic cross-section of the radial valleys, S flank. dc = deposit of dome collapse. II-VII y.p.s. = units of the modern pyroclastic sequence (Fig. 5). ign 200-0 BC = radiocarbon dated pumice-rich pyroclastic-flow deposit.

were channeled into five radial valleys as far as the present suburbs of Arequipa and Chiguata (Figs. 5, 6 and 7), and formed a pyroclastic fan ≥20 km^2 in area on the Misti' S flank. At the break-in-slope between the stratocone and the piedmont, the 20- to 30-m-thick pyroclastic-flow deposits show two flow units, suggesting that the lithic-rich unit was decoupled from the pumice-rich flow during flow transportation.

3.1 *Explosive activity has continued through historical time at Misti*

An ash layer interbedded in block-and-ash flow deposits on the SE flank (uppermost Huarangal valley) is dated at Cal 1292–1412 AD (620≥50 yr B.P., GrN-22163). Beneath the 1600 AD tephra-fall layer from Huaynaputina, a ≤20-cm-thick, black scoriaceous ashfall layer of andesitic composition bears witness to the last eruption at 1440–1480 AD (Group VII, Fig. 7), which caused some damage in the Inca city of Chiguata (a town now to the E of Arequipa city), as referred to in historical narratives (ZAMACOLA Y JAUREGUI 1804, CHÁVEZ CHÁVEZ 1992).

The historical record mentions several questionable events (HANTKE & PARODI 1966, SIMKIN & SIEBERT 1994): 1542? 1599? 1826–08? 1830–08 and 1831? 1869–09 and 1870 –03? Most of them are believed to be episodes of strong fumarolic acitivity. However, one moderate (VEI 2) seismic and phreatic (?) explosive event was recorded on 2 May 1677 and two phreatic (?) events on 9 July 1784 and 28 July–10 October 1787 (SIMKIN & SIEBERT 1994, CHÁVEZ CHÁVEZ 1992, BARRIGA 1951).

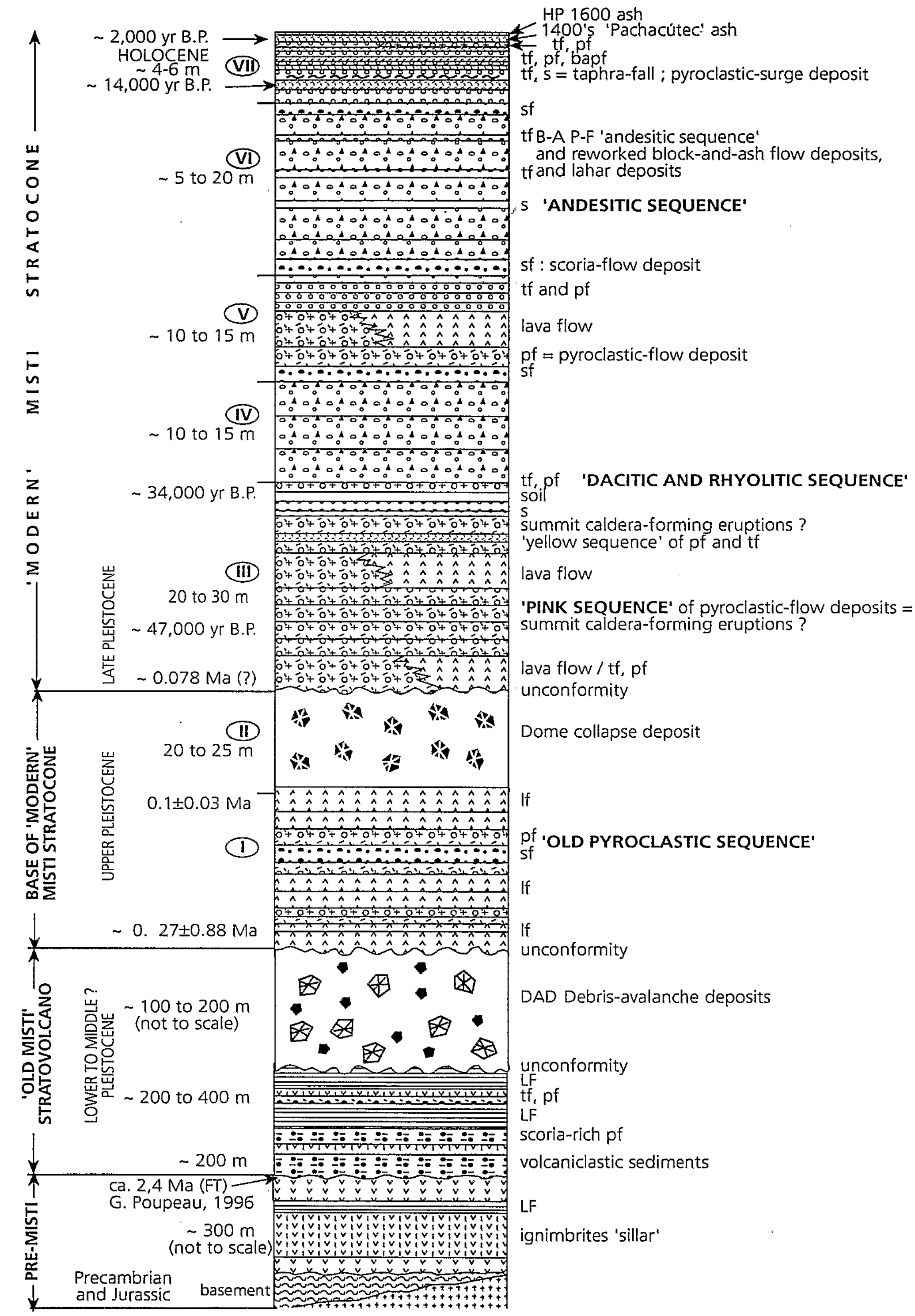
Since then, persistent, high-temperature fumarolic activity has been observed at the plug, in and around the younger crater (Fig. 4D), as recently as 1948–1949 and 1984–1985. Measurements carried out from time to time in the active crater by two alpinists from Arequipa indicate that the plug has grown by as much as 20 m over the past 40 years. Yet no geophysical monitoring has been undertaken so far.

3.2 *Petrology of the Misti lavas*

Despite a wide range of deposits and a ≤1–my-long lasting activity, Misti volcano has delivered magmas whose geochemistry is homogeneous. The SiO_2 ranges from 58 to 64 % (Fig. 8 A). Petrological data of 60 lavas of Misti (plot of $SiO_2/Na_2O + K_2O$: Fig. 8B) show that the calk-alkaline lavas belong to a high-K_2O series (LEFÊVRE 1979), which includes andesites and dacites, whereas basic andesites and rhyolites are scarce. The mineral assemblage encompasses plagioclases, clinopyroxenes and orthopyroxenes, amphiboles, biotites, and oxides Fe-Ti. There is no significant change between the 'old Misti' stratovolcano (mostly lava flows) and the 'modern Misti' stratocone (pyroclastic deposits and lava domes). One rhyolithe (JMi95-64), a few pre-Misti lavas (JMi 95-58, 68) and one Chachani's lava (JMi-69) are the only samples plotted away from the main series.

4 *Hazard assessment at Misti volcano and in the Arequipa area*

Hazard assessment is based on two methods. (1) Data on eruption processes, behaviour, and frequency have been derived from the study of historical, Holocene, and late Pleis-


HP 1600 ash
1400's 'Pachacútec' ash
tf, pf
tf, pf, bapf
tf, s = taphra-fall ; pyroclastic-surge deposit
~ 2,000 yr B.P.
HOLOCENE
~ 4-6 m
VII
~ 14,000 yr B.P.
sf
tf B-A P-F 'andesitic sequence'
and reworked block-and-ash flow deposits,
tf and lahar deposits
VI
~ 5 to 20 m
s 'ANDESITIC SEQUENCE'
sf : scoria-flow deposit
tf and pf
V
~ 10 to 15 m
lava flow
pf = pyroclastic-flow deposit
sf
IV
~ 10 to 15 m
~ 34,000 yr B.P.
tf, pf 'DACITIC AND RHYOLITIC SEQUENCE'
soil
s
summit caldera-forming eruptions ?
'yellow sequence' of pf and tf
III
20 to 30 m
lava flow
'PINK SEQUENCE' of pyroclastic-flow deposits =
summit caldera-forming eruptions ?
~ 47,000 yr B.P.
LATE PLEISTOCENE
~ 0.078 Ma (?)
lava flow / tf, pf
unconformity
'MODERN' MISTI STRATOCONE
II
20 to 25 m
Dome collapse deposit
0.1±0.03 Ma
lf
I
pf 'OLD PYROCLASTIC SEQUENCE'
sf
lf
UPPER PLEISTOCENE
BASE OF 'MODERN' MISTI STRATOCONE
~ 0. 27±0.88 Ma
lf
unconformity
~ 100 to 200 m
(not to scale)
DAD Debris-avalanche deposits
unconformity
LF
tf, pf
LF
~ 200 to 400 m
LOWER TO MIDDLE ? PLEISTOCENE
'OLD MISTI' STRATOVOLCANO
scoria-rich pf
~ 200 m
volcaniclastic sediments
ca. 2,4 Ma (FT)
G. Poupeau, 1996
LF
~ 300 m
(not to scale)
ignimbrites 'sillar'
PRE-MISTI
Precambrian
and Jurassic
basement

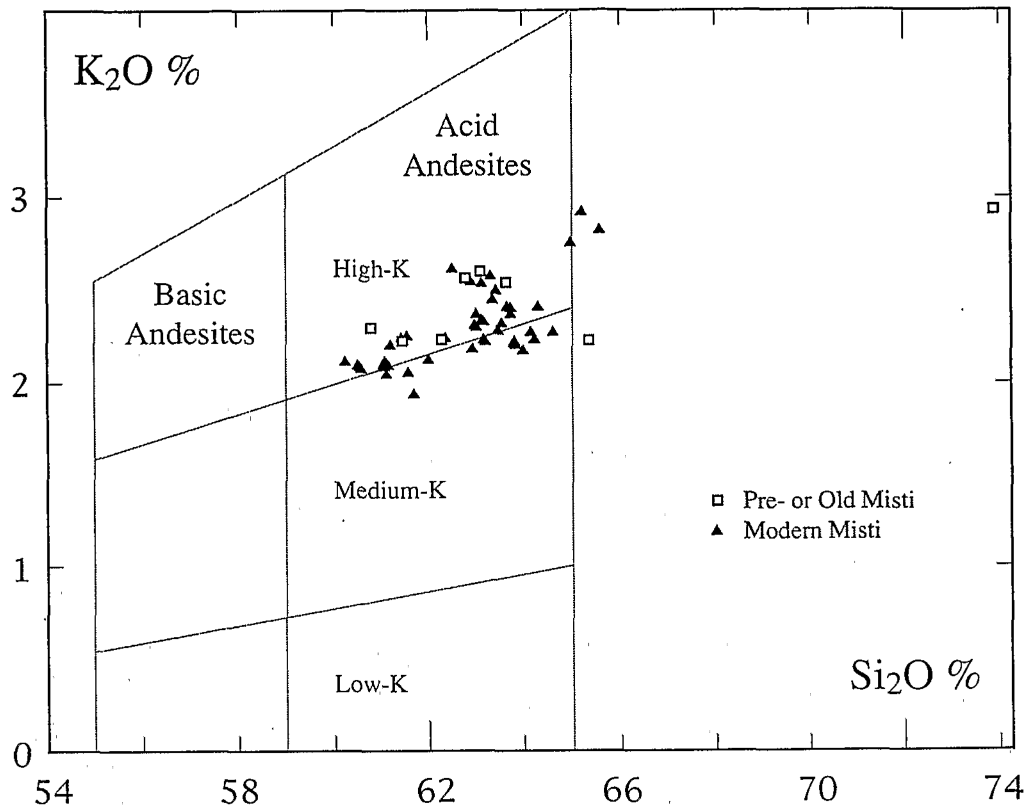
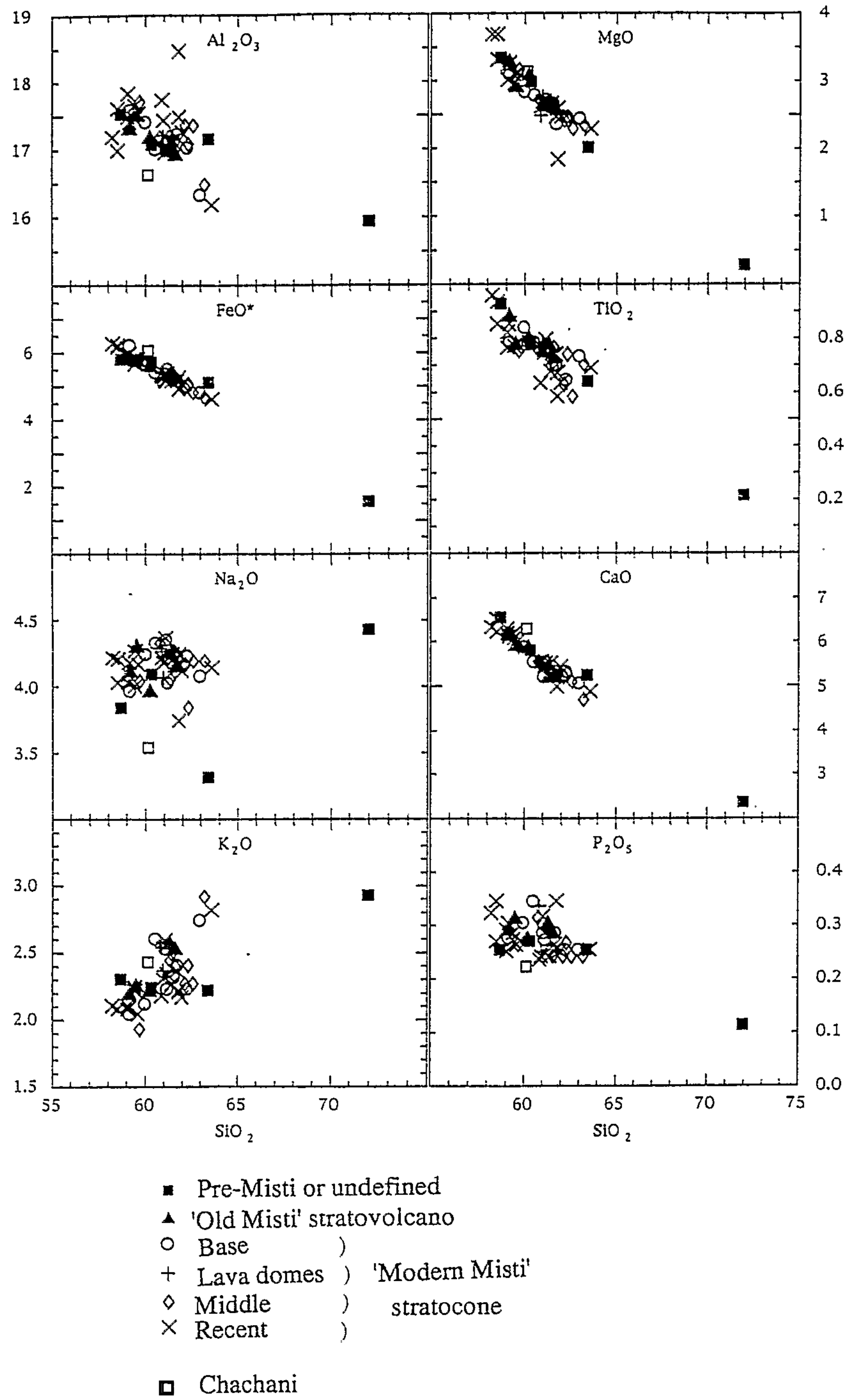


Fig. 8A. Plot K_2O/SiO_2 for 60 lavas from Misti volcano and nearby volcanoes (plot after LE BAS et al. 1986) and 8B. 'HARKER'plots of SiO_2 and Major Elements Al_2O_3, MgO, FeO, TiO_2, Na_2O, CaO, K_2O, and P_2O_5, showing the homogeneous composition of the erupted magmas from Misti volcano. ICP-AES bulk rock analyses done at the University of Brest. Analyst: JOSEPH COTTON. Total recalculated to 100%, LOI free.

← Fig. 7. Composite stratigraphical section of the Misti stratovolcano. 1. Basement: folded sedimentary rocks of Jurassic age (Yura Group), and Precambrian gneiss. 2. Pre-Misti: Nonwelded and welded ignimbrites (sillars) of Neogene to Plio-quaternary age. 3. 'Old' Misti stratovolcano: LF, lf = Lava flows (LF when large- volume, lf when small-volume). DAD = debris-avalanche deposits of (middle ?) Pleistocene age. 4. Base of the Modern Misti stratocone: Andesite lava flows or block-lava flows (= Unit I); Deposit of dome collapse = Unit II. 5. 'Modern Misti' stratocone: Units III to VII. bapf = block-and-ash pyroclastic-flow deposit; sf = scoria-rich pyroclastic-flow deposit and/or scoria-fall deposit; pf = pumice-rich pyroclastic-flow deposit; ps = pyroclastic-surge deposit; tf = tephra-fall deposit (ash and/or pumice lapilli); s = poorly developed soil in ash.



Al2O3
MgO
FeO*
TiO2
Na2O
CaO
K2O
P2O5
SiO2
SiO2
Pre-Misti or undefined
'Old Misti' stratovolcano
Base
Lava domes
Middle
Recent
'Modern Misti' stratocone
Chachani

Fig. 8B

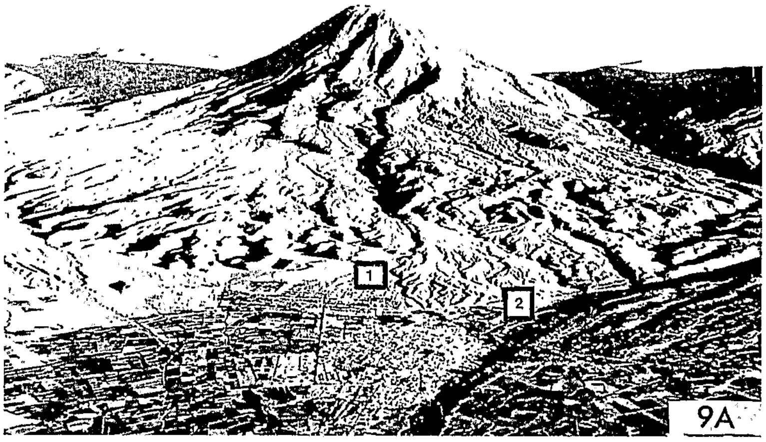
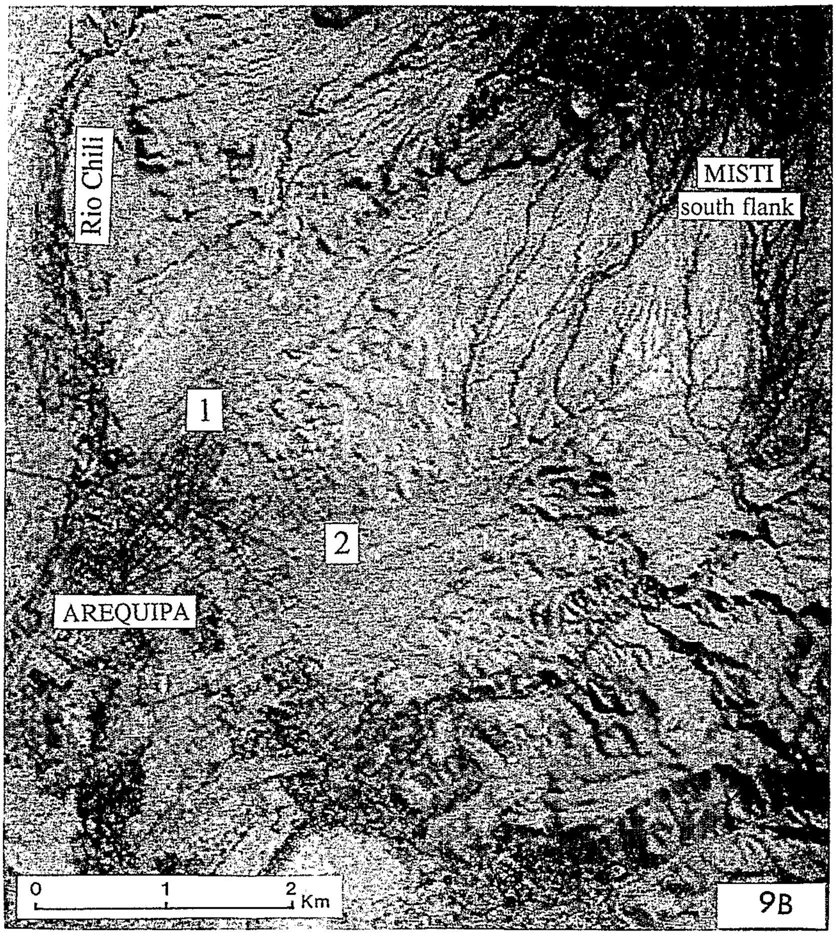


Fig. 9. Extent of Arequipa city in the early 1940's (air photograph, 9A) compared to that of 1991 (enlarged SPOT satellite image, 9B, revealing the rapid expansion of the built area on the volcaniclastic fans towards the SW flank of Misti volcano.



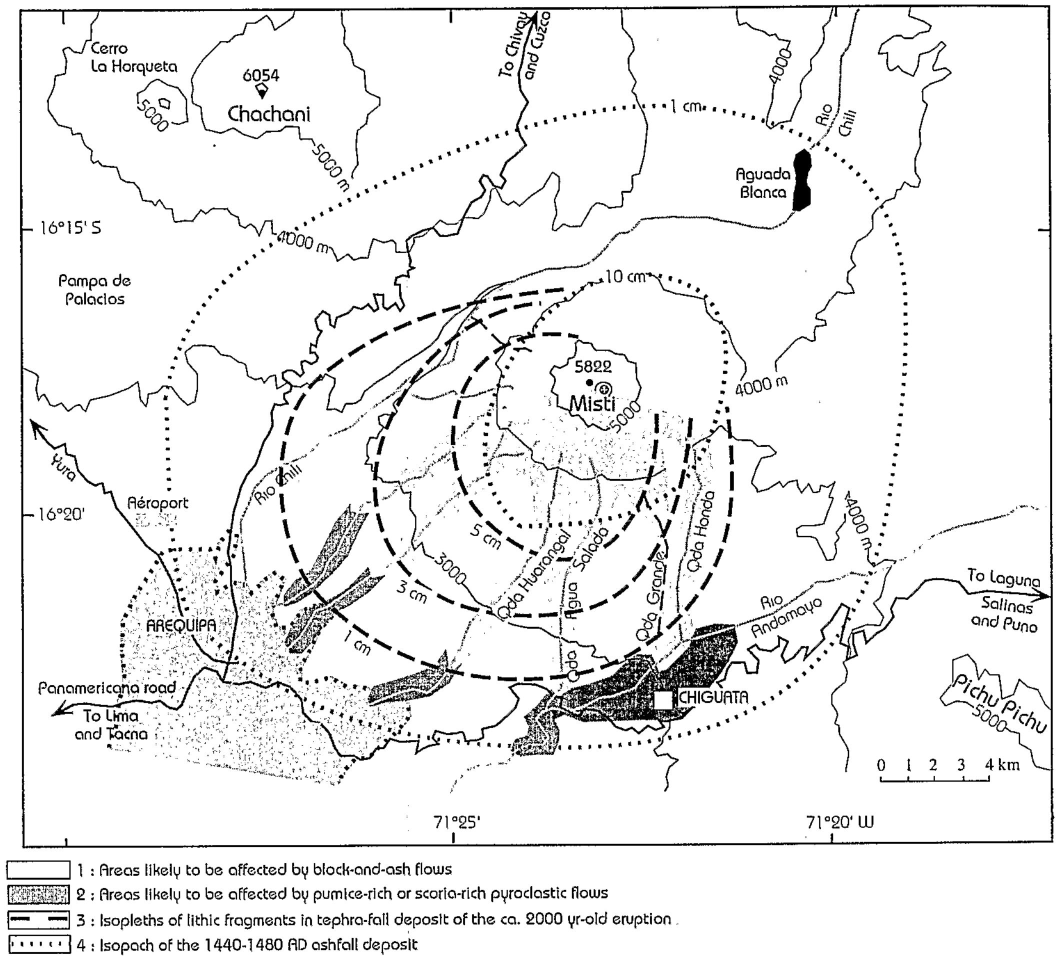


Fig. 10. Expected extent of future pyroclastic flows and tephra falls at Misti based on two recent eruptive episodes. Grey areas represent block-and-ash flows with H/L = 0.25 and an energy line of < 16° as typical values at Misti. Black areas represent more mobile pumice flows with H/L = 0.20 and an energy line of < 13° as typical values at Misti. The 10 and 1-cm isopachs of the area covered by the mid-1400's ashfall deposit show the area likely to be affected in case of a moderate-scale explosive event. The 5, 3, and 1-cm isopleths of the lithic fragments from the 200 BC–200 AD Plinian pumice-fall deposit are also shown.

tocene deposits. (2) Existing models of dispersal of tephra (CAREY & SPARKS 1986), flowage of pyroclastic debris (HAYASHI & SELF 1992), and debris avalanches (CRANDELL 1988) have been used to outline the areas likely to be affected by future eruptions.

The city has expanded dramatically upstream toward Misti, as demonstrated through the comparison of a photograph taken in the early 1940's with a SPOT satellite image acquired in 1991 (Fig. 9A,B). People in the Arequipa area (pop. 700,000) and the town

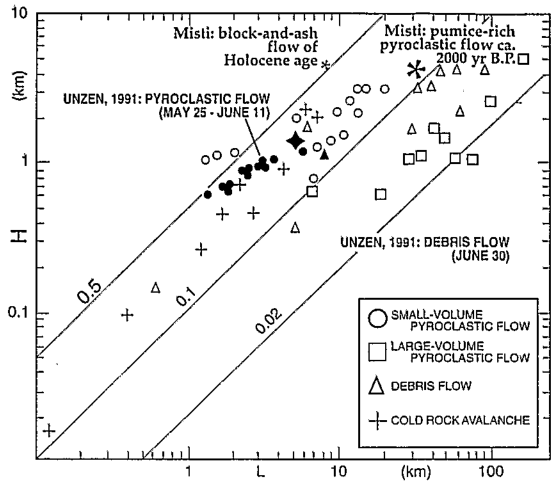


Fig. 11. Plot of height of origin (H) and travel distance (L) for observed block-and-ash flows and pumice-rich pyroclastic flows at Misti volcano (S flank), compared with the 1991 pyroclastic flows and other types of gravity flows from Unzen (after YAMAMOTO et al. 1993). Lines of equal H/L ratio are also shown.

of Chiguata (pop. 2,000) are threatened by at least four types of volcanic hazards (Figs. 10–13): ash falls, pyroclastic flows, lahars, and debris avalanches.

1) Low eruptive columns (≤3 km) may cause ashfall in the city; the approximate extent of the mid-1400's tephra indicates that ashfall occurs mostly to the NE when the eruptive column does not exceed 3 km in height above the crater (Fig. 10). Winds near the crater (elevation 5,800 m) prevail towards the N and NE (except between April and June when they blow to the W).

For higher columns (20–25 km), our estimate of the size of the Plinian column is based on mapping of the 3- and 5-cm-isopleths of the lithic fragments (Fig. 10) emplaced in the 200 BC–200 AD Plinian pumice-fall deposit carried towards Arequipa by prevailing E winds. The thickness of the relevant layer could amount to 30 cm in the city. Winds at 9,000 m elevation prevail towards the W and SW (except between December and March when they shift towards the S).

2) The expected direction of future pyroclastic flows is towards the S, owing to the crater wall geometry and to the steep-sided S flank. All the recent pyroclastic flows were valley-confined downstream into the Chiguata area and have travelled into the N and NE area of Arequipa city (Fig. 10).

Destruction of the summit dome can yield block-and-ash flows which are expected to travel 8 to 12 km downstream when valley-confined; thus, they might hit the NE suburbs of Arequipa. Grey areas on Fig. 10 represent block-and-ash pyroclastic flows, with H/L = 0.25 and an energy line of <16° as a typical values, observed at Misti. More mobile pumice flows are expected to travel another 4–8 km further downstream into the Chiguata and Arequipa areas. Black areas on Fig. 10 represent mobile pumice flows, with H/L = 0.20 and an energy line of <13° as typical values. The H/L plot for observed pyroclastic flows (Fig. 11, after YAMAMOTO et al. 1993) shows that pyroclastic flows at Misti, although of small-to-intermediate scale, acquire a high momentum due to the 2.8 km height/8 km distance between the vent and the break-in-slope of the S piedmont. Such a momentum provides a long runout distance in excess of that observed at Unzen volcano in Japan.

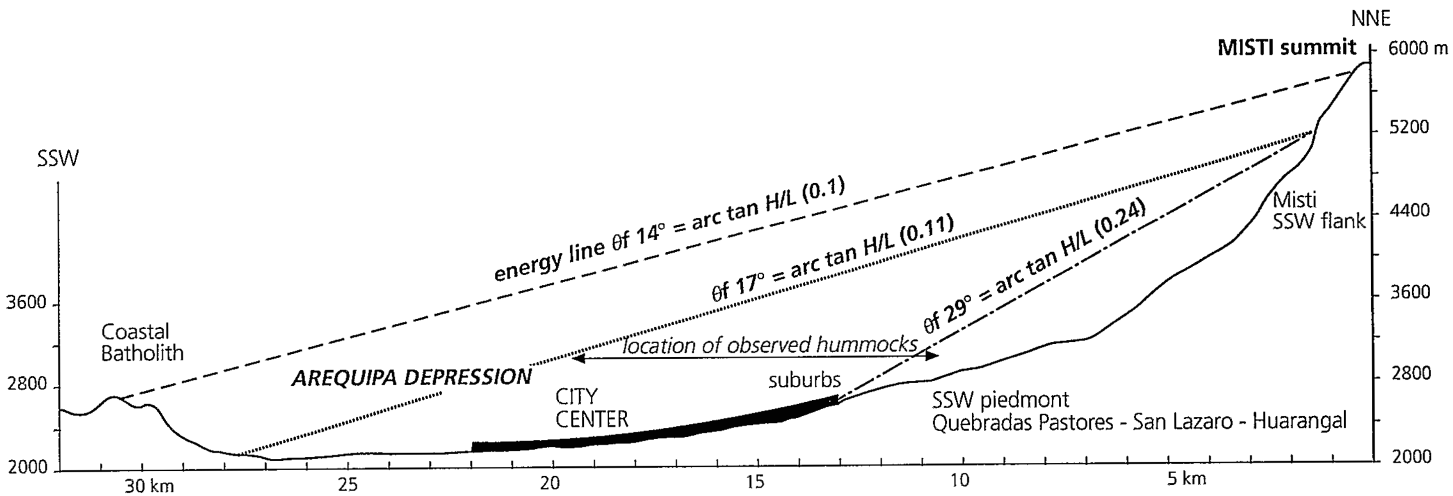


Fig. 12. Three hypothetical energy lines for potential debris avalanches at Misti. The energy line of 17° is based on the average value (H/L 0.11) of 40 volcanic debris avalanches (after HAYASHI & SELF 1992). The energy line of 29° (H/L 0.24) is based on the extent of observed hummocks in the Arequipa city area.

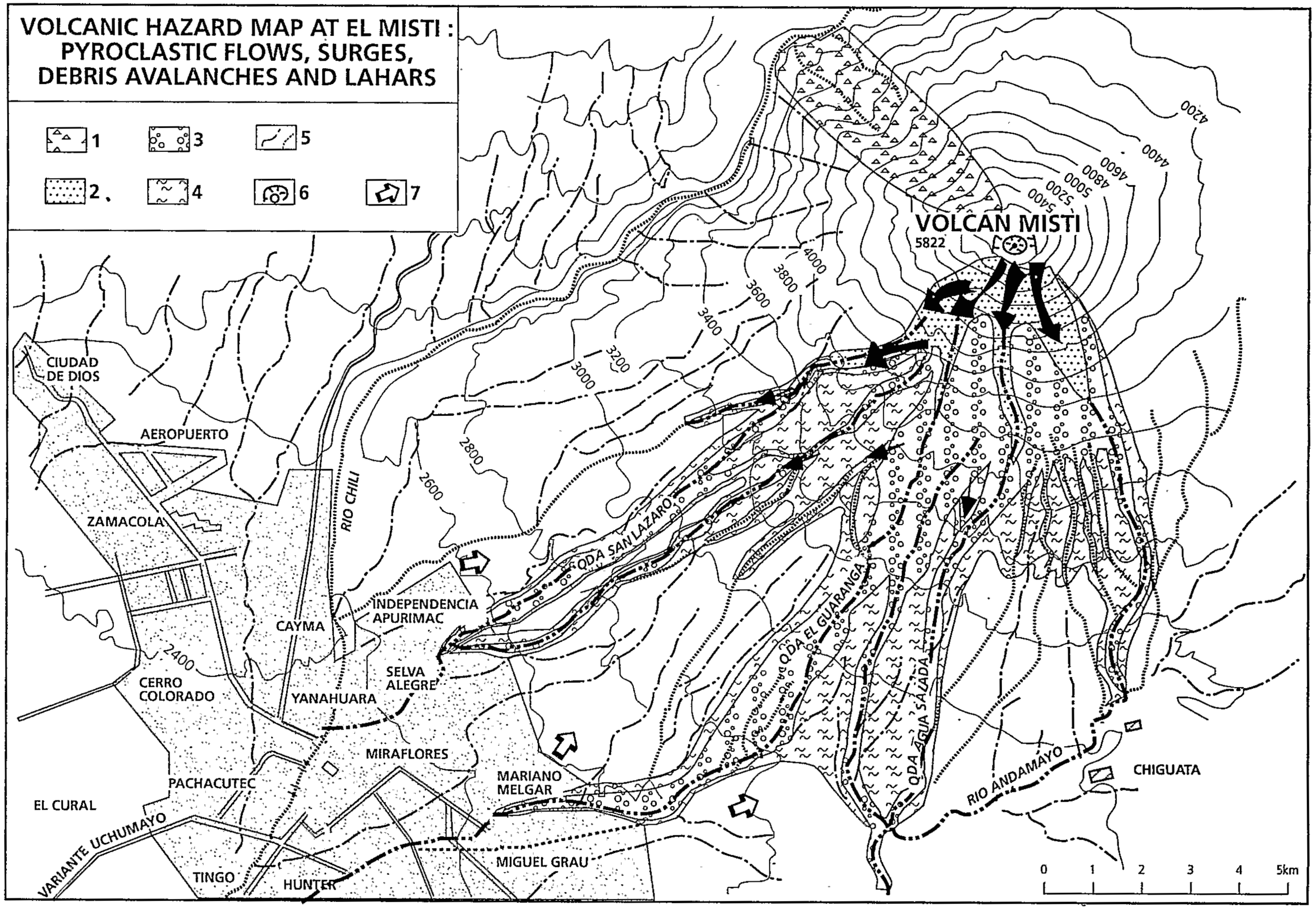


Fig. 13. Sketch map of volcanic hazards at Misti: areas likely to be affected by pyroclastic flows and surges, debris avalanches and lahars, based on the 200 BC–200 AD eruptive episode. Areas likely to be affected by: 1. Rockslide-debris avalanches. 2. Block-and-ash flows. 3. Pumice-rich pyroclastic flows. 4. Pyroclastic surges. 5. Lahars or debris flows (large-scale = heavy dashed lines, small-scale = dotted lines). The crater (6) open towards to S and the rapid extent of the suburbs (7) towards the SW piedmont through the 1990's are also shown.

3) Over the past centuries, lahars, streamflows, and floods have swept down the radial valleys and have devastated the S, SW and SE piedmonts (Fig. 13). For example, lahars as indicated by debris-flow deposits 12 km from the source (Huarangal valley) followed the ignimbrite-forming eruption ca. 2000 years old. This is the area where the suburbs of Arequipa are spreading out at present. If lahars were triggered by heavy rains and meltwater (e.g., due to the flowage of pyroclastic debris on temporary snowfields 7 km^2 in area), the volume of the channeled flows could exceed 4.4 million m^3 and the thickness of deposits 3 to 5 m at the break in slope on the piedmont.

4) Flank failures can occur along fractures on the steep-sided W and S flanks of the volcano. Subsequent debris avalanches may choke the Chili valley (where five hydroelectric stations are located: Fig. 3) and spread out on the S piedmont. A debris avalanche flowing from the cone summit could override the Arequipa depression and the N flank of the batholith, given a H/L ratio reaching a range of 0.1 to 0.11, very close to the average value for volcanic debris avalanches (HAYASHI & SELF 1992). Should H/L equal 0.24 and the volume be small, a debris avalanche would still reach the city suburbs where hummocks are still preserved (Fig. 12).

5 *Summary and conclusion*

The available stratigraphy and the study of the pattern of the eruptive activity of Misti over the past 100,000 years provide five results:

(1) Seven eruptive sequences have successively built up the modern Misti stratocone over the Late Pleistocene ($\leq$ca. 0.3 Ma);
(2) Repeated episodes of growth of lava domes/dome destruction have triggered dome collapse avalanches and block-and-ash flows, including pyroclastic surges. They have alternated with subplinian-Plinian eruptions whose collapsing eruptive columns have released pumice- and lithic-rich pyroclastic flows;
(3) Moderate-scale ignimbrites, corresponding to a differentiated magma of dacite-rhyolite, probably led to the formation of a summit explosive caldera, probably around 47,000–34,000 years ago and ca. 2,000 years ago;
(4) A sustained eruptive regime has delivered at least 20 distinct tephra falls over the past 34,000–47,000 years: Plinian pumice fall occurred on an average 2,000 to 4,000 years and ash fall on every 500 to 1,000 years;
(5) The injection of an andesitic magma (JACQUEMIN et JORON 1984) triggered recent scoria flows and led to the formation of the young crater less than 2,000 yr B.P., and to historical scoria-rich ash falls.

Although the historical events at Misti consist of minor block-and-ash flows and ash falls, the last strong Plinian eruption 2,000 years ago only released an ignimbrite $\geq$ 0.5 km^2. Therefore, considerable hazards remain at Arequipa (Fig. 13): (1) several decimeter-thick Plinian tephra-fall deposits could mantle the whole city; (2) channeled pyroclastic flows could hit the nearest suburbs 12 km away from the vent, and (3) debris flows could be induced on the high-mountain during the wet season (December-March).

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