Boletín de la Sociedad Geológica del Perú v. 93 (2002) p. 45-61

LATE PLEISTOCENE AND HOLOCENE TEPHRO-STRATIGRAPHY AND CHRONOLOGY IN SOUTHERN PERU

J.-C. THOURET [1], E. JUVIGNE [2], J. MARIÑO [3], M. MOSCOL [4], I. LOUTSCH [2], J. DAVILA [3], A. LEGELEY-PADOVANI [5], S. LAMADON [1] & M. RIVERA [3]

[1] *Laboratoire Magmas et Volcans UMR 6524, Université Blaise-Pascal, CNRS et OPGC, 63038 Clermont-Ferrand., France – Fax +33 4 73 34 67 44 ; thouret@opgc.univ-bpclermont.fr*
[2] *Laboratoire de Géomorphologie, Université d'état à Liège, Sart Timan Bât. 12, 4000 Liège, Belgique*
[3] *IGP Instituto Geofísico del Perú, Calle Calatrava 216, Urb. Camino Real, La Molina, Lima 12, Peru*
[4] *Universidad Agraria, Lima, Peru.*
[5] *IRD Institut de Recherche pour le Développement, Centre Ile de France, 34 rue Henri Varagnat, 93170 Bondy cedex, France*

ABSTRACT

Multidisciplinary investigations have found more than 40 tephras over the past 50,000 ^{14}C years in southern Peru.

Late Pleistocene tephras **have been dated on Nevado Sara Sara between ca. 49,200 and 44,000 yr BP and on Yucatan volcano. Around Nevado Coropuna, ashfalls yielded ^{14}C ages of ca. 27,200-37,370 yr BP. Sustained explosive eruptions of the composite Misti cone have produced at least 12 pumice falls during the past 50,000 years.**

Late-Glacial and Holocene tephras. **Two cores extracted from the Laguna Salinas include 7 tephra-fall deposits from Huaynaputina, Misti, and Ubinas over the past 15,000 years. Around the Ticsani domes, a dacitic pumice-fall deposit has been dated ca.11,600 yr BP and ejecta preceding the youngest dome are historical in age. Ubinas has produced several tephra falls; two widespread plinian pumice-fall deposits >7840 yr BP and ca. 980 yr BP-old, of a volume >1 km^3 each, are linked to the formation of the summit caldera. A peat sequence in a peat-bog nearby Nevado Sabancaya includes 4 ash-fall layers from Sabancaya, Ampato, Misti, and Huaynaputina.**

Historical tephras. **The last explosive episode ca. 2,300-2,050 yr BP at Misti produced pumice-fall and flows 0.75 km^3 in volume. Spanish chronicles refer to an AD 1440-1470 eruption, which produced the small-volume 'Pachacútec ash'. The AD 1600 Huaynaputina plinian eruption produced the most widespread and voluminous (12 km^3) pumice-fall deposit in the Andes in historical times. Vulcanian eruptions of Nevado Sabancaya (1990-1998) dispersed a small volume of ash.**

In sum, 1) heavy ash fall can recur every 500 to 1500 years on average; 2) voluminous pumice fall can happen every 2000 to 4000 years on average; 3) three plinian eruptions occurred over the past 2,300 years and the large-scale eruption of Huaynaputina caused havoc and famine all over southern Peru.

RESUMEN

Investigaciones multidisciplinarias han puesto en evidencia más de 40 tefras pertenecientes a los últimos 50,000 años ^{14}C.

Tefras del Pleistoceno tardío. **Se han datado tefras entre 49,200 y 44,000 años BP en los volcanes Sara Sara y Yucamane. Las caídas de cenizas del Nevado Coropuna arrojaron edades ^{14}C de 27,200-37,370 años BP. Erupciones explosivas sostenidas del volcán Misti, han producido por lo menos 12 caídas de pómez durante los últimos 50,000 años.**

Tefras de la Última Glaciación y del Holoceno. **Dos "cores" (testigos) de turba extraídos de la Laguna Salinas, registran 7 depósitos de caídas de tefras en los últimos 15,000 años, pertenecientes a los volcanes Huaynaputina, Misti y Ubinas. Alrededor de los domos del Ticsani, un depósito de caída de pómez dacítico se ha datado en 11,600 años BP y la erupción que precedió al domo más joven es de edad histórica. El Ubinas ha producido varias caídas de tefras; dos depósitos extensos de caídas de pómez entre 7840 y 980 años BP, de más de 1 km^3 de volumen cada uno, ligados a la Formación de la caldera de la cumbre. Una secuencia de turba próxima al Nevado Sabancaya, incluye 4 caídas de cenizas de los volcanes Sabancaya, Ampato, Misti y Huaynaputina.**

Tefras históricas. **La erupción sub-pliniana de 2,300-2,050 años BP del Misti, produjo un volumen de 0.75 km^3 de caídas y flujos de pómez. Cronistas españoles refieren un evento entre los años 1440 a 1470 D.C., que produjo la "ceniza Pachacútec" de pequeño volumen. La erupción pliniana del año 1600 D.C., del volcán Huaynaputina, originó el más extenso y voluminoso (12 km^3) depósito de caída de pómez en los Andes en épocas históricas. Las erupciones vulcanianas del Nevado Sabancaya (1990 y 1998), dispersaron cenizas de limitado volumen.**

En suma, 1) caídas de cenizas pueden repetirse cada 500 a 1500 años en promedio; 2) caídas voluminosas de pómez pueden suceder cada 2000 a 4000 años en promedio; 3) tres erupciones plinianas ocurrieron en los últimos 2,300 años; una erupción similar al del año 1600 del volcán Huaynaputina, causaría estragos en el sur del Perú, oeste de Bolivia y norte de Chile.

INTRODUCTION

Here we present results obtained in the framework of the TESSOPE project, Tephro-Stratigraphy of Southern Peru, funded by the INQUA Commission on Tephrochronology and Volcanism. Multidisciplinary investigations of stratigraphic sections and cores extracted from peat-bogs and lakes in the Western Cordillera (Figs. 1-3), enable us to find out more than 40 tephras over the past 50,000 ^{14}C years (Table I).

TEPHROSTRATIGRAPHY AND CHRONOLOGY IN SOUTHERN PERU, NORTH-CENTRAL ANDEAN VOLCANIC ZONE

TABLE 1

TIME PERIOD	VOLCANOES	SARA-SARA	COROPUNA stratovolcano and domes	ANDAHUA-HUAMBO, ORCOPAMPA monogenic field	AMPATO MASSIF and NEVADO SABANCAYA lava domes	EL MISTI STRATOVOLCANO	UBINAS STRATOVOLCANO	HUAYNAPUTINA VOLCANIC CENTER	TICSANI CUMULO-DOMES	TUTUPACA	YUCAMANE
HISTORICAL	AD 1500 – Incaïc – 2000 yr BP			AD 1400-1600 af, Chilcayoc cone Andahua group	1990-98 ph / phmag / vulc 1750 - 1784; af AD 1460 ± 30 ?; ≥1680 ± 30 (HP) peat-bog	1784-87 1677 ph; AD 1440-80 af; AD 1304-1398 af; AD 655-865 af	active since 1552; af, ph, phmag 1677 sf; 980 ± 60 P, pf	Feb-March 1600 pf, PF, ps (dacite)	Sp, pf, af	1902,1862 **1802** 1780 pf, af	1787
HOLOCENE	2000 yr BP – 5000 – 10,000			2650 ± 50 sf. Keyocc cone; <2810-2970 ± 50 af; 4060 ± 50 af Ticsho and Puca Mauras cones Andahua group and Huambo; 8770 ± 50 Andahua group and Huambo	voluminous block-lava flows <5440 ± 40 lf southwest flank; 8520 ± 80 af	AD 430 - 160 BC P, pf, PF 2300 ± 60 PF <2370 ± 90 af; 2770 ± 190 df, PF; 3800 ± 50 af; 4750 ± 40 ps; 5200 ± 80 ps; 6390 ± 50 PF; 8140 ± 80 PF	Debris-avalanche deposit >3670 ± 60; >7480 ± 40 P, pf	<7480 ± 40 P, pf; 9700 ± 190 P, pf	three domes	Tutupaca dome collapse PF	
LATE GLACIAL	10,000 – 15,000	P, pf		Orcopampa group of subdued cones and lava flows	voluminous block-lava flows	~ 10,600 ± 240; TP1 pf, TP2 pf, TP3 da pf; ~ 13,640 ± 330	11,280 ± 70; 11,480 ± 220 pf, PF, ps; 14,690 ± 200		11,600 ± 80 P, pf	pf	
LATE PLEISTOCENE	15,000 – 20,000					TP4 and. pf: contempory to glacial retreat					
	20,000 – 25,000					20,960 ± 380/360 pf; 24,840 ± 480 PF					
	25,000 – 30,000		27,200 ± 300 af								
	30,000 – 35,000					31,200 ± 1330 PF; 33,400 ± 2800 / 2160 PF; 33,900 ± 3200 / 2300 PF					
	35,000 – 40,000		37,370 ± 1010 / 1160 af			38,300 PF; 39,680 ± 1370 / 1170 PF; 40,200 ± 820/740 PF					
	40,000 – 45,000	>44,500				43,970 ± 1180 / 1030 PF					44,000 ± 2130 / 2910 pf
	45,000 – 50,000 yr BP	pf; >49,200				47,350 ± 2100 / 1700 PF; 48,640 ± 2270 / 1170 PF					

af: ash fall; pf: pumice fall; PF: pyroclastic flow; ps: pyroclastic surge; sf: scoria flow; ph: phreatic; phmag: phreatomagmatic; st: strombolian vulc: vulcanian; sp: subplinian; P: plinian; and: andesite; da: dacite

(shaded box) voluminous tephra-fall deposit ≮ km 3

Table 1. Tephrostratigraphy and chronology in southern Peru, North-Central Andean Volcanic Zone.

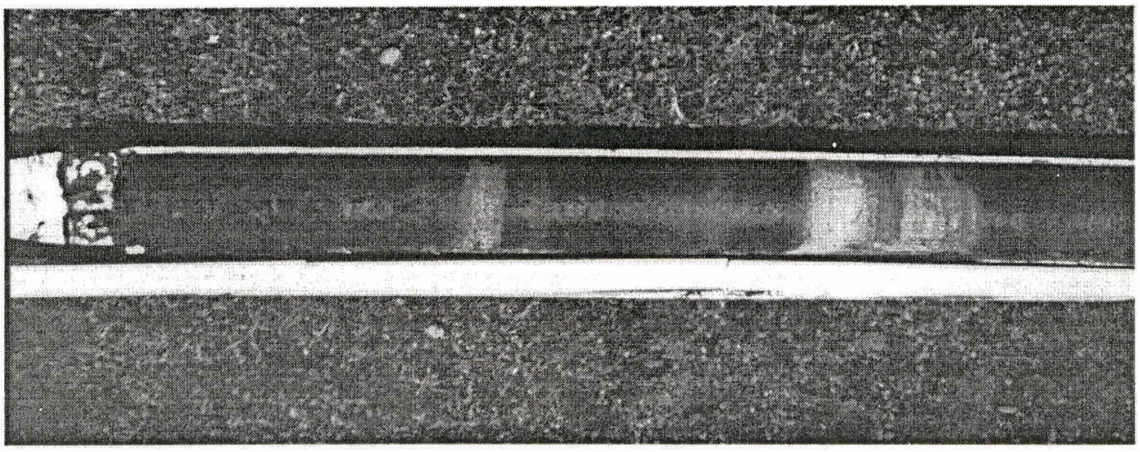


Photo 1: Peat core 50 cm long extracted from a peat-bog 21 km north of Ubinas (Carmen de Chaclayo). The 3-cm-thick whitish layer is the AD 1600 dacitic ash of Huaynaputina volcano whose vent is located 51 km due south (photograph: J.-C. Thouret).
Photo 2: Nevado Coropuna northern flank, showing the glacial-shaped valley of Qda. Cavalca, 4700 m asl. COR 100 was extracted from the peat-bog and COR 200 from above the rock bar (photograph: J.-C. Thouret).

The TESSOPE project encompasses five research themes: (1) the stratigraphy of tephra measured in sections and drillings in peat-bogs and lakes (photos 1 and 2); (2) the sedimentology, mineralogy, and geochemistry of tephra based on grain-size and mineral analyses, and glass chemistry using microprobe; (3) the chronology of tephra and peat layers based on the ^{14}C and TL methods, and the Ar-Ar dating of lavas; (4) the stratigraphy of glacial deposits and peat layers interbedded with tephra; (5) the Holocene and Late-glacial paleo-environments of the Western Cordillera and the Altiplano inferred from pollen and diatoms found in peat cores.

The tephrostratigraphy enables us to reconstruct the frequency of recent eruptions in Southern Peru and to outline the areas potentially affected by future eruptions of ten volcanoes located within 20-150 km distance from Arequipa (800,000 people, second Peruvian city), Moquegua and Tacna (200,000 people each), and many towns (Figs.1-3). As much as six volcanoes, Huaynaputina, El Misti, Ubinas, Nevada Sabancaya, Tutupaca, and Yucatan, have been active since the Spanish conquest in 1520.

VOLCANOES AND VOLCANIC FIELDS IN SOUTHERN PERU, CENTRAL ANDEAN VOLCANIC ZONE

Table 1 encompasses 40 tephra over the past 50,000 years, with emphasis on 8 widespread (>1,000 km^2) and voluminous (= 1 km^3) pumice-fall deposits.

The tephra have been found out around ten stratovolcanoes or volcanic fields in the western Cordillera, from northwest to southeast (Figs. 1-3):

1) the dormant Nevado Sara Sara (5600 m), 180 km WNW of Arequipa;
2) the dormant dome complex of Nevado Coropuna (6380 m) (Fig. 4);
3) the monogenetic field of the Orcopampa, Andahua and Huambo areas at mid-distance of Nevados Coropuna and Ampato-Sabancaya (Fig. 8);
4) the active Nevado Sabancaya volcano (5980 m) in the Ampato massif (Figs. 12 and 13);
5) the fumarolic El Misti volcano (5820 m) whose crater lies 17 km of the city of Arequipa (Fig. 7);
6) the Laguna Salinas (4300 m) at mid-distance of El Misti and Ubinas volcanoes (Fig. 8);
7) Ubinas (5600 m), the most active volcano in Peru in historical times (Fig. 11),
8) Huaynaputina (4600 m) which produced the largest eruption in historic times in the Andes (Figs. 14 and 15);
9) The youthful domes of Ticsani (5470 m), east of Arequipa and north of the city of Moquegua (Fig. 10)
10) the fumarolic Tutupaca volcano (5815 m) and the historically active Yucamane volcano (5450 m) NE of Moquegua.

LATE PLEISTOCENE TEPHRAS

Late Pleistocene tephra have been dated on the west flank of Nevada Sara Sara between >49,200 and >44,500 yr BP (nearby Parinacota lake) and on the south flank of Yucamane (ca. 44,000 yr BP) nearby Candarave. They have been found also around Nevada Coropuna but El Misti was probably much more active at that time (Table 1).

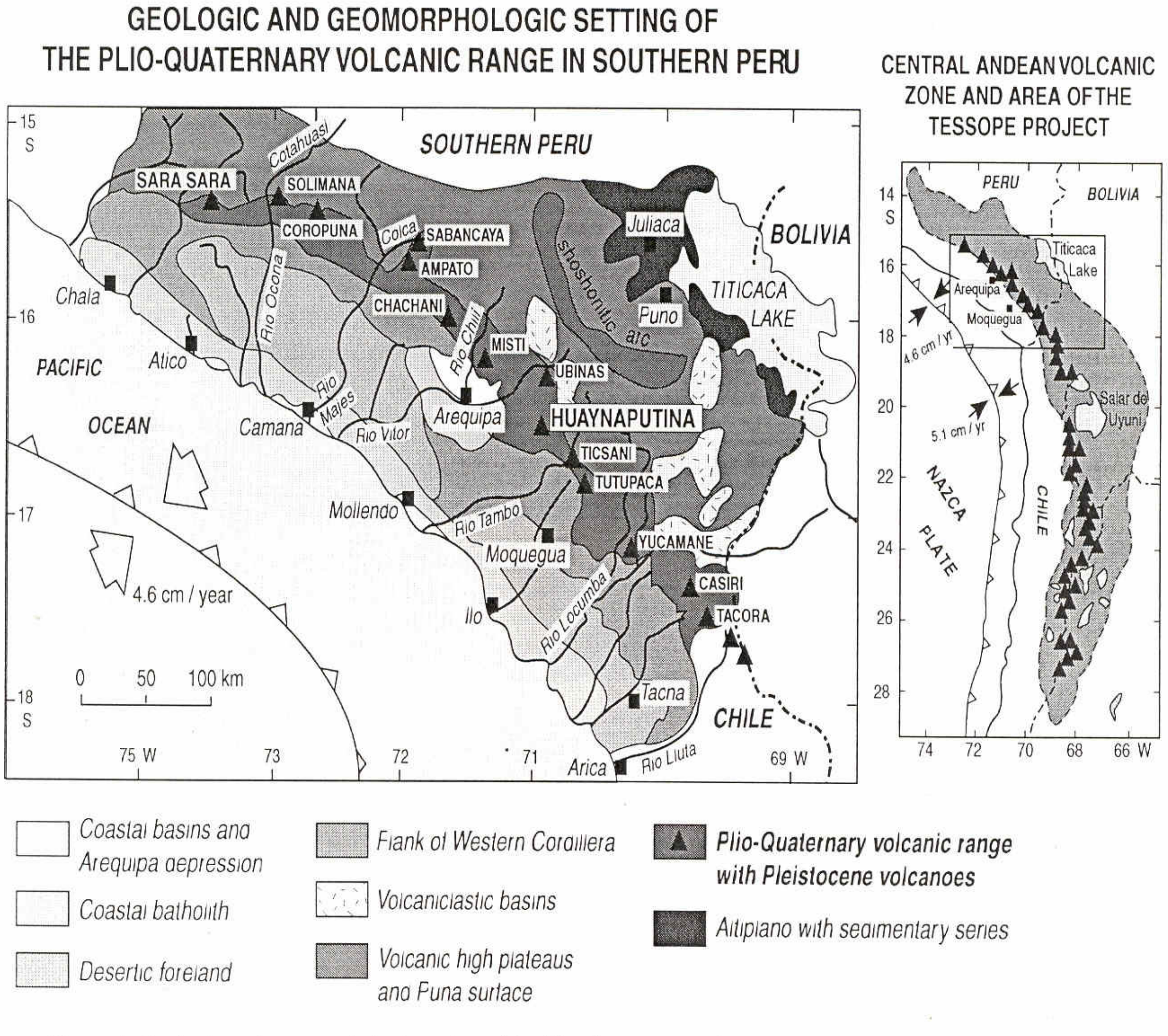
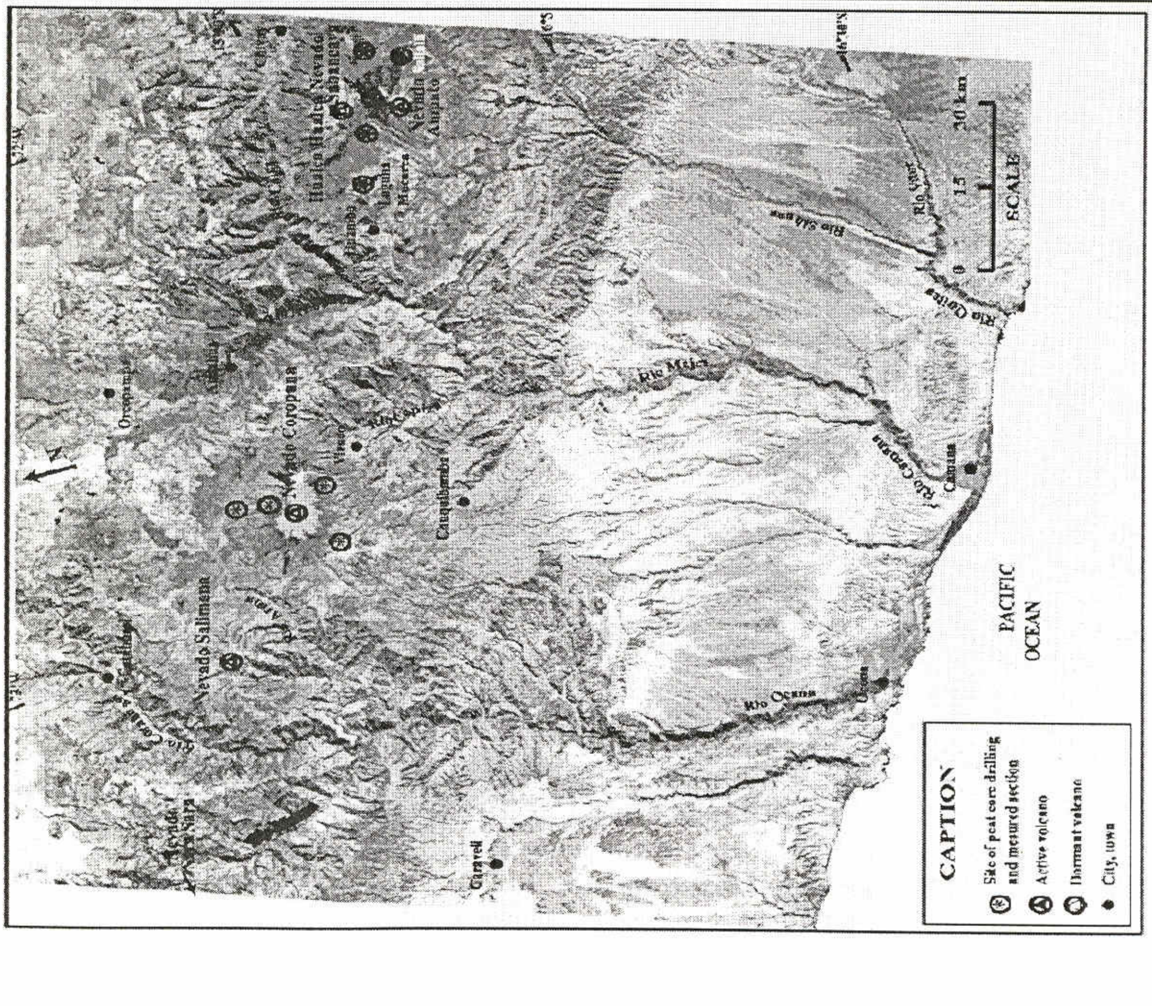


Figure 1: Geologic and geomorphologic setting of the Plio-Quaternary volcanic range in southern Peru. Inset map: Central Andean Volcanic Zone and area of the TESSOPE Project.



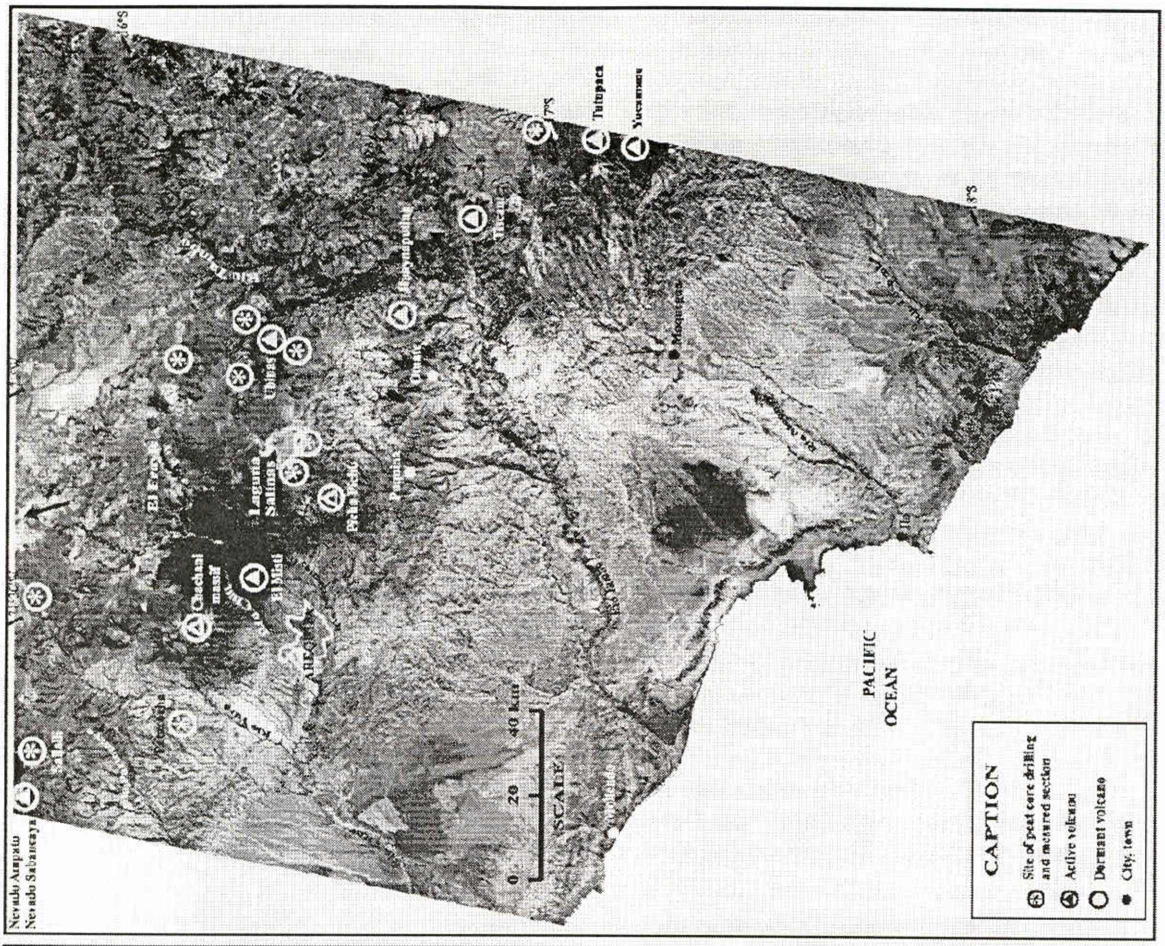


Figure 2: (left) Landsat image as of 1987 showing the western area under study in southern Peru.
Figure 3: (right) Landsat image as of 1987 showing the eastern area under study in southern Peru.

Nevada Coropuna has probably been dormant since the Late Glacial

The ice-clad domes and stratovolcano of Nevada Coopuna 6380 m high have grown on ignimbrites of Tertiary age (photo 2). Coropuna has apparently not been active during since the Late Glacial but three youthful lava flows, not dated yet, filled glacial-shaped valleys on the west, northeast and southeast flanks (Fig. 4; Lamadon, 1999). One ashfall in a soil section outside of the moraine field of the Last Glacial Maximum yielded a ^{14}C age of ca. 27,200-37,370 yr BP. No conspicuous tephra has been discovered in the three peat cores extracted from high-altitude peat bogs which span the entire Holocene period (photo 2). The base of the longest peat core (COR 300, Fig. 5) dated at 10,090 ± 150 yr BP shows that glaciers have melted away before the Holocene at 4300 m asl. on the south flank of Coropuna.

The pollen spectrum elaborated by M. Moscol (Fig. 6) on the basis of the 10-m-long peat core is dominated by grassland types (*Gramineae*) and contains little contribution from the Andean cloud forest.

The pollen diagram shows five major pollen zones:

- Zone I begins with pronounced decreases in *Gentianaceae* type and *Azorella* (moisture-loving taxa), suggesting a dry and cold climate. Then increasing local wetness is indicated by the abrupt appearance of cf. *Juncaceae*.
- Zone II can be interpreted as the warmest period of the diagram due to the great variety and high frequency of pollen taxa. Moist conditions can be inferred at the upper part of this zone as it coincides with the highest percentages of *Gentianaceae* type, *Azorella* and *Polylepis*.
- In Zone III, local pollen continues to occur but in the upper part, drier conditions seem responsible for the highest level of *Chenopodiaceae* and the lowest levels of moisture indicators.
- Zone IV shows a sudden presence of cf. *Cyperaceae*. This could signal a especially wet interval. Also *Gramineae* and *Compositae* percentages begin to decline, suggesting a *climatic perturbation or increased cultural disturbance* as we assume that this period could already represent the Late Holocene.
- In Zone V, the *Compositae* become dominant, indicating relatively cold and not very wet conditions, as experienced today in the region. The highest peak of *Myrtaceae* is a fact we cannot easily explain (as well as its former two high values), since we lack precise ecological information and this taxon has elements in both the puna and the Andean cloud forest. The possibility of increased anthropogenic activity should also be taken into consideration.

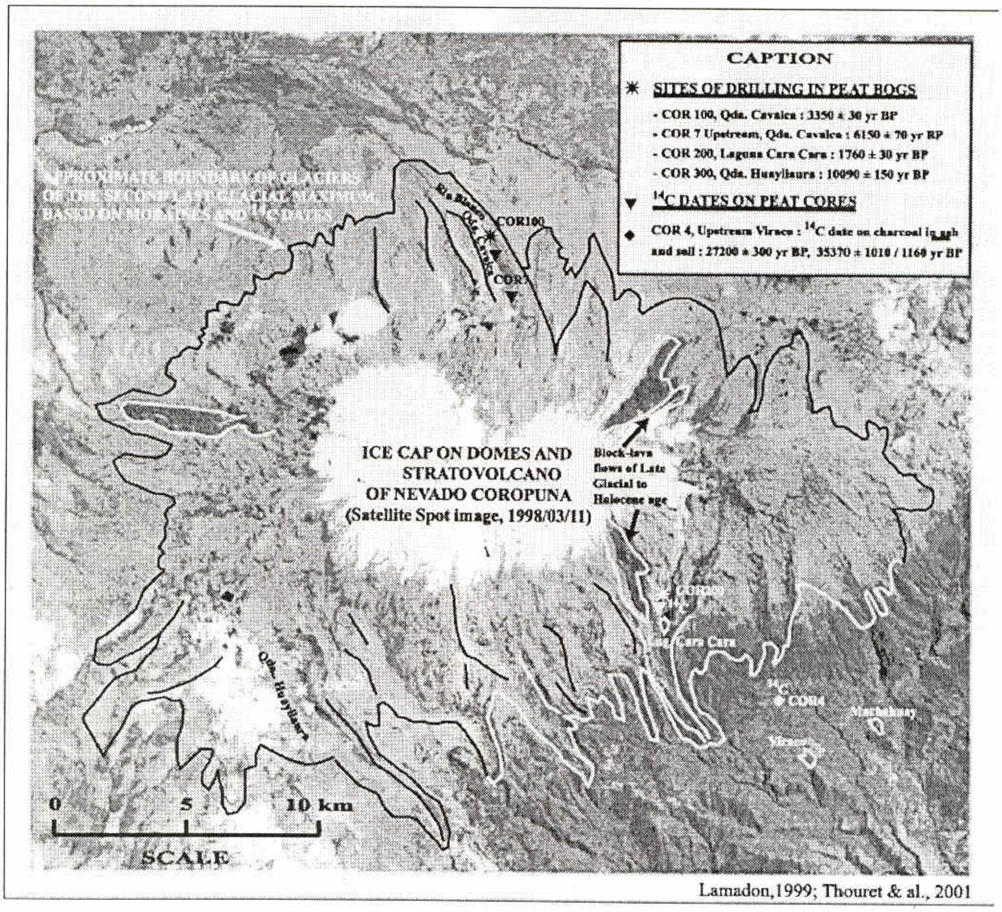


Figure 4: Spot scene as of 1998 showing the area of Nevado Coropuna. The extent of the Late- Glacial glaciated area has been outlined. The sites of drilled peat cores, measured stratigraphic sections and ^{14}C datings have been shown.

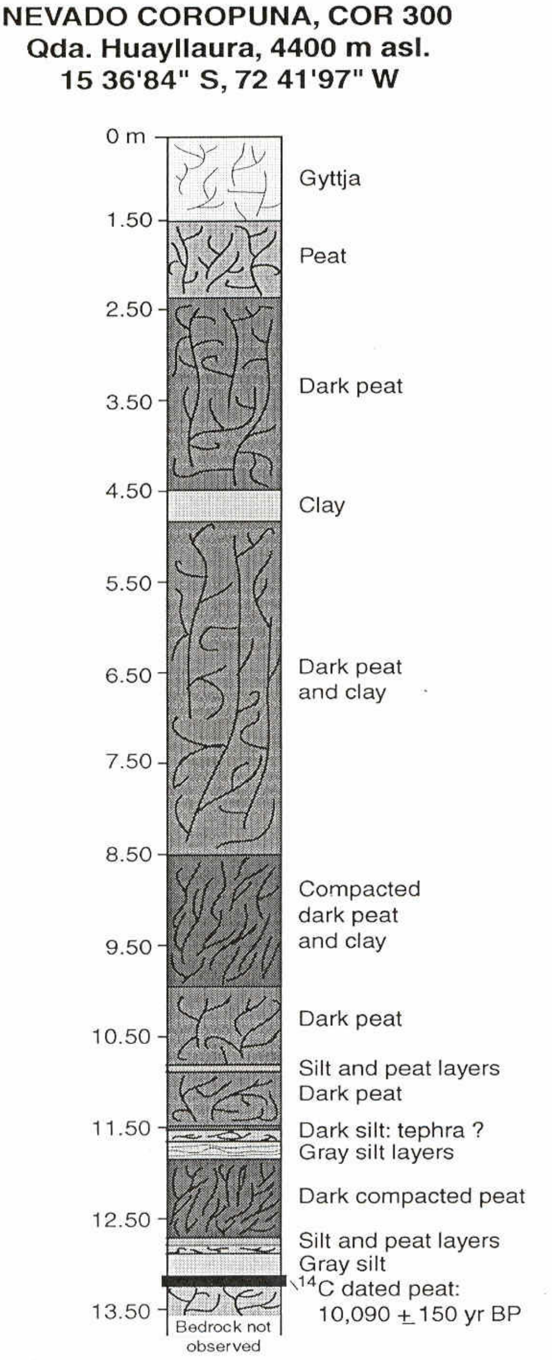


Figure 5: Stratigraphic section on the south-southwest flank of Nevado Coropuna (peat core COR 300), Quebrada Huayllaura, 4,400 m asl. (located in Fig. 4).

Voluminous and frequent tephras at El Misti

The historically active El Misti volcano poses considerable threats to the 750,000 people of the city of Arequipa whose center lies 17 km from the summit (5820 m asl.). The composite El Misti edifice comprises a stratovolcano termed Misti 1 (ca. 833 - 112 ka), partially overlapped by two stratocones termed Misti 2 and 3 (=112 ka), and a summit cone Misti 4 =11 ka (Thouret et al.,1999a, 2001a; Suni, 2000).

The study of the geology and tephro-stratigraphy of El Misti (Fig. 7, photo 3) shows that:

1) Seven eruptive periods have successively built up Misti 2 - 4 during a period of ca. 112 ka.
2) Repeated episodes or growth and destruction of domes have triggered dome collapse avalanches and block-and-ash flows, including pyroclastic surges. The dome episodes have alternated with plinian eruptions which produced pumice flows and falls.
3) Nonwelded dacitic ignimbrites with a bulk volume of 4 - 6.5 km^3 probably reflect large explosive eruptions that may have led to an incremental caldera collapse between ca. 50,000 - 40,000 yr BP, and again to a summit caldera between ca. 13,700 and 11,300 yr BP.
4) Misti 4 erupted less evolved andesites with a distinct mineral suite compared to that of Misti 2 and 3. Scoria-flow and fall deposits of Misti 4 are related to the formation of the summit caldera ca. 13,700 - 11,300 yr BP, of the nested craters, and of the AD 1440 - 1470 event (Chávez Chávez, 1992).
5) Sustained explosive eruptions have delivered at least 12 pumice falls during the past ca. 50,000 years. (Sub)plinian pumice falls occurred every 2000 to 4000 years on average and ashfalls occurred every 500 to 1500 years on average.
6) A subplinian and ignimbrite-forming eruptive episode occurred at El Misti between 2,300 and 2,050 yr BP (400 BC - 340 AD) that emplaced a pumice-fall deposit 20-30 cm thick on the area where the city of Arequipa has grown. Pumice-flow deposits 0.5-1 km^3 in bulk volume were channeled on the southern slopes of El Misti and travelled 8-12 km downvalley, an area where the more recent suburbs of Arequipa are being built on (Fig. 7).

LATE-GLACIAL AND HOLOCENE TEPHRAS

The recent monogenetic field of Orcopampa-Andahua and Huambo

In the volcanic field of Andahua-Orcopampa (Fig. 8) and Huambo, the strombolian cones and their "aa" lava flows of mafic andesite composition belong to four generations:

1) Late Pleistocene subdued cones in the Orcopampa area, built up on lava-flow bedrock of 0.5 to 0.26 Ma;
2) early Holocene cones in Huambo and Andahua areas;
3) middle to late Holocene cones, from ca. 4050 yr B.P. (Ticsho cone) to ca. 2750 yr BP (Mucurca tephra found in the Laguna Mucurca, Fig. 12), and;
4) historical cones like the Chilcayoc ones. These fresh strombolian cones produced a historical ashfall ca. 1400-1600 AD which mantled the populated valley of Andahua and Ayo (Fig. 8).

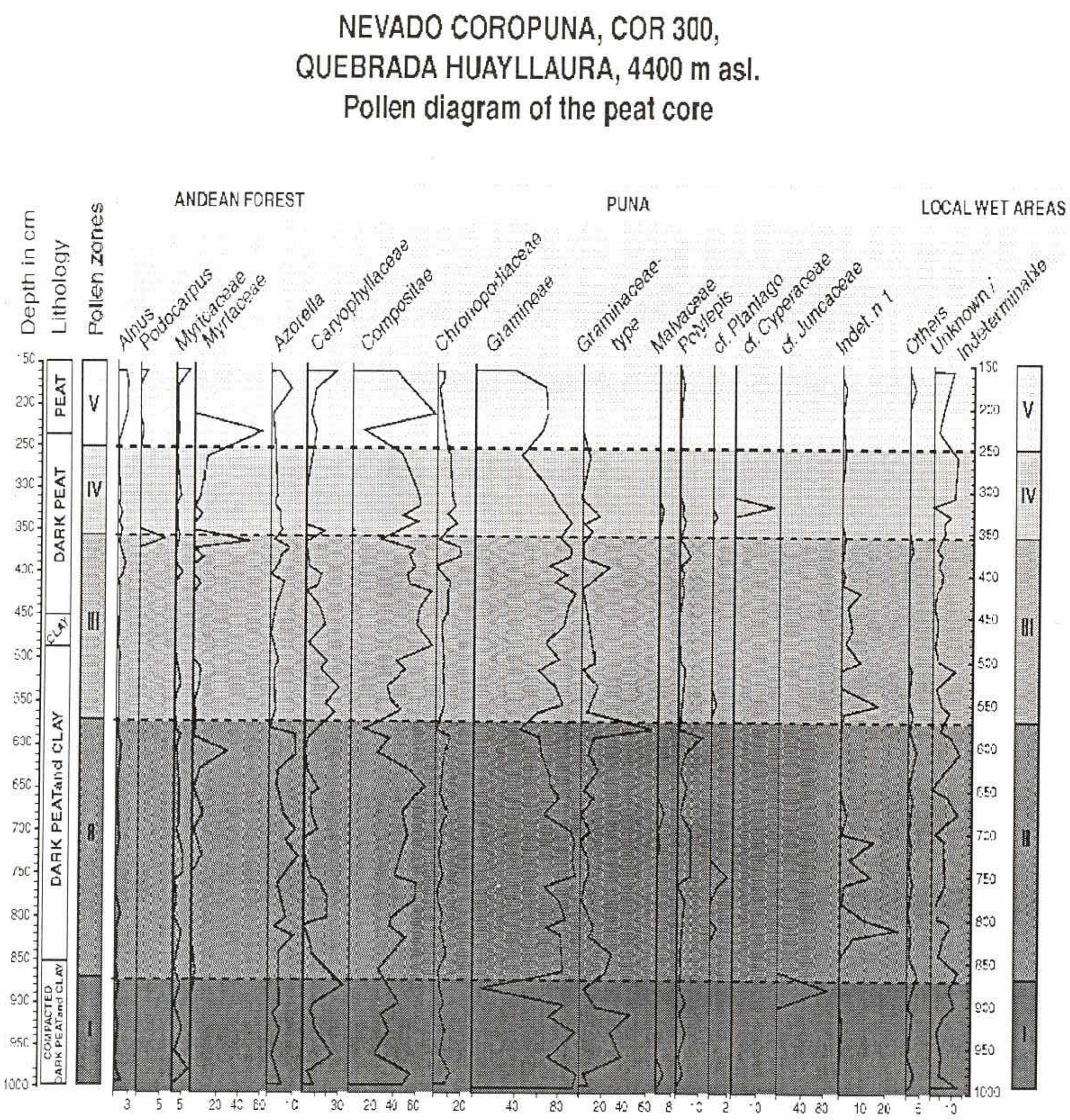


Figure 6: Pollen diagram established by M. Moscol, from the peat core COR 300, Nevado Coropuna (located in Figs. 4 and 5).

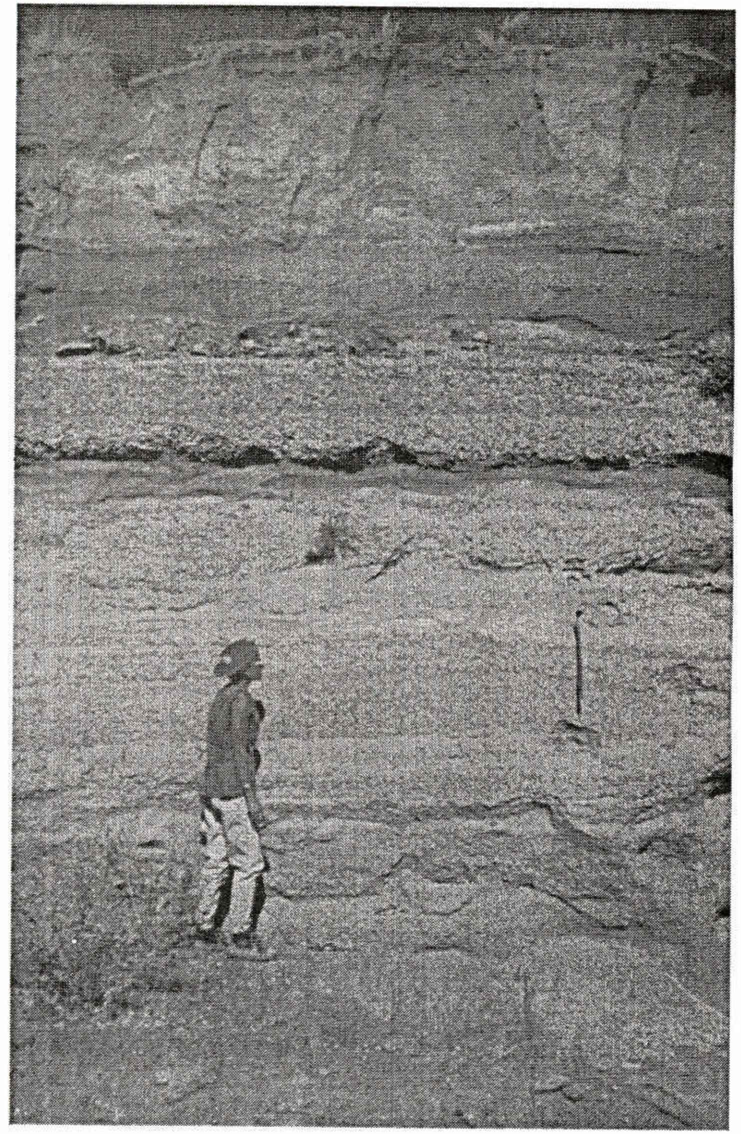


Photo 3. Section 8 km west of the Misti summit showing 4.5-m-thick plinian pumice-fall, surge, and ashfall deposits of the late-Glacial and Holocene group 4 (photograph: J.-C. Thouret)

Seven Late-Glacial and Holocene tephra in and around the Laguna Salinas

Two cores were extracted from the *salar* of Laguna Salinas located in a volcano-tectonic depression 35 km east of Arequipa, which acts as a sediment trap at 4,300 m elevation (Fig. 9A). Two measured road sections yielded additional stratigraphic relationships in nearby roadcuts (km 101 and 103; Fig. 9A,B). Juvigné et al. (1997) show that the cores and sections encompass the past 15,000 years and include 7 tephra-fall deposits from Huaynaputina, Misti, and Ubinas. Around the Laguna Salinas salar, TP1 to 4 are andesitic pumice falls (of Misti and/or Ubinas) contemporary with glacier retreat ≥ 14,690 yr BP, while a dacitic ashfall LS3 probably of Huaynaputina is dated ≥ 9,700 yr BP (Fig. 9C). One pumice-fall is linked with the 2,300-2,050 yr BP-old eruption of El Misti. The uppermost tephras are the distal black ashfall LS2 from El Misti's 1400's event and the whitish dacitic ash T.HP from the large-scale AD 1600 Huaynaputina eruption (Fig. 9C,D). Additional studies of pollen and diatoms indicated that the Holocene period was drier but less cold than the semi-arid and cold Late Glacial period at this elevation.

DEPOSITS OF THE AD 1440 - 1470 VULCANIAN EVENT AND OF THE ca. 2,300 - 2,050 yr BP SUBPLINIAN ERUPTIONS AT EL MISTI VOLCANO

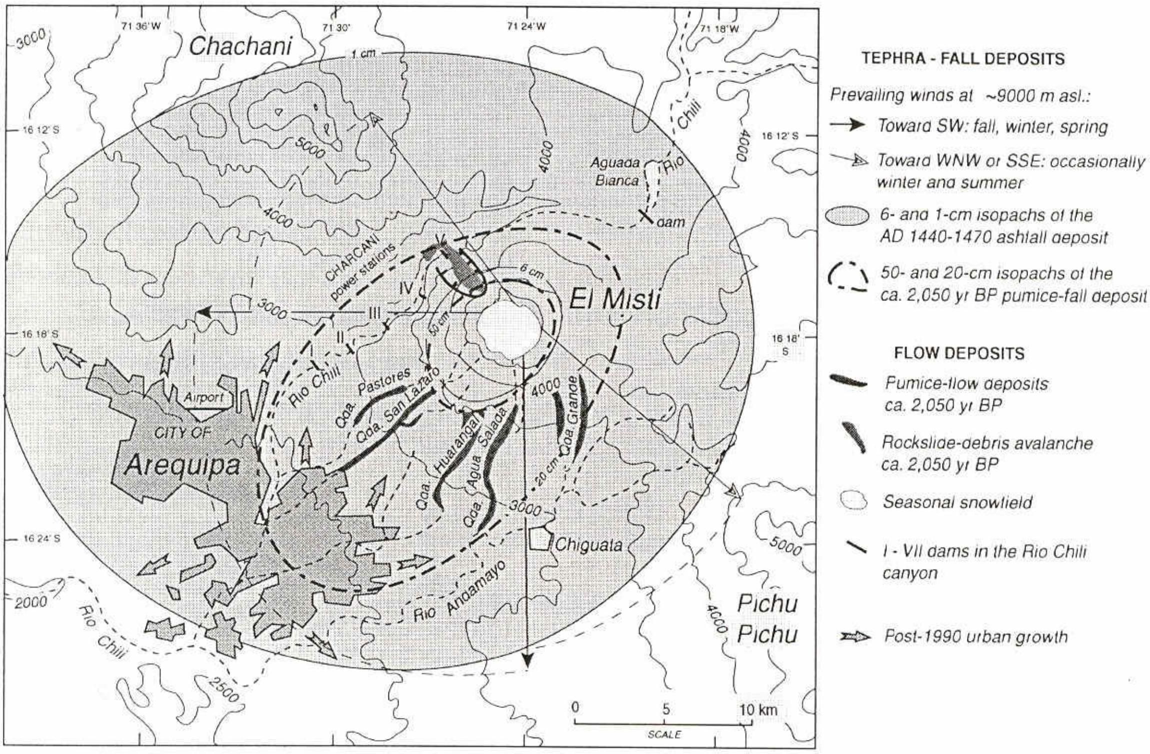


Figure 7: Deposits of the AD 1440-1470 AD vulcanian event and of the ca. 2,300-2,050 yr BP subplinian eruptions at El Misti volcano (after Thouret et al., 1999a, 2001a).

Two recent pumice falls of the Ticsani domes

The subplinian "gray" dacitic pumice fall whose dispersal is shown on Fig. 10 has been dated at ca. 11,600 yr BP. We estimate the volume to be about 0.4 km^3 and a 16-km high eruption column (Mariño, 2001). The three youthful Ticsani domes follow a SSE-NNW trend on a horseshoe-shaped scar formed by a flank failure towards the west. The third, youngest dome filled a crater whose ejecta are phreatomagmatic bombs and brown pumice scattered around the summit. As the ejecta overlie the 1600 AD Huaynaputina ash, the last explosive events at Ticsani are probably historical in age.

Recurrent explosive activity and tephras of Ubinas

Ubinas is the most active volcano in southern Peru with at least 17 small events reported since 1552 (Rivera, 1998; Rivera et al., 1998). Modern Ubinas < 250 ka has been built on an older stratovolcano. The lava flows of modern Ubinas have been truncated by a summit caldera at the transition Late Pleistocene/ Holocene.

The explosive activity which characterizes the most recent Ubinas behaviour produced several ashfalls and pumice falls, including two widespread plinian pumice-fall deposits towards the south, SW and SE of the edifice (Fig. 11). The dacitic pumice-fall deposit >7840 yr BP and the most recent plinian pumice-fall of dacitic and rhyolitic composition, ca. 980 yr BP old, are 4 m thick 6 km south of the vent and as much as 70 cm thick 25 km away from the volcano. Both pumice falls, rich in lithics and exceeding 1 km^3 in bulk volume, may be linked to the formation of the summit caldera.

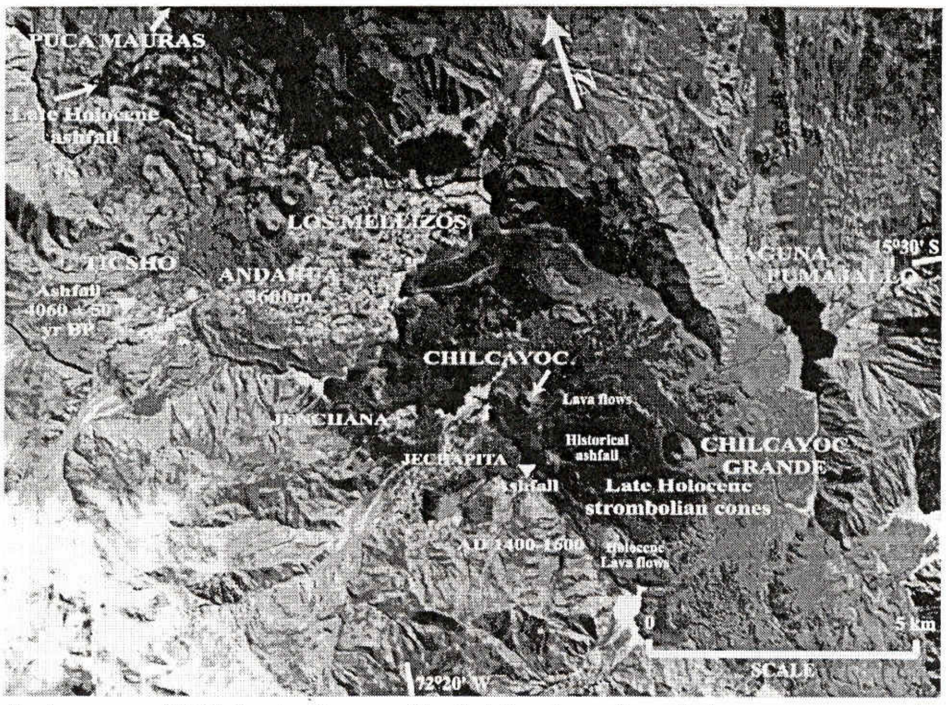


Figure 8: Spot scene as of 1997 showing the area of the Andahua-Ayo valley, which encompasses several strombolian cones and extensive lava flows of late Pleistocene and Holocene age.

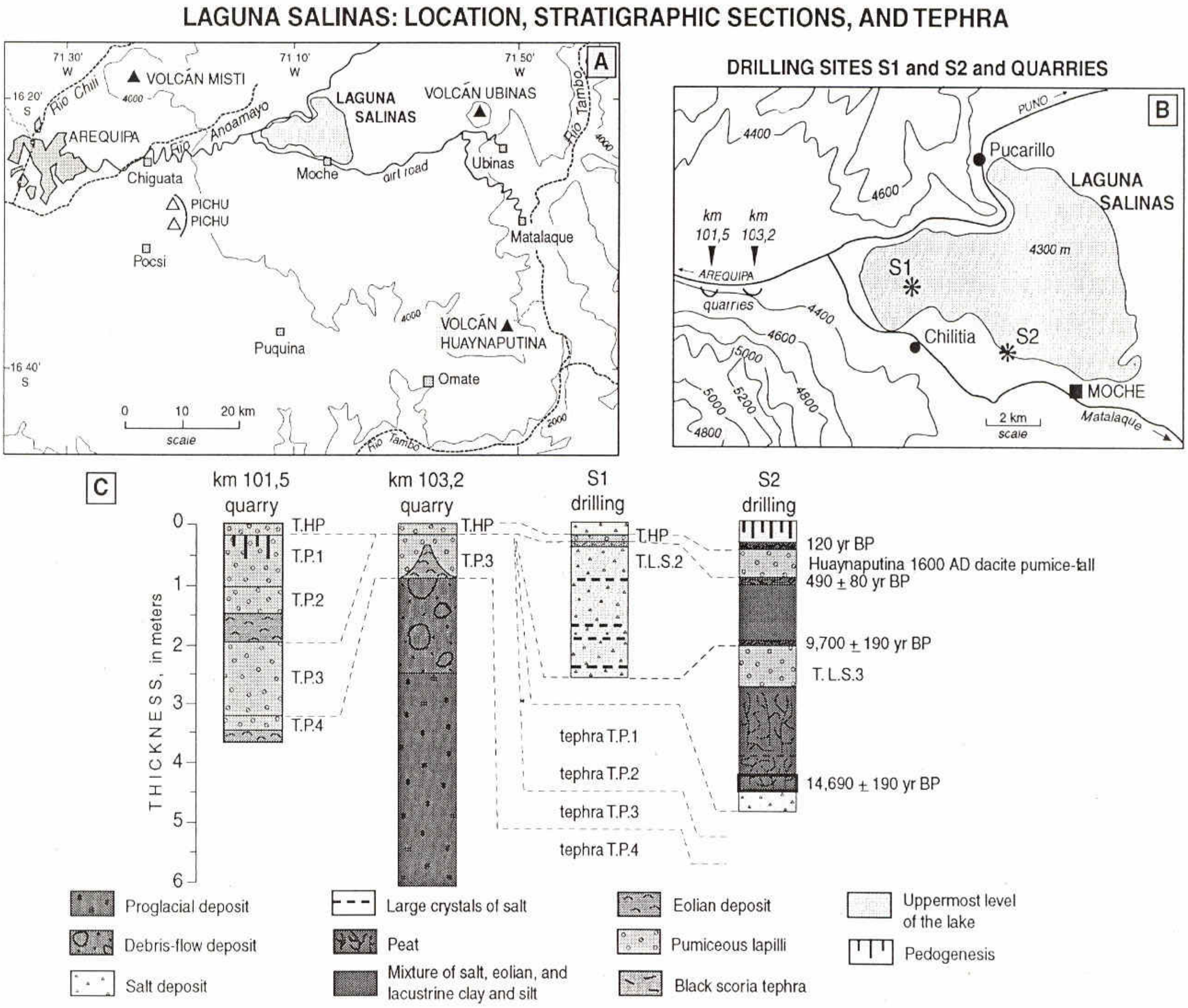


Figure 9: Laguna Salinas 35 km east of Arequipa: location, stratigraphic sections, and tephras (after Juvigné et al., 1997).

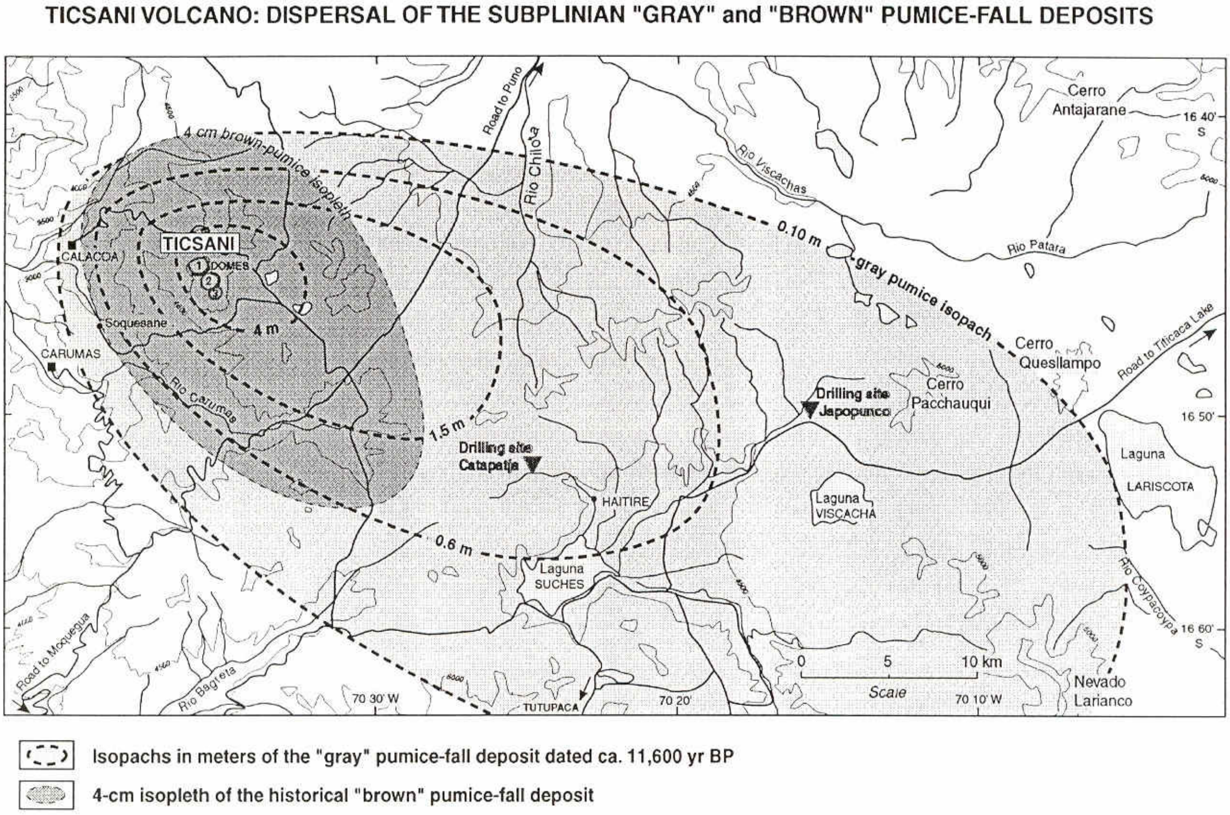


Figure 10: Ticsani volcano: dispersal of the subplinian "gray" and "brown" pumice-fall deposits (after Mariño, 2001)

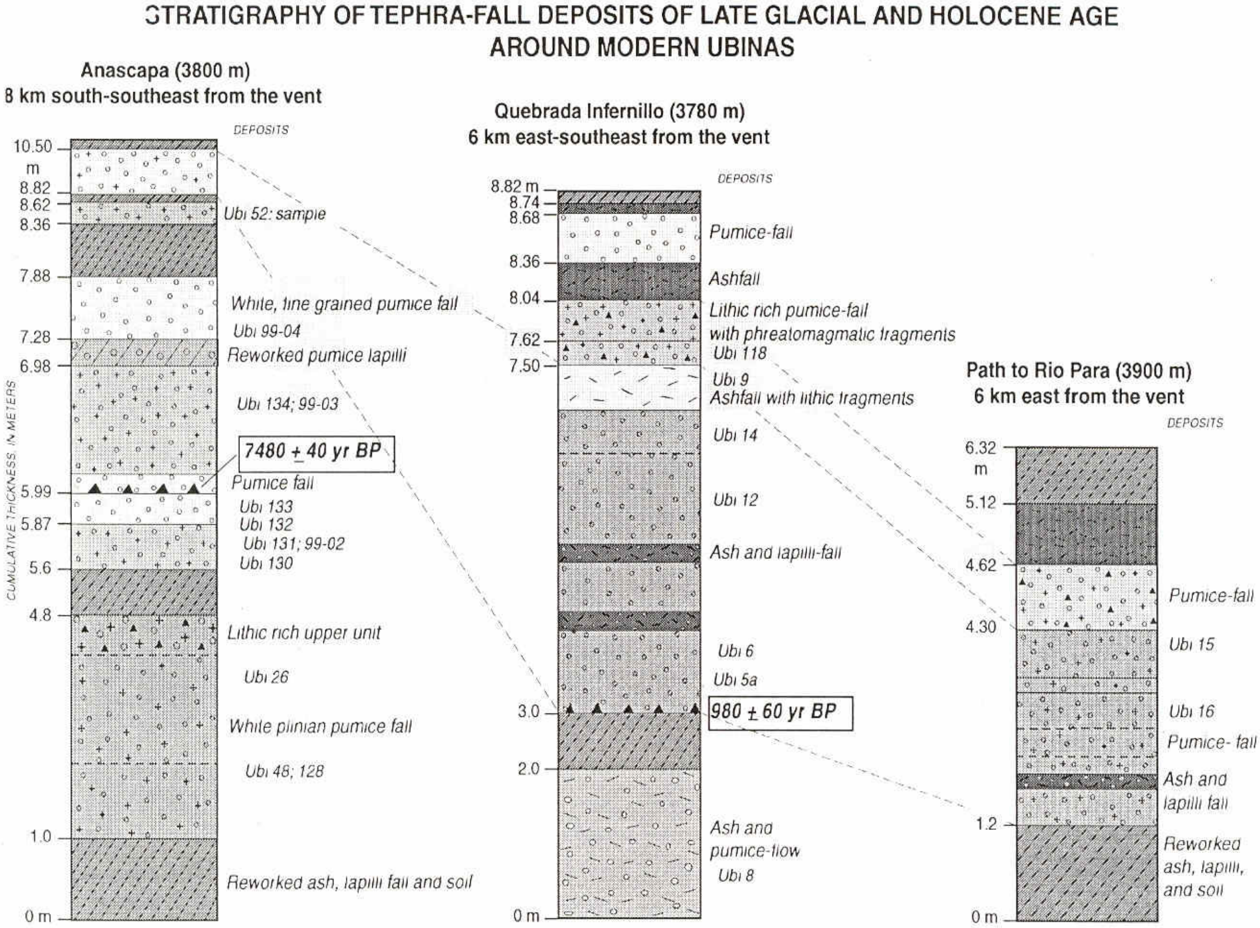


Figure 11: Three stratigraphic sections of tephra-fall deposits of late Glacial and Holocene age around Modern Ubinas (after Rivera et al., 1998)

Holocene eruptive activity of Nevado Sabancaya and the Sallalli peat-bog

The ice-clad, active Nevado Sabancaya (5980 m, photo 4) forms the northern edge of the Nevado Ampato massif in the Rio Colca area (Thouret et al., 1994, 1995; Fig. 12). The domes and lava flows, which overlie a volcanic bedrock of about 0.6 Ma, cover an area of about 70 km^2 and their volume is approximately of 25 km^3. About ten block-lava flows, high-K andesite to dacite in composition and Holocene in age, have flowed to a distance of 8 km toward the NW and SE sides of the volcano (Fig. 12). A "fresh" block-lava flow on the northwest side of the volcano overlies a peat which yielded a ^{14}C age of ca. 5400 yr BP. Block-and-ash and scoria-flow deposits, and tephra-fall deposits are observed as far as 9 km from the summit, recording Late Pleistocene explosive activity of Nevado Sabancaya and/or Nevado Ampato.

Two cores were drilled and one trench was digged in the large Sallalli peat-bog (Fig. 13) located at 4300 m in a glacially-shaped valley dammed by moraines and young lava flows, 10 km away SE from the Sabancaya's vent (Loutsch, 1999; Juvigné et al., 1998). The peat sequence comprises a large part of the Holocene and includes 4 thin tephra-fall layers (Fig. 13): the AD 1600 Huaynaputina ashfall, one historical Sabancaya/Ampato ashfall (1200-1400's), one thin black tephra probably from Misti (ca. 2,370 yr BP), and one Sabancaya/Ampato ashfall of lower Holocene age (ca. 8,550 yr BP). The maximum age of the drilled section in Sallalli (ca. 9,650 yr BP) provides a chronological limit for the formation of the peat-bog in the former glacial valley.

VOLCANIC AREA OF NEVADO AMPATO AND NEVADO SABANCAYA :
LAVA FLOWS, ICE CAPS, SITES OF CORE DRILLINGS AND ^{14}C DATES, AND EXTENT OF 1990-98 ASHFALL

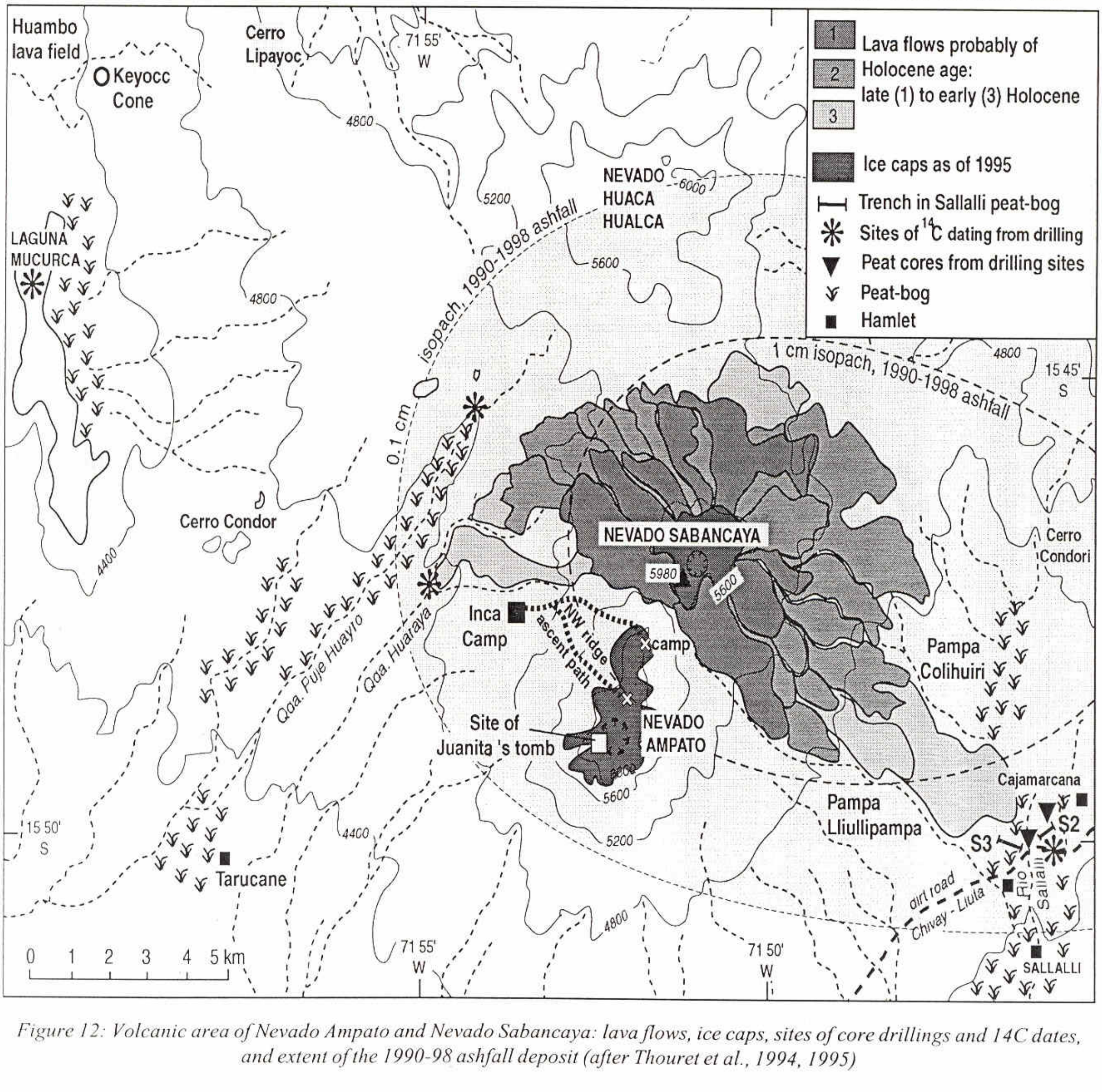


Figure 12: Volcanic area of Nevado Ampato and Nevado Sabancaya: lava flows, ice caps, sites of core drillings and 14C dates, and extent of the 1990-98 ashfall deposit (after Thouret et al., 1994, 1995)

Photo 4: Nevado Ampato on the left and Nevado Sabancaya spewing ash on the right. Nevado Sabancaya consists of two domes and a series of block-lava flows which have flowed as far as 8 km to the southeast (photograph: J.-C. Thouret).

HISTORICAL TEPHRAS

Ubinas, El Misti, Huaynaputina, Tutupaca, and Nevado Sabancaya have been the most active volcanoes in historical time in South Peru.

Historical eruptions of El Misti and severe hazards

The last subplinian explosive episode ca. 2,300-2,050 yr BP produced pumice-fall and flows ca. 1 km^3 in volume (Thouret et al., 2001a). Spanish chronicles derived from oral Incaic accounts refer to an explosive eruption of El Misti between ca. 1440 and 1470 A.D. (Chávez, 1992), which produced an ashfall termed 'Pachacútec ash' (Thouret et al., 1999a). The 1440-1470 AD vulcanian eruption of Misti emplaced a small volume of ashfall deposit ($\leq 6 \times 10^6$ m^3), but widespread as shown by Fig. 7. The black, scoriaceous ashfall deposit observed beneath the AD 1600 Huyanaputina ash has been found 35 km eastward in the Laguna Salinas (Fig. 9C) and as far as 60 km WNW in the Sallalli peat-bog (Fig. 13). At least two phreatic events were reported in 1677 and 1784-1787; lahars swept down the Río Chili valley and tributaries in the 1600's, and fumarolic activity is persistent at the crater.

The extent and volume of historical tephra indicate that future El Misti's eruptions, even moderate in magnitude, will entail considerable hazards to the densely populated area of Arequipa as suggested by Fig. 7. At least 750,000 people may be affected indirectly by tephra-fall deposits, pyroclastic flows and surges, and debris flows or flash floods.

Historical eruptive activity and human sacrifices

Mummies of children were sacrificed by the Incas on top of three volcanoes in southern Peru from the 13th to the 15th centuries: Nevado Ampato, El Misti, and Nevado Sara Sara. The famous mummy 'Juanita' or the 'Ice Maiden' (Reinhard, 1996), was found in 1995 on top of the Nevado Ampato (Fig. 12); she is now displayed in the Museum of Andean Sanctuaries at Arequipa. The ^{14}C age of Juanita is 530 ± 30 years BP, i.e cal 1290 et 1450 AD (Thouret et al., 2001b). We assume that the sacrifices were perpetrated by the Incas in order to appease the earth Gods. Our hypothesis is supported by the facts that all sacrifices took place at the top of volcanoes and the items containing usually water that were found in the graves, might have aimed to extinct earthfire.

The grave of Juanita was built on a colluvium overlying a coarse sand deposit 20 cm thick. Grain size distribution, glass and heavy mineral composition point to a trachydacite tephra, termed Ampato tephra and comparable to the 1990's ash of Sabancaya (Thouret et al., 2001b). The sacrifice of Juanita on the Nevado Ampato may have been related to the eruptive activity of the Ampato-Sabancaya massif. Although we link volcanic activity with human sacrifices, we do not exclude the fact that a dry period and subsequent famine may have taken place in the same Incaic period.

The 1990-1998 explosive activity at Nevado Sabancaya

Nevado Sabancaya has been erupting almost continuously, albeit moderately, from May 1990 until 1998.

This eruption ended an apparent dormant stage of 200 years duration, following the moderate 1752 and 1784 events as suggested by historic reports (Travada y Córdova, 1958). Since Nevado Sabancaya is still ice-clad, the eruptive activity poses a particular threat to about 30,000 people living in the Rio Colca and Sihuas valleys (Figs. 2 and 3).

The May 28-June 4, 1990, eruption expelled ash as far as 20 km towards the east (Fig. 12). The moderate vulcanian activity in 1990-94 consisted of a series of short "canon-like" explosions at 15 to 60 minute intervals. They produced slug or small eruptive columns (0.5-3 km) intercalated with long degassing stages (photo 4). The juvenile material consists of black, vitreous and unweathered fragments, andesitic and dacitic in composition (58-63 % SiO_2; Thouret et al., 1994, 1995). Although its bulk volume was small (0,025 km^3), the vulcanian fine ash was widely dispersed, as pointed out by the fragmentation index of 50% and the dispersal of about 250 km^2.

The AD 1600 large-scale plinian and ignimbritic eruption of Huaynaputina

The AD 1600 Huaynaputina plinian eruption produced the most widespread and voluminous dacitic pumice-fall deposit in the Andes in historical times. The eruption (VEI 6) began on February 19 and continued until March 6-15, 1600 at Huaynaputina, a small dacitic center located in the Rio Tambo area (Fig. 14). Tephra falls, pyroclastic flows, and surges disrupted life in an area of ~4,900 km^2 around the volcano, and ashfall was reported 250-500 km away in south Peru, west Bolivia and north Chile (Fig. 15). By linking up the series of events inferred from Spanish chronicles with the lithofacies of the tephra (bulk volume of ~12 km^3), we distinguish five eruptive phases (Dávila, 1998; Thouret et al.,1999b, 2002).

1) During the plinian phase, a sustained column 27-35 km high on February 19-20 delivered a dacitic pumice-fall of 7.9 km^3 in bulk volume (photo 5).

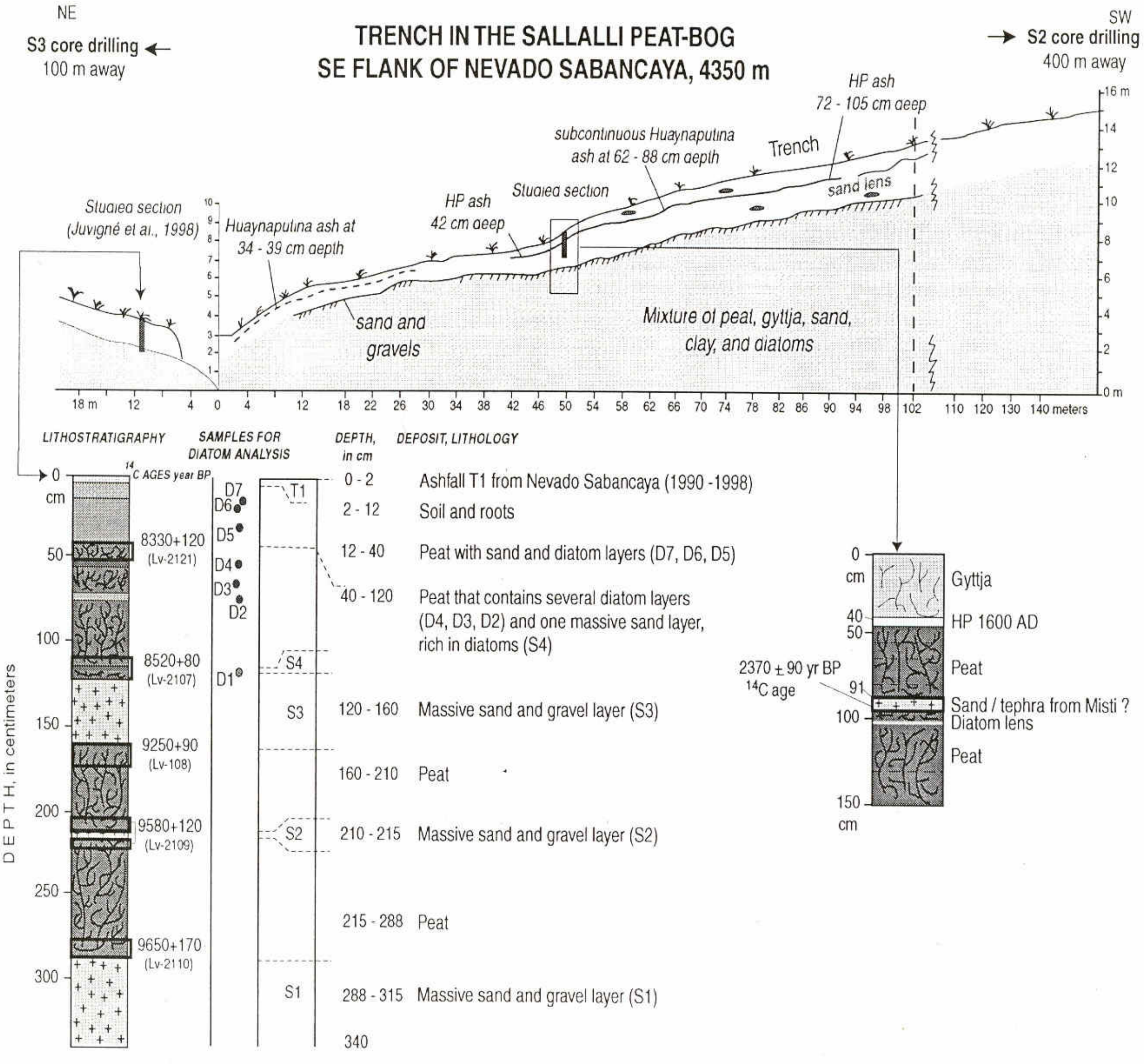


Figure 13: Trench in the Sallalli peat-bog, SE flank of Nevado Sabancaya, 4,350 m (after Loutsch, 1999).

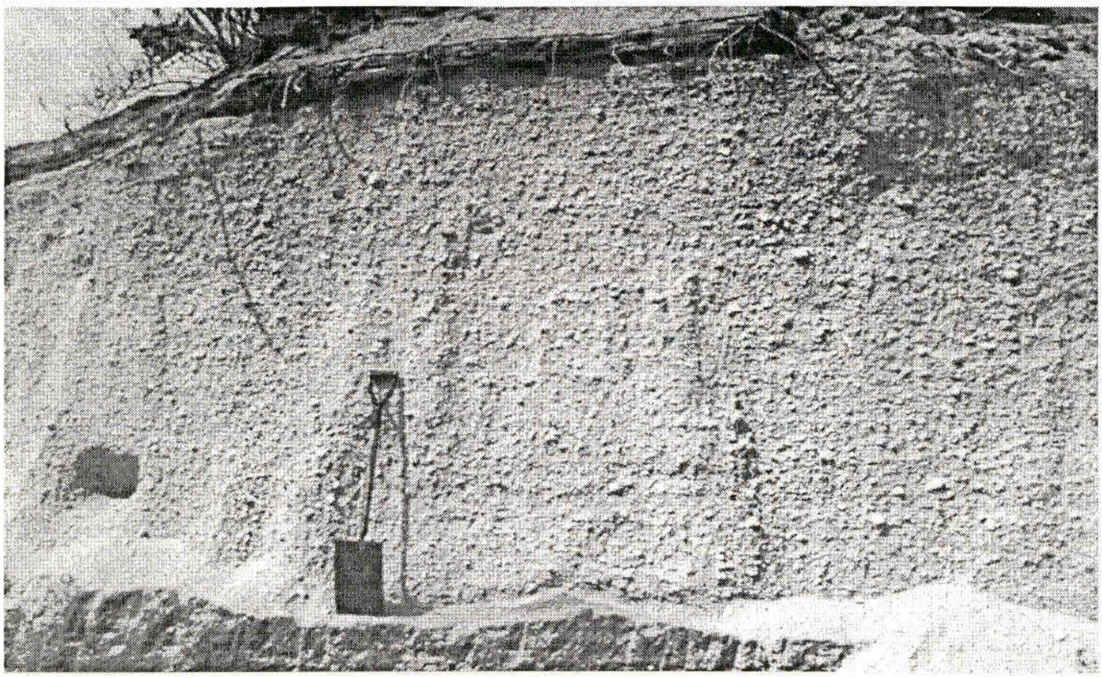


Photo 5: Proximal pumice-fall deposit 2.4 m thick (Chichilín, 14 km west of the vent) showing the crudely stratified, coarse pumice of the plinian unit 1 (photograph: J.-C. Thouret).

The plinian pumice formed a widespread lobe of = 95,000 km² within the 1-cm-isopach; strong winds carried fine ash = 500 km to the west into the Pacific Ocean (Fig. 15)

2) During the second phase, a dwindling column sent ashfalls on proximal to medial areas and pyroclastic surges on proximal slopes.
3) During the third ignimbrite-forming phase with interspersed hydromagmatic events, pyroclastic flows 1.5-2 km^3 in volume were channeled into the Río Tambo canyon and tributaries. The flows probably produced vigorous columns over the high, rugged relief around the Huaynaputina plateau. Winds winnowing the columns dispersed a widespread co-ignimbrite ash over an area of ~ 265,000 km^2.
4) During the fourth phase, an unusual crystal ashfall was deposited when the residual magma with a crystal content as high as 80% was tapped.
5) During the fifth phase, ash flows produced surge deposits and lag-fall breccias near vent, small-volume ash-flow deposits in proximal catchments, and a thin ashfall layer in medial to distal areas.

Geochemistry and mineralogy of the plinian and post-plinian units point to an unusual zoned magma sequence. The ignimbrite-forming phase tapped a magma batch richer in silica than the less differentiated plinian magma. The total DRE volume (ca. 5 km^3) of erupted tephra did not lead to caldera collapse. Ring fractures cutting multiple vents are probably associated with a dyke swarm intruding the weathered volcanic bedrock. This suggests the onset of a funnel-type or piecemeal collapse.

CONCLUSIONS

From the Late Pleistocene and Holocene tephro-stratigraphy and chronology, we can draw six concluding remarks :

1) At least 40 tephras including 8 widespread and voluminous pumice falls occurred in southern Peru over the past 50,000 years BP.
2) At least three voluminous plinian eruptions occurred over the past 2,300 years and the large-scale (VEI 6) eruption of Huaynaputina produced about 12 km^3 of pyroclastic deposits 400 years ago.
3) Tephras intercalated in peat cores and dated will help us to better constrain the climatic changes that occurred at the transition from the cold and semi-arid Late Glacial to the less cold but drier Holocene, and during the Holocene.
4) Heavy ashfall can recur every 500 to 1500 years on average (El Misti) but small ashfall can occur on a 100-years basis (e.g., Ubinas).
5) Voluminous pumice-fall deposit can occur every 2000 to 4000 years on average (e.g., El Misti, Ubinas).
6) In southern Peru, several million people are indirectly at risk from large-scale but uncommon explosive eruptions. Over one million people living in Arequipa, Chiguata, and Ubinas district are directly at risk from future eruptions at El Misti and Ubinas. Additional lahar hazards exist around the ice-clad, potentially active volcanoes (Nevado Coropuna), and around the ice-clad, active Nevado Sabancaya and Tutupaca volcanoes.

ACKNOWLEDGEMENTS

TESSOPE project has benefited from a grant of the COTAV Commission on Tephrochronology and Volcanism (INQUA) and from assistance of the Instituto Geofísico del Perú and IRD Institut de Recherche pour le Développement in Peru. This is a contribution to the Study

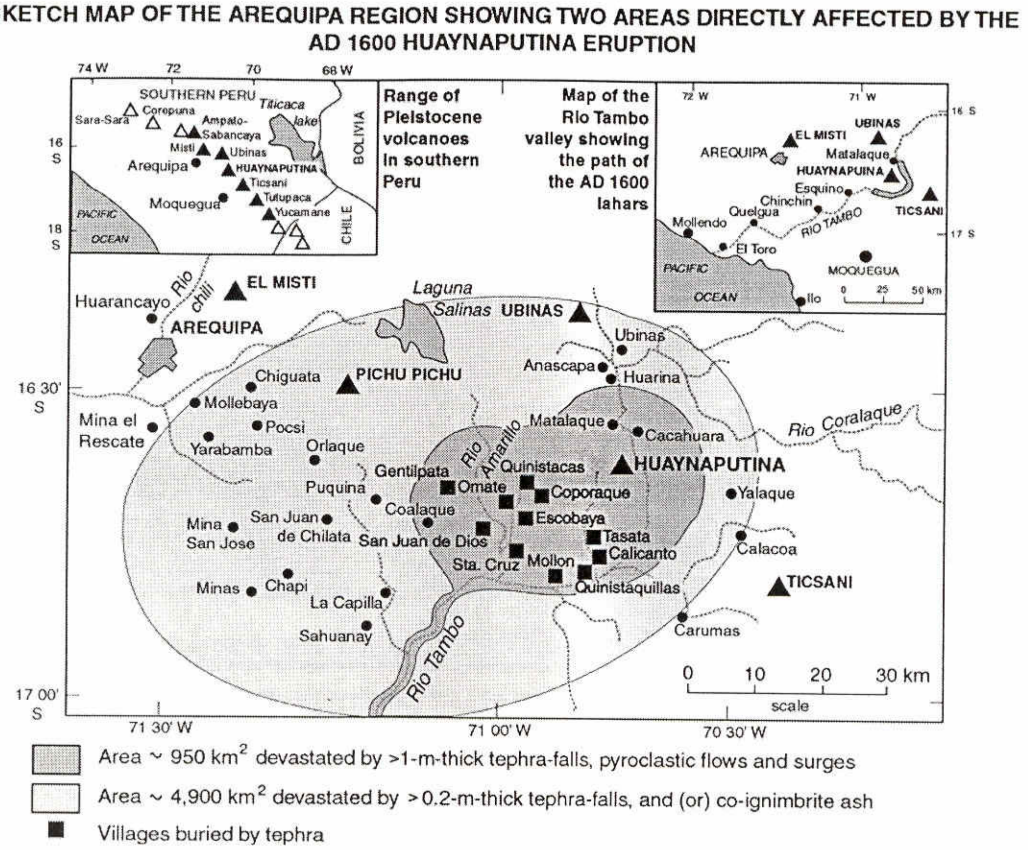


Figure 14: Sketch map of the Arequipa region showing two areas directly affected by the AD 1600 Huaynaputina eruption (Thouret et al., 1999b, 2002)

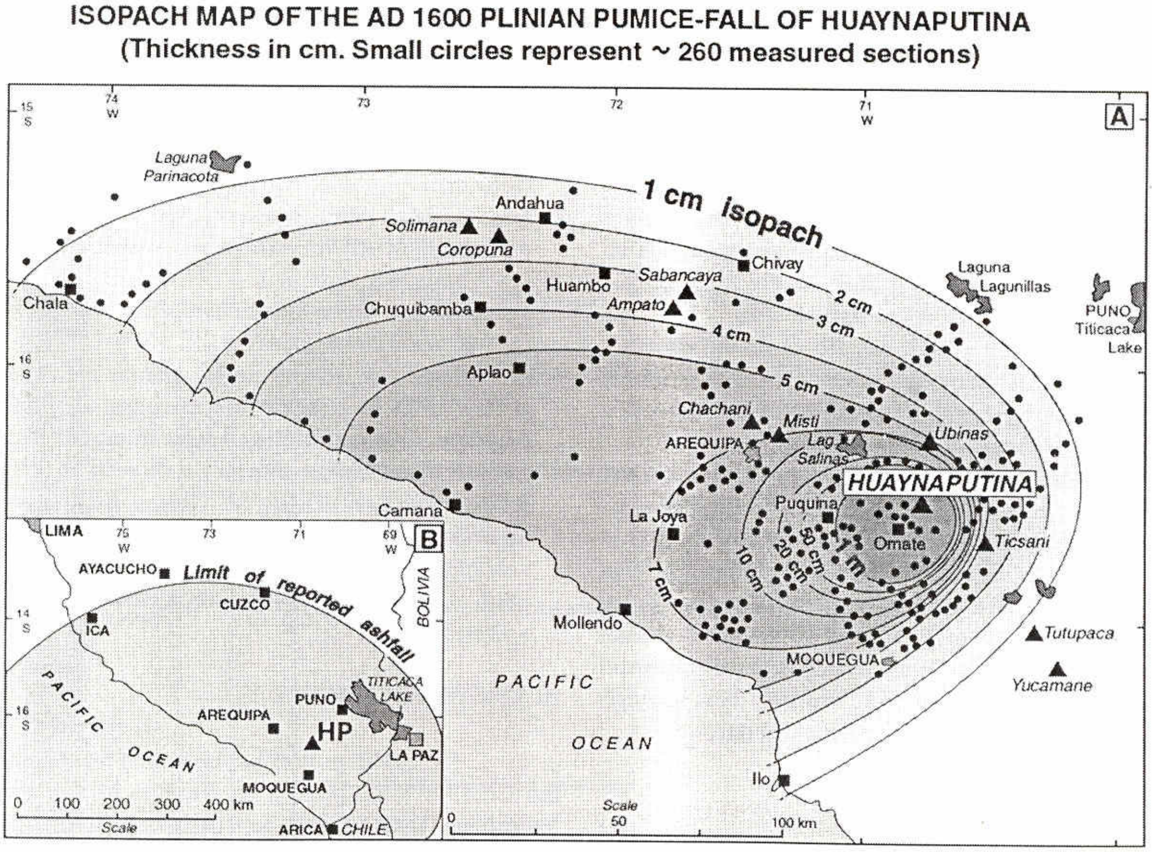


Figure 15: Isopach map of the AD 1600 plinian pumice-fall of Huaynaputina (after Thouret et al., 1999b, 2002)

Group "Geomorphic consequences of volcanic events, including hazards" of the International Association of Geomorphologists.

REFERENCES

CHÁVEZ CHÁVEZ J. A. (1992).- *La erupción del volcán Misti. Pasado, Presente, Futuro*. Imprenta Zenit, Arequipa, 158 p.

DÁVILA J. (1998).- *El volcán Huaynaputina (Sur del Peru): estudio estratigráfico, sedimentológico de las tefras y efectos de la erupción de 1600 D.C.* Tesis de grado, Universidad Nacional Mayor de San Marcos, Lima, 180 p.

JUVIGNE E., THOURET J.-C., GILOT E., GOURGAUD A., LEGROS F., URIBE M. & GRAF K. (1997).- Etude téphrostratigraphique et bioclimatique du Tardiglaciaire et de l'Holocène de la Laguna Salinas, Pérou méridional. *Géographie physique et Quaternaire* (Canada), 51, 2: 219-231.

JUVIGNE E., THOURET J.-C., GILOT E., LECLERCQ L. & GOURGAUD A. (1998).- L'activité du volcan Nevado Sabancaya (Pérou) au cours de l'Holocène.*Quaternaire*, Hommes et Volcans, 9, 1, 45-51.

LAMADON S. (1999).- *Fluctuations glaciaires et téphrostratigraphie dans les montagnes intertropicales : une revue et applications dans les Andes du Sud du Pérou (massifs des Nevados Ampato et Coropuna)*. Mémoire DEA, Université Blaise Pascal, Clermont-Ferrand, 205 p.

LOUTSCH I (1999).- *Récurrence de l'activité volcanique au Pérou méridional durant les trois derniers millénaires*. Mémoire Licence Sciences géographiques, Université de Liège, 2 tomes, 71 p.

MARIÑO S. J. (2001).- *Estudio geológico-vulcanológico y evaluación de peligros del volcán Ticsani (Sur del Perú)*. Tesis de grado, Universidad Nacional de Ingenieria, Lima, 120 p.

REINHARD J. (1996).- Peru's Ice Maidens, Unwrapping the secrets. *National Geographic*, June 1996, Vol. 1, 2, 62-81.

RIVERA M. (1998).- *El volcán Ubinas (Sur del Perú) : geología, historia eruptiva y evaluación de las amenazas volcánicas actuales*. Tesis de grado, Universidad Nacional Mayor de San Marcos, 123 p., anexos.

RIVERA M., THOURET J.-C. & GOURGAUD A. (1998).- Ubinas, el volcan más activo del Sur del Perú desde 1550: geología y evaluación de las amenazas volcánicas. *Boletin Sociedad Geológica del Perú*, 88, 53-71.

SUNI J. (2000).- *Estudio geológico y vulcanológico del Volcan Misti y sus alrededores*. Tesis de grado, Universidad Nacional de San Agustin, Arequipa, 179 p.

THOURET J.-C., GUILLANDE R., HUAMAN D., GOURGAUD A., SALAS G. & CHOROWICZ J. (1994).- L'activité actuelle du Nevado Sabancaya (Sud Pérou) : reconnaissance géologique et satellitaire, évaluation et cartographie des menaces volcaniques. *Bulletin Société géologique de France*, 165, 1, 49-63.

THOURET J.-C., GOURGAUD A., URIBE M., RODRIGUEZ A., GUILLANDE R. & SALAS G. (1995).- Geomorphological and geological survey, and spot remote sensing of the current activity of Nevado Sabancaya stratovolcano (south Peru): assessment for hazard-zone mapping. *Zeitschrift für Geomorphology*, 39, 4, 515-535.

THOURET J.-C., SUNI J., EISSEN J.-Ph. & NAVARRO P. (1999a).- Assessment of volcanic hazards in the Arequipa area based on the eruptive history of Misti volcano, Southern Peru. *Zeitschrift für Geomorphology*, Suppl.-Bd.114, 89-112.

THOURET J.-C., DÁVILA J. & EISSEN J.-Ph. (1999b).- Largest historic explosive eruption in the Andes at Huaynaputina volcano, south Peru. *Geology*, 27, 5, 435-438.

THOURET J.-C., SUNI J., FINIZOLA A., FORNARI M., LEGELEY-PADOVANI & FRECHEN M. (2001a).- Geology of El Misti volcano near the city of Arequipa, Peru. *Geological Society of America Bulletin, 113, 12, 593-610.*

THOURET J.-C., JUVIGNE E., LOUTSCH I. & CHÁVEZ CHÁVEZ J.A. (2001b).- Activité volcanique historique et sacrifices humains chez les Incas au Pérou méridional. *In*: E. Juvigné et J.-P. Raynal, eds., *Tephras : chronologie/ chronology, Archeologie/arquaeology*, p. 219-226, Les dossiers de l'Archéo-Logis n°1, CDCRAD, Goudet.

THOURET J.-C., JUVIGNE E., GOURGAUD A., BOIVIN P. & DÁVILA J. (2002).- Reconstruction of the AD 1600 eruption at Huaynaputina volcano, Peru, based on the correlation of geologic evidence with early Spanish chronicles. *J. Volcanology and Geothermal Research*, 115, 3-4, 529-570.

TRAVADA & CÓRDOVA V. (1752).- *El suelo de Arequipa convertido en cielo (Historia general de Arequipa)*. Primer festival del libro Arequipeño, edición 1958, 15 p.