Annales Societatis Geologorum Poloniae (2011), vol. 81: 1–19.

THE EXTENT AND VOLCANIC STRUCTURES OF THE QUATERNARY ANDAHUA GROUP, ANDES, SOUTHERN PERU

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Gałaś, A., 2011. The extent and volcanic structures of the Quaternary Andahua Group, Andes, southern Peru. *Annales Societatis Geologorum Poloniae*, 81: 1–19.

Abstract: The Quaternary Andahua volcanic group in southern Peru has been studied by present author since 2003. The Andahua Group stretches out at intervals within an area, which is 110 km long and 110 km wide. Seven regions bearing centres of volcanic eruptions have been distinguished: the Valley of the Volcanoes, Antapuna, Rio Molloco, Laguna Parihuana, Rio Colca Valley, Jaran, and Huambo. The Valley of the Volcanoes, where the Andahua Group was identified for the first time, contains the biggest variety of volcanic landforms. The valley is covered by a nearly 60 km long, continuous cover of lava flows. 165 individual eruption centres of the Andahua Group were distinguished including apparent pyroclastic cones, 50–300 m high, and usually smaller lava domes and fissure vents. Domes, eruptive vents and lava craters greatly outnumber pyroclastic cones. Most commonly, lava flows start from lava domes or craters. Small domes are often aligned along their feeding fissures. Lava domes and pyroclastic cones of the Andahua Group are aligned mainly along N–S and WNW–ESE trending fault systems. Projection points of the analysed Andahua lavas on the TAS diagram concentrate in the lower part of the trachyandesite field, entering also the basaltic trachyandesite or trachyte/trachydacite fields.

Key words: lava dome, pyroclastic cone, minor volcanic centres, Andahua Group, Peruvian Andes.

Manuscript received 20 January 2011, accepted 7 April 2011

INTRODUCTION

The Quaternary volcanic Andahua Group (*sensu* Caldas, 1993) is the subject of this study. The first mention of dwarf volcanic cones belonging to this group is comprised in Sheppe's report (1934). In 1960, Portocarrero described young volcanic landforms around Andahua in the Valley of the Volcanoes and his observations are treated as the beginning of scientific studies.

The Andahua Group is located in the Central Volcanic Zone (CVZ) of the Andes. In this part of CVZ, Coropuna is the largest volcano, rising about 3,000 m above the surroundings and reaching an elevation of 6,425 m a.s.l. The last eruption date in unknown, but three young Holocene lava flows are clear at the slopes of the volcanic massif. The nearby stratovolcano Sabancaya (5,976 m a.s.l.) has been recently active and the Misti volcano (5,822 m a.s.l.) is in a solfatara stage.

Contrary to big stratovolcanoes, the Andahua Group has not evoked much interest, being much smaller in size and distant from densely inhabited areas. Till today, only few scientific publications have described the Valley of the Volcanoes either in a superficial way or have concentrated on the landscape aspects (Hoempler, 1962; de Silva & Francis, 1991). Italian, French, German and, recently, Danish studies provided detailed information on petrology and geochemistry of the Andahua Group (Venturelli *et al.*, 1978; Delacour, 2002; Delacour *et al.*, 2002; Sørensen & Holm, 2008). Readers of the *Bulletin of Volcanology*, vol. 69, can find characteristics of the volcanic Andahua Group in a paper by Delacour *et al.* (2007), who tried to explain pre-eruptive magma evolution from the volcanic centres in question. Notwithstanding, very profound and advanced geochemical and petrological studies as well as detailed volcanological characteristics are lacking.

The papers on the Andahua Group, which have been published so far, have not defined clearly the notion of the Andahua Group, neither its range nor typical forms (Gałaś, 2008). The work by Delacour *et al.* (2007) distinguished three monogenetic lava fields, Ruprecht and Wörner (2007) used the notion "Andahua Volcanic Fields" only once, while Sørensen and Holm (2008) applied the extent after Caldas (1993) changing also the name of the group for Andagua Group. In fact, the name of the village is Andagua, however, Peruvian publications (and also maps) apply the name Andahua group.

The age range of the Andahua Group has been gradually determined. Datings of the oldest rocks of the group exposed near Chivay in the Rio Colca Valley by means of the K-Ar method show approximate ages of 400–64 ka (Kaneoke & Guevara, 1984; Eash & Sandor, 1995). These figures agree with geological observations, which suggest that the group intermingles in some places with fluvioglacial formations near Orcopampa and that it developed after formation of the canyons. Further data on the age of the Andahua Group have been obtained after the K-Ar method applied to rocks and the ^{14}C method on the remnants of plants burnt by hot ash. Such investigations were carried out by Kaneoke and Guevara (1984). The catalogue of volcanoes by Simkin and Siebert (1994) mentioned Andahua volcanic activity in 1913, but the position of active cinder cones is pointed out near the vicinity of Pampacolca where lavas from Coropuna belonging to the Barroso Group occur, 40 km south from the nearest centre of the Andahua Group. The youngest centre of activity – Chilcayoc Chico – was radiocarbon dated at 370 years BP (Cabrera & Thouret, 2000).

Attempts to date particular pyroclastic cones according to the morphometric parameters (Wood, 1980) were made by Cabrera and Thouret (2000) and in more detail by Delacour *et al.* (2007). These results proved that successively younger age groups had more and more steeply inclined slopes. Inclination of slopes of several, apparently Pleistocene pyroclastic cones (Cerro Mauras, Llajuapampa, Marbas Chico Norte) is in the range of 28–34° that suggests, according to the mentioned classification, their almost recent origin. Hence, it is surprising that graphic images of the age of the cones were based on morphometric parameters in the above-mentioned work (Delacour *et al.*, 2007). There were a few volcanoes whose calculated slope inclination had similar values, *i.e.* 29°, but their estimated ages were different: Chalhue Mauras (Late Pleistocene), Marbas Chico Norte (Early/Middle Holocene) and Chilcayoc Grande (historical time). The discrepancy might be caused by the fact that calculations were based on topographic maps, which offered very low accuracy in determination of the relative height. The other weak point of the morphometric dating method consisted in its limitation to pyroclastic cones, although most of the Andahua Group is built of lavas outpouring from lava domes and cracks.

Minute traces of erosion and weathering of some of the volcanic forms and the lack of vegetation cover prove they are not older than 300–400 years. A dusty brown soil has formed on older ashes and volcanic slag lavas from the Andahua Group, and its thickness is from 0.5 to 1 m. Such soils develop under the influence of water and the process is relatively slow. As the current climate in that part of the Andes is dry, we assume (Gałaś & Paulo, 2005) that they were formed in the glacial epoch and accompanying periods of glaciers melting, at least 10,000 years ago (Thouret *et al.*, 2002).

Lavas of the Andahua Group compositionally straddle the olivine-rich basaltic andesites to dacites (Delacour *et al.*, 2007). They are aphyric, porphyritic or trachytic, with 0–2% of microphenocrysts of mainly clinopyroxene, plagioclase in a glassy matrix with plagioclase microlites and 1–2% of oxides (Sørensen & Holm, 2008).

It follows from Delacour *et al.* (2007) that magma is most primitive in southern Peru and it probably ascended from deep crustal through regional faults.

Within different fields, lavas show considerable variability even when compared within one particular field (Delacour, 2002; Sørensen & Holm, 2008). Their silica content varied between 52.1 and 68.1 %, the extreme values being adopted after Delacour *et al.* (2007).

ANALYTICAL METHODS

The aim of this work is to define the origin and evolutionary stage of the Andahua Group for the dwelling areas.

The main volcanic fields were the subject of detailed studies in the seasons of 2003, 2004, 2006, 2008 and 2010. The study area is rather difficult to approach, mostly waterless and high-mountain one, and situated within the altitudinal zone of 1,400–5,200 m a.s.l.

The research was based on 1: 100,000 geological maps of Peru, sheets: Cayarani, (Moncayo, 1994), Orcopampa and Huambo (Caldas, 1993; Caldas *et al.*, 2001, 2002), Aplao

Table 1

Quantitative characteristics of volcanic fields belonging to Andahua Group (from Gałaś 2008 modified)

Regions	Lava fields	Pyroclastic cones	Lava domes and fissures	Volume of lava (km^3)	Volume of pyroclastic cones (km^3)	Age*
A. Valley of the Volcanoes	13	24	57	26	0.78	I,II,III
B. Antapuna	6	4	4	6.4	–	I,III
C. Rio Molloco	5	1	11	1.7	0.03	II
D. Laguna Parihuana	0	6	0	–	0.07	II
E. Valley of Rio Colca	3	0	11	0.8	–	I, II
F. Jaran	5	11	16	7.7	0.34	I, II
G. Huambo	5	1	23	5.9	0.01	I
Total	36	47	118	48.5	1.26	

* I – Pleistocene, II – Late Pleistocene–Middle Holocene, III – Holocene

(Guizado, 1968), Caylloma (Davila *et al.*, 1988) and Chivay (Quispesivana & Navarro, 2001), satellite photographs (Landsat), and an aerial-photo set of the southern part of the Valley of the Volcanoes (Servicio Aerofotografico Nacional, Peru). The research specified the eruption centres determining their GPS location, characteristics and morphology of volcanic landforms and provided samples for petrographic investigation and future petrologic analyses.

The eruption centres or the areal extent and the approximate age of individual Andahua forms are specified. Seven volcanic regions where the centres of eruption occur have been distinguished. They stretch out at intervals in an area that is at least 110 km long and 110 km wide (Fig. 1). There are several lava fields built of single or sequential lava flows, pyroclastic cones and other centres of lava effusion, including domes and fissures (Table 1). The limits of each region were determined according to the lineaments, relief and tectonic settings. The lineaments reflect the system of NW–SE oriented faults, tectonic framework of the Rio Colca Canyon (oriented SW–NE), and Quaternary graben of the Valley of the Volcanoes (segments oriented N–S and NW–SE).

Three age generations were distinguished on the map of the group: the older (Pleistocene), the middle (Pleistocene–Holocene), and the youngest (Holocene and historical) ones. The old group is covered with vegetation, quite often changed into farmlands, weathered and cut by glacial erosion. Borders of old lava flows are indefinite.

The landforms of the middle group are often eroded. Initial soils have formed on the lavas and they are sometimes covered by grass and plants.

The surface of the young lavas is coarse as the aa type, the places where lava was squeezed out are distinct, slopes of lava flows are steep and unstable with distinct flow structures. Formations of a few young forms occurring near Andahua were examined by means of the ^{14}C method. They were formed in the period between 4050 and 370 BC (Cabrera & Thouret, 2000), while dating of Chilcayoc Grande volcano shows the period of 1451–1523 A.D. (Delacour *et al.*, 2007). Hence, lava was flowing there in the time when the Spaniards conquered the Inca Empire.

130 samples for petrochemical investigations were collected from individual outcrops, lava flows and domes or pyroclastic cones in all distinguished regions in the period of 2003–2010. 55 thin sections were studied in polarised light. Chemical analyses of 34 samples were carried out at the Activation Laboratories Ltd. – ACTLABS (Canada). Major elements were determined by the ICP method. Petrological analyses are still under study and future results will be published in subsequent papers.

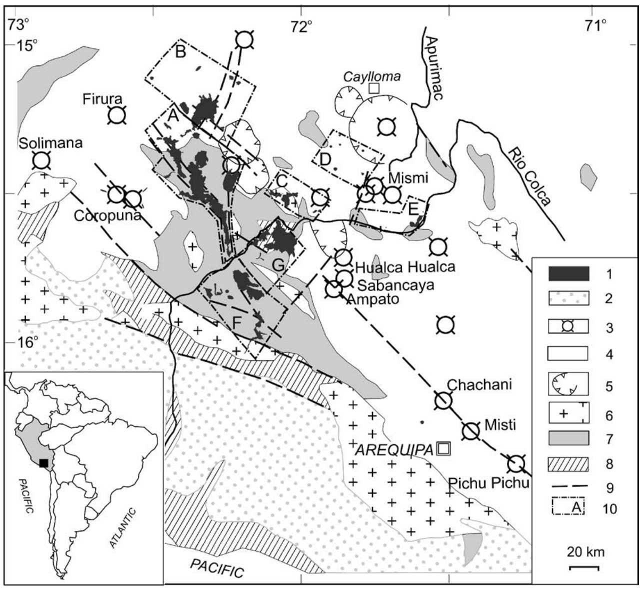

Fig. 1. Geological map of Rio Colca region (based on Paulo, 2008): *1* – Quaternary: Andahua Group, *2* – Pleistocene: alluvial gravels, *3* – Pliocene–Quaternary: stratovolcanoes of Barroso Group, *4* – Neogene–Quaternary: pyroclastic and lacustrine deposits, slopewash sediments, *5* – Neogene: caldera complexes, *6* – Jurassic, Cretaceous, Palaeogene: plutons, *7* – Jurassic, Cretaceous: sedimentary formations, *8* – Proterozoic: Arequipa massif gneisses, *9* – major faults, *10* – Andahua Group occurrence area

ERUPTION CENTRES

Most of the volcanoes are typified by simple structure characteristic for monogenetic volcanoes. However, some of them have erupted many times. On the slope of the Jenchana volcano, scoria and bombs are intercalated with layers of soils; the Gloriahuasi volcano was spewing lava and ashes alternately. Dating of pre-Ticsho lavas indicates an age of 0.27 Ma (Kaneoka & Guevara, 1984) and burned twigs in ash from Ticsho are 4060 years old (Delacour *et al.*, 2007). The term monogenetic volcanic fields (Delacour *et al.*, 2007) cannot be applied to the whole of the Andahua Group, contradicting the common definition (Schmincke, 2004; Walker, 2000). Some of the areas in the Andahua Group correspond rather to basaltic volcanic fields (*sensu* Connor & Conway, 2000).

Young monogenetic scoria and cinder cones are easy to find and they are frequently described as the main places of eruption in the Andahua Group (Delacour *et al.*, 2007; Ruprecht & Wörner, 2007; Sørensen & Holm, 2008). Several such volcanoes (Table 2) have been found (Figs 2, 3). Some of them have broken edges of the craters and flows of lava started from them. Most of the cones are built almost exclusively of pyroclastic material. There is only one volcano, Gloriahuasi, which is built of lava and tephra layers and can therefore be better classified as a small stratovolcano. Pyroclastic cones indicate that locally the amount of volatiles in magma was quite significant. Most of the cones are 50–170 m high, with the maximum of 400 m. The highest volcano was probably Antapuna, whose cone was modified by a glacier (Gałaś, 2008). Scoria cones are formed in eruptive styles from Hawaiian/Strombolian to violent Strombolian.

The scoria cones are usually associated with lava fields. The only exception is a group of six separate cones around Laguna Parihuana, on a high plateau (4,300–5,100 m a.s.l.).

Most commonly, lava flows start from lava domes, craters or fractures. Small domes are often aligned, most proba-

Table 2

Index of volcanic cones belonging to Andahua group

No	Region	Name (Sample)	GPS coordinates	Altitude m a.s.l./ Cone height, m/ Volume, km^3	Characteristics	Age
1	2	3	4	5	6	7
1	Valley of the Volcanoes	Panahua	787695 8298546	4215/59/0.004	monogenetic cone, destroyed by directed explosion	I
2		Ucuya (AC3)	785312 281913	3670/70/0.005	breached cone, with lava flow originated in the crater	I
3		Pampalquita	7884506 281307	3818/70/0.007	breached cone, with lava flow originated in the crater	I
4		Yanamauras Sur	783910 8286304	3761/181/0.012	monogenetic cone	II
5		Yanamauras	784214 8286652	3760/108/0.019	monogenetic cone	II
6		x	783956 8287271	3571/25/0.001	cone, destroyed by erosion	II
7		Cerro Puca Mauras	785722 8293030	4181/334/0.229	cone, with lava flow originated in the crater	II
8		Cerro Mauras	787022 8302521	4317/161/0.136	cone, with fragment of wall older cone	II
9		Collopampa	7878 83025*	4158/83*/0.005	monogenetic cone, in collapsed lava dome Collopampa	II
10		Santa Rosa	7875 82945*	3940/100*/0.018	monogenetic cone	II
11		Santa Rosa Sur	7867 82934*	3960/50*/0.007	monogenetic cone	II
12		Challhue Mauras	7847 82998*	4260/160*/0.102	monogenetic cone	II
13		Misahuana Mauras	770325 8311264	3915/168/0.051	monogenetic cone	II
14		Pabellon Mauras	7729 83084*	4507/ 107*/0.006	monogenetic cone	II
15		Yana Mauras (YM1)	775612 8305161	4605/155/0.058	monogenetic cone destroyed by river erosion	III 2900 years**
16		Ticsho	781375 8286482	3871/60/0.008	monogenetic cone	III 4050 years*
17		Mauras	7840 83124*	4007/107/0.012	monogenetic cone	III 2900 years **
18		Jenchana	784664 8282346	3624/~100/0.005	monogenetic cone	III
19		Jechapita (J1)	788499 8280856	3388/~100/0.012	monogenetic cone	III
20		Chilcayoc Grande (CH2S)	790847 8280756	3243/~143/0.022	monogenetic cone	III A.D. 1500**
21		Chilcayoc	788139 8282003	3347/~70/0.003	breached monogenetic cone, with lava flow originated in the crater	III
22		Chilcayoc Chico	787693 8282304	3343/65/0.002	breached cone by lava flow originated in the crater rebuild	III 370 ± 50 years *
23		Cerro Pucamauras	7974 82898*	4915/185*/0.065	monogenetic cone	I
24		Cerro Ticlla	No data	5258/58	cone destroyed by glacial erosion	I

Table 2 continued

No	Region	Name (Sample)	GPS coordinates	Altitude m a.s.l. / Cone height, m/ Volume, km^3	Characteristics	Age
1	2	3	4	5	6	7
25	Antapuna	Cerro Antopuna	788955 8323619	4890/190	cone destroyed by glacial erosion	I
26		parasitic Cerro Antapuna	791296 8322876	4754/24	vent destroyed by glacial erosion	I
27		Ares I	804174 8333531	4985/85	cone destroyed by glacial erosion	II
28		Ares II (AR2)	800936 8335962	4982/42	cone destroyed by glacial erosion	II
29	Rio Molloco	Marhuas (VM21)	800936 8335962	4483/120/0.031	monogenetic cone	II
30	Laguna Parihuana	Antaymarca (HT1)	196077 8306538	4646/235/0.057	cone	II
31		Saigua	2004 83136*	4100/~50/0.002*	monogenetic cone	II
32		Challpo	2000 83075*	4100/~50/0.001*	monogenetic cone	II
33		Andallullo	1980 82976*	5063/100/0.005*	monogenetic cone	II
34		Antaccollo	2098 83049*	4650/100/0.002*	monogenetic cone	II
35		Sani	2095 82954*	4950/200/0.004*	monogenetic cone	II
36	Jaran	Gloriahuasi (H58)	792860 8243760	2650/412/0.108	stratovolcano	I
37		Gloriahuasi Sur (GL8)	791856 8242754	2899/29/0.001	cone destroyed by erosion	I
38		San Cristobal	7953 82449*	2614/250*/0.01	monogenetic cone	I
39		Honda	7855 82440*	2426/200*/0.005	monogenetic cone	I
40		Marbas Chico Norte	808170 8244494	4105/ 139/0.041	monogenetic cone	II
41		Marbas Chico Sur	807408 8243274	4110/144/0.023	monogenetic cone	II
42		Cerro Pucaguada (CP4)	803335 8241700	4241/ 160/0.001	monogenetic cone destroyed by directed explosion	II
43		Marbas Grande (MBS)	802111 8244972	3844/105/0.039	monogenetic cone	II
44		Llajuapampa	807137 8247181	4324/175/0.058	monogenetic cone	II
45		Uchan Sur	807336 8233573	4177/100/0.053	monogenetic cone	I
46		Tururunca (H44)	806564 8235286	4024/106/0.02	monogenetic cone	I
47	Huambo	Keyoc	No data	4400/100/0.013	monogenetic cone	II 2650 years*

Column 4 & 5 – * Smoll *et al.* 1997
Column 7 – *Cabrera & Thouret, 2000; ** Delacour *et al.* 2007

bly along their feeding fissures. It can be exemplified by a line of small domes south of the road Huambo – Cabanaconde, parallel to the Colca Canyon.

The lava eruption loci like domes, fissure vents and craters are more numerous than pyroclastic cones. As much as 118 solely lava emitting loci have been found. The lava usually flowed from confined craters, which piled up rapidly, cooling down and becoming more viscous to form domes. Such basaltic-andesitic lava domes are usually 20 to 150 m high. The highest lava dome was found near Paula gold mine; it is Cerro Coropuna (5,170 m a.s.l.) of relative height of 250 m.

The lengths of individual lava flows are from 0.5 to 20 km. The thicknesses of the flows are usually between 15

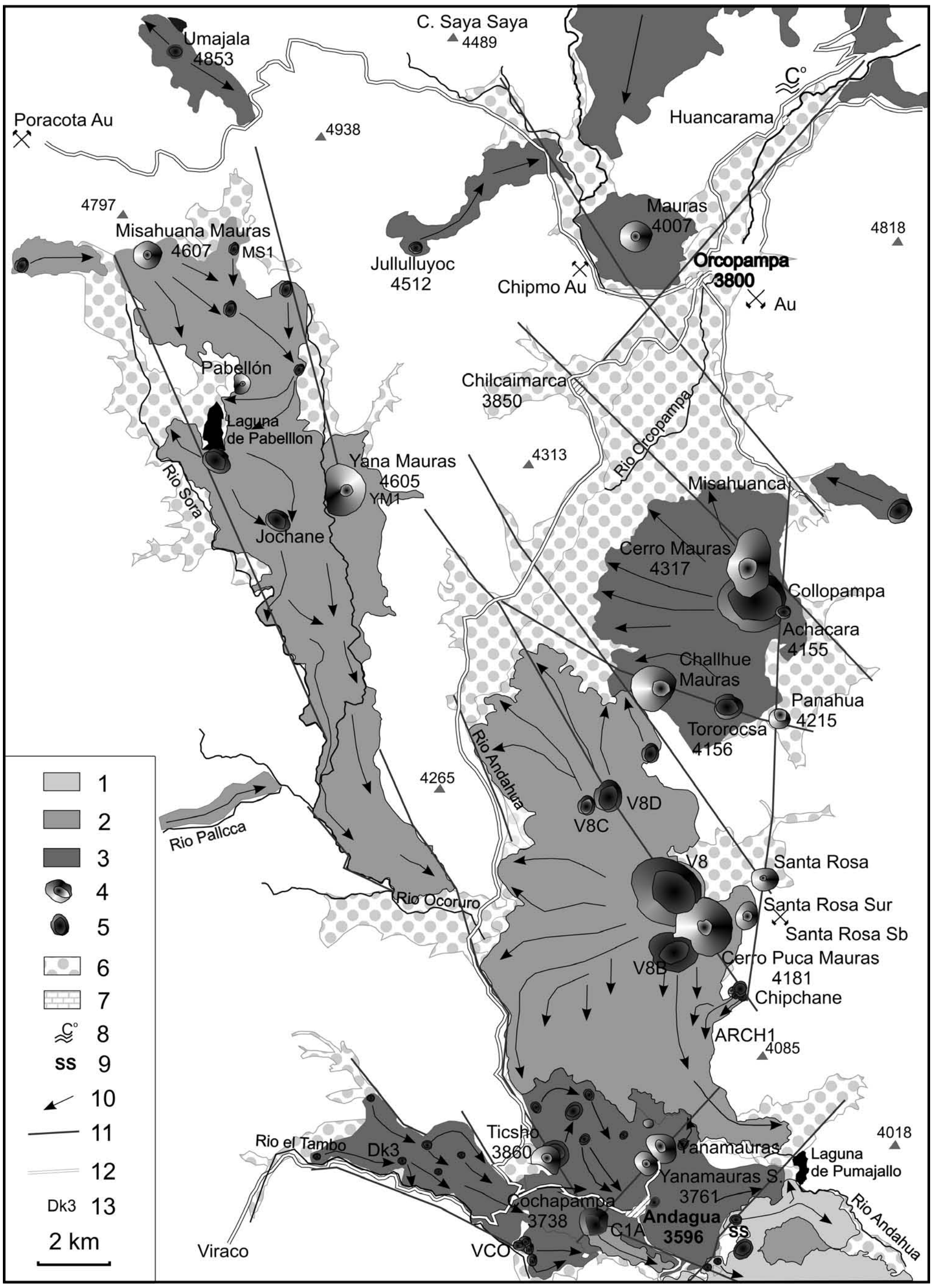

Fig. 2. Andahua Group in the northern part of the Valley of the Volcanoes and Rio Sora Valley (after Gałaś, 2008; modified). *1–3* Andahua group (*1* – Holocene, *2* – Pleistocene–Holocene, *3* – Pleistocene), *4* – pyroclastic cone, *5* – lava dome, *6* – alluvia (Pleistocene–Holocene) , *7* – travertines (Pleistocene–Holocene), *8* – hot springs, *9* – native sulphur, *10* – lava flow direction, *11* – faults, *12* – roads, *13* – samples (see Table 3)

and 80 m, and if such flows overlie the other ones or pile up at the front they are even bigger. Slow effusion rates generated flow fields that have large and small flow lobes and channels. Typical is blocky lava with same cleft lava near fissures and at crevasse structures. The surfaces of the youngest flows are covered by irregularly shaped cindery blocks characteristic for the aa type. Exceptionally, on the Antaymarca volcano (Laguna Parihuana region) intenstine lava was found.

The surface and volume of the lava flows (Table 1) are much larger than those of the pyroclastic cones. The lavas build 97% of the Andahua Group volume.

Attempting to measure volcanic activity (*sensu* Connor & Conway, 2000), one may relate the total number of Andahua vents (165) to the period of activity of the group, *i.e.* some 0.4 Ma. Volcanic activity (λ_t) of the Andahua Group is 3–4 10^{-4} vents/year. For example, the Eifel Volcanic Field (Germany) had 5 10^{-4} vents/year (Schmincke *et al.*, 1983).

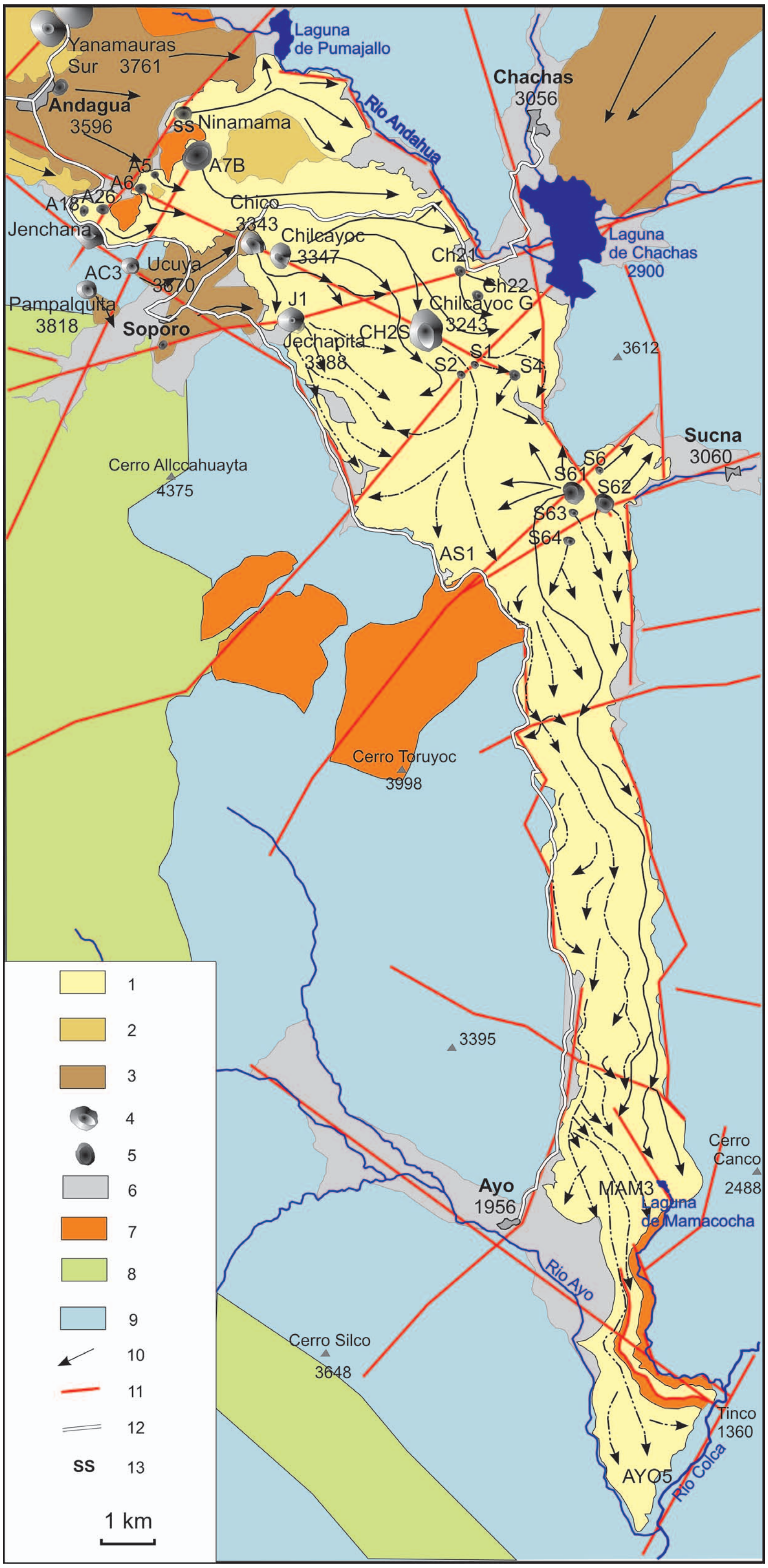

Fig. 3. Geological map of the southern part of the Valley of the Volcanoes (after Gałaś, 2008; modified): *1–3* Andahua Group (1 – Holocene, 2 – Pleistocene–Holocene, *3* – Pleistocene), *4* – pyroclastic cone, *5* – lava dome, *6* – alluvia (Pleistocene–Holocene), *7* – Barroso Group (Pliocene), *8* – sedimentary rocks (Lower Cretaceous), *9* – sedimentary rocks (Jurassic), *10* – lava flow direction, *11* – faults, *12* – roads, *13* – native sulphur

DISTRIBUTION AND FIELD CHARACTERISTIC

The area covered by the Andahua Group can be subdivided into seven volcanic regions (Table 1). The subdivision is based on the relation to the geological formations, tectonic structure and morphology; hence, the region boundaries are in part arbitrary.

The Valley of the Volcanoes. The valley covers the largest part of the area of the Andahua Group and it is also this part, which is the richest in products of volcanism. The surroundings of Andagua village can be treated as *locus typicus* of the group, which has been confirmed by author's investigation. The Valley of the Volcanoes is approximately 90 km long and its course is generally meridional, but in the middle part the axis of the valley turns towards NW–SE and this part is about 30 km long. Elevation of the mountains surrounding the valley changes between 3,500 and 5,000 m a.s.l. The mouth of the valley leading to the Colca Canyon is placed at 1,360 m a.s.l. The elevation of the valley floor in the upper part, at Orcopampa, is 3,800 m a.s.l.

Lavas fill in the Valley of the Volcanoes between Misahuanca and Ayo at a distance of 60 km. It seems likely that the oldest eruptions took place in the vicinity of Andagua (Fig. 2). The first generation of lava was flowing out from the domes located in the centre of the valley. Apparently, one of the lava flows moved towards the present Laguna de Pumajallo. Another lava field was formed west of Andagua in the lateral valley of the Rio Tambo River.

Seven centres of eruption were located in the bottom of the arm, approximately 500 m below Andagua. Lava covered the bottom of the valley, partly flooding the fluvial sediments in its upper part and flowed towards the Valley of the Volcanoes, covering the older Andahua lava field. The valley of the Rio Tambo is a graben oriented WNW–ESE. One smaller field occurs on its southern border slightly above the slope. Effusion of lavas proceeded from four centres, which are currently in the form of regular, interconnected lava craters. It could have been an eruption centre on a short ridge, which was confined by the graben of the Valley of the Volcanoes.

The next field is located 8 km to the south of Andagua (Fig. 3). Above the Soporo village, a strongly eroded dome occurs from where lava was flowing down towards the Valley of the Volcanoes. The other two centres are placed on the ridge which borders the valley from the NW. This ridge rises about 400 m above Soporo. Two scoria cones: Pampalquita and Ucuya were formed there. The cones had 70-m-deep craters and are composed of loose, black, vesicular scoria lapilli with blocks. They are breached by a lava flow which was flowing down its slope to the SE. The lava flows are partially eroded with regular *levée*.

Another field of the older phase was formed *ca.* 15 km north of Andagua, near Misahuanca (Fig. 2). The eruption centres were attached to the edge of the graben forming the present Valley of the Volcanoes. The lavas pouring out towards the west partly dammed the valley. The successive lava flows piled up and finally formed an over 100 m thick layer covering horizontal pampa over the area of more than 32 km^2. The main centre apparently had several large eruption phases. Currently, remnants of an eroded structure with small renewed domes of Collopampa and Achacara (Smoll *et al.*, 1997) can be found there. Previously, it could have been one big centre of lava effusion. Three craters are preserved there. A resurgent scoria cone appears in the western crater. The Cerro Mauras volcano, whose relative height amounts to 170 m, tops the centre. The inclination of the volcano slopes is equal to 28° (Gałaś, 2008). It is a pyroclastic cone mounted on the slope, with the western slope being a remnant of an older cone whose crater was located several dozens of metres to the west. The second dome, Tororocsa, located farther south, was much smaller. There are two pyroclastic cones in its vicinity – Challhue Mauras and the other one called Panahua. Challhue Mauras is a typical monogenic cone slightly older than the lavas, which surround it forming a kind of an apron. The second and smaller one – Panahua – exploded with violent Strombolian styles almost horizontally towards the north. Remnants of the crater walls build a crescent form that looks like a barchan. The Cerro Mauras and Panahua cones are composed of loose, red, vesicular scoria lapilli, blocks and bombs (up to 30 cm in size).

The lava cover west of Orcopampa, lying below Mauras volcano (4,007 m a.s.l.), is probably of the same age (*i.e.* the oldest one). This isolated lava field closes the valley of Rio Chilcaymarca partly covering alluvial deposits, and then pushes the river to the southern side of the valley. Lavas in this field are 35 to 120 m thick and cover an area of 6.5 km^2. The fields are covered with vegetation.

The next zone of eruption centres is located south of the Rio Andahua canyon (Fig. 2). Contrary to the described fields, volcanic activity occurred there in two or more cycles. Domes and volcanoes are significantly smaller and they are scattered over the whole width of the valley. In the first cycle, lavas erupted from two large and five small lava domes. The lavas are composed of few stacked flow units. The lava dome Pra-Ticsho was dated at 0.27 Ma (Kaneoke & Guevara, 1984). Four cones are located at the edge of the field. These are: Ticsho, Yanamauras Norte and Sur, and a smaller cone damaged by an explosion just at the Rio Andahua canyon. Scoria cones represented the youngest episode of the Andahua Group activity. Burned twigs from Ticsho were dated to 4,050 years BP (Cabrera & Thouret, 2000).

The Santa Rosa lava field, occurring south of the Misahuanca field (Fig. 2), belongs already to the second generation. Lavas cover the whole valley (4–6 km wide) at a distance of 16 km, between the Misahuanca and Andahua fields. The Andahua River turns east sharply in the lower part of the field and cuts a narrow, 50 m long canyon in the lavas of the Andahua Group. Then it disappears beneath the lavas and emerges on the other side of the valley forming a waterfall near Yanamuras Norte volcano. The main eruption centres are situated on the eastern edge of the valley in the vicinity of Santa Rosa, an abandoned mine of antimony ores. It seems likely that the activity was strongest in the Valley of the Volcanoes. The area of the lava fields is approximately 70 km^2. Lavas poured out of four large and one small domes. Locations of the centres (V8C, V8D – V8, Puca Mauras, V8B – Chipchane) were controlled by faults running NW–SE, which continued along the bent axis of the valley in its middle part. The diameter of the largest one (V8b) is over 2 km. Lavas spread radially towards the north, west and south building a 100 to 150 m thick cover, with eight main flow lobes and numerous channels. The longest lava flow is approximately 10 km long and 2 km wide (Gałaś, 2009). A small lava dome Chipchane formed on a slope rising 65 m above the valley bottom. The dome has a small crater with a 5 m high rim and it is breached on its slope side where lava started to flow with regular *levée*. From the crater, lava flowed on the surface of the earlier-stage lava field. The youngest eruptions within the field built three pyroclastic cones including Cerro Puca Mauras, which is the biggest one in the Valley of the Volcanoes. The cone is 350 m high, its crater diameter is 300 m across, and the depth is 80 m. The cone is breached to the SW, forming a lava flow. The base of the cone is composed of welded scoria lapilli (1 mm in size or smaller). The upper part of the cone is built of lapilli, blocks and bombs. The total volume of eruptive pyroclastic material is 0.229 km^3 (Table 2). The other two cones, Santa Rosa (100 m high) and Santa Rosa Sur (50 m), situated near the fault of the graben, are monogenetic in character.

The lava dome Cochapampa, with a crater and over 2 km long flow containing a well preserved *levée*, probably belongs to the second generation of volcanic eruptions (Fig. 2). It is located in an older lava field being much younger than the surroundings. A small resurgent dome occurs inside the crater. The Cochapampa dome is slightly over 100 m high and has a crater 50 m deep. Walls of the crater are built of lava and red scoria. Numerous quartzite xenoliths, originating from the valley bed, have been found in the lava (Gałaś, 2008). The surface of the lava flow is composed of block and highly brecciated lava.

An isolated lava dome of the second generation occurs east of the village Misahuanca (Fig. 2) where the lava fills a small hanging valley.

The southern part of the Valley of the Volcanoes, up to the place where it joins the Colca Canyon, is covered with lavas of the third generation, which form the Chilcayoc lava field (Fig. 3). Three stages of formation of the Chilcayoc lava field have been determined according to mutual relations between the borders of the lava flows. The Jechapita volcano, which is an example of an ideal pyroclastic cone (Fig. 4) with only incipient erosional gullies, seems to be the oldest eruption centre (Jechapita stage). The cone is piled up in the place of an earlier outflow of lava, which is proved by clearly visible structures of two small lava flows. The longer one is 3 km long and its surface consists of lava blocks. The flows below Ayo-Laguna Mamacocha line should also be assigned to this stage. Considering their level of weathering, they are probably slightly older but it is hard to connect them to the same eruption centre. The flows are 7 km long and covered by a younger lava from the northern side. If they had flowed from Jechapita they would have been 24 km long. Along the eastern border of the valley, the lava cover is cut by a young fault with the downthrow of the eastern wing equal to about 100 m.

The second stage is mainly connected with two centres: Chilcayoc Grande and Sucna, which are within the distance of 4.5 km. Lava effusion started from the domes occurring in the forefield of the lateral valley where Sucna village is located. Two big and three smaller lava domes have been distinguished there. The highest one is elevated 70 m above the bottom of the lateral valley. The other lava flows were heading south flooding the Valley of the Volcanoes. Most of the lava outpoured towards the Rio Colca Canyon, forming flows whose lengths exceeded 20 km. This lava was less liquid. The width of the flow rarely exceeded 1 km. The flows were running across two faults transverse to the valley axis forming short cascades with elegant *levée*. The surface of the flows is reddish, which might be the effect of weathering in the zone of warmer climate occurring below the altitude of 2,500 m a.s.l.

Fig. 4. Jechapita volcano and the youngest lava flows. At the left Chico and Chilcayoc volcanoes with lavas

The charcoal derived from ash of the Chilcayoc Grande cone was dated at 1451 to 1523 A.D. (Delacour *et al.*, 2007). This is the most prominent cone in this lava field. It is 140 m high and its oval crater is approximately 60 m deep (Gałaś, 2008). There are three small lava domes or, possibly, landforms of the tumulus-type in a close vicinity of the volcano towards the SE. The lava flow running directly from the Chilcayoc Grande volcano splits into two lobes; the eastern one pushed the Andahua River to the edge of the valley. The other flow widens towards the south. Its length exceeds 7 km and the width at the front is over 3 km. The flow was blocked by the lava flowing from the Sucna dome. At that time, the course of the Andahua River was cut off and a dam lake, the Chachas lagoon, was formed. Farther down, the Rio Andahua disappears under lava flows. After 18 km it unexpectedly emerges from under the lava and forms the Laguna de Mamacocha and a short but relatively deep (200 to 300 m) gorge leading to the Rio Colca.

During the third stage, which could have taken place in the period of 1600–1800 A.D., lava effusions occurred in different places. The transverse Jenchana–Ninamama fault zone in the Valley of the Volcanoes became volcanically active again. At the beginning, lava was emitted from the fissures located among the outcrops of the Barroso Group. The lavas were flowing east, *i.e.* downslope, and surrounded the cover of black ashes from the eruptions of Jechapita and

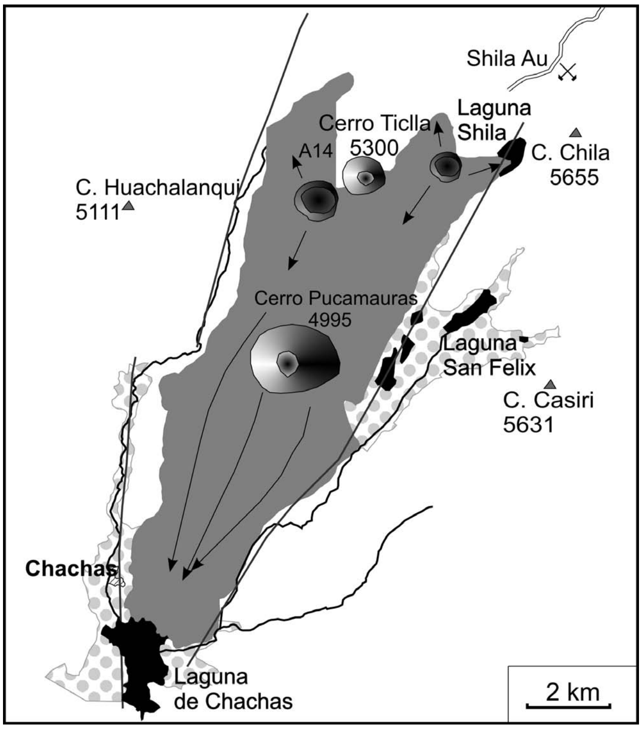

Fig. 5. Andahua Group in the Valley of the Volcanoes region, near Shila gold mine (after Gałaś, 2008; modified). See Fig. 2 for explanation

Chilcayoc Grande and possibly even older volcanoes, like Yanamauras and Ticsho.

Less regular pyroclastic cones situated slightly down the Valley of the Volcanoes are younger. These are Chico (370±50 years BP; Cabrera and Thouret, 2000) and Chilcayoc cones breached by lavas, which flowed out of them and surrounded Jechapita (Fig. 4). The valley became flat there and at least one lava dome was active in the vicinity of Sucna in that time. Lava derived from the dome (S61) was winding among older flows and directed southwards forming cataracts on the edges of transverse faults. The Sucna lava flow is 14 km long and ends at Laguna Mamacocha. The bottom of the Sucna Valley rises towards the NE and lava flowed only one kilometre inside it and blocked its connection with the Valley of the Volcanoes.

The youngest eruptions in the Andahua Group occurred along the Jenchana–Ninamama fault (Fig. 3). It is a steep fault with a downthrown side approximately 40 m to the SE. Outcrops of the Neogene volcanic Barroso Group, surrounded in the north by the first generation of lavas from the Andahua field, occur along the fault. The lava poured out there at least in seven centres forming domes charging the flows. As the fault scarp is relatively steep, the lava accumulated and formed in the north an over 30 m high front flow and then flowed to the SE in the form of a steep lateral flow. The biggest flow, Ninamama, is about 4 km long and 1 km wide. Angular blocks and pinnacles of *aa* lava occur on the surface of the flow. Hydrogen sulphide is emitted through a vent in the SW edge of the dome and native sulphur and gypsum crystallise in open fractures (Gałaś, 2009). It is apparently the youngest form among the Andahua Group.

An abandoned settlement called Antaymarca occurs on another lava flow in this zone, NW from the pyroclastic cone of Jenchańa (Fig. 3). Ruins of houses and pavements built of Andahua lava blocks are covered with thinly growing cactuses. The village was founded no more than 200–300 years ago (M. Sobczyk, pers. comm.).

The rugged mountain massif Shila (Chila), a relict of Huayta caldera of the Miocene age (Marcoux *et al.*, 1998; Paulo & Gałaś, 2006), builds the NE border of the Valley of the Volcanoes. The highest eruption centres of the Andahua Group (Fig. 5) have been distinguished in the vicinity of the Shila gold mine galleries, which are located in hydrothermally altered volcanic rocks of the Orcopampa Formation. These are two lava domes and a pyroclastic cone Ticlla (5,300 m a.s.l.). Their activity probably belongs to the first generation. All landforms bear distinct signs of glacial erosion. The flow of block lava near Shila lagoon is smoothed by ice. The lava flowed mainly towards the Lagoon de Chachas in the Valley of the Volcanoes, covering an area of over 35 km^2 (Gałaś, 2008). Soil has already formed on the lava and the lower part of the cover is already used as a farmland by inhabitants of the Chachas village. The front of the lava flow is currently covered by water and lagoon sediments lying at an altitude of 2,900 m a.s.l. A relatively large pyroclastic cone Pucamauras (approximately 250 m high) was formed in the middle of the flow. The volcano is a significantly younger landform in the region, probably belonging to the second generation.

The Rio Sora valley is controlled by tectonic structures and it is a lateral arm of the Andahua–Orcopampa graben (Fig. 2). Otherwise, it forms the continuation of the middle segment of the Valley of the Volcanoes as its course is similar. The upper part of the Rio Sora Valley is flat and forms a vast pampa at the altitude of 4,400–4,600 m a.s.l.

The oldest eruptions (of the first generation) took place on the ridges surrounding the Rio Sora Valley in the north and west. Two small domes occur there: Umajala and Jullulluyoc. In both cases the outflow started from the ridge. The Umajala dome was glaciated, the flows are partly eroded and their interiors are built of massive smooth-sided blocks of lava. The crater shape has been preserved in the Jullulluyoc dome and the flows have preserved a characteristic *levée*. The length of the flows reaches up to 4.5 km. On the western side, at the small valley of Rio Pallcca, lava flowed down from the centre on the foothill massif of Coropuna.

Successive eruptions (of the second and third generations) occurred at the bottom of the valley, probably beginning in its upper part. Lavas poured out from at least five centres (Fig. 2). Currently, two of them can be seen and the pyroclastic cone Misahuana Mauras is in the place of the third one. Lava flows spread vastly over the pampa and then flowed down towards the Valley of the Volcanoes. At Pabellón Lagoon, the lava field widens covering the whole width of the valley (6 km). Other eruption centres in this area include the Jochane dome and two pyroclastic cones of Pabellon and Yana Mauras. Smaller domes appear down the valley, but due to erosion and vegetation cover they are less

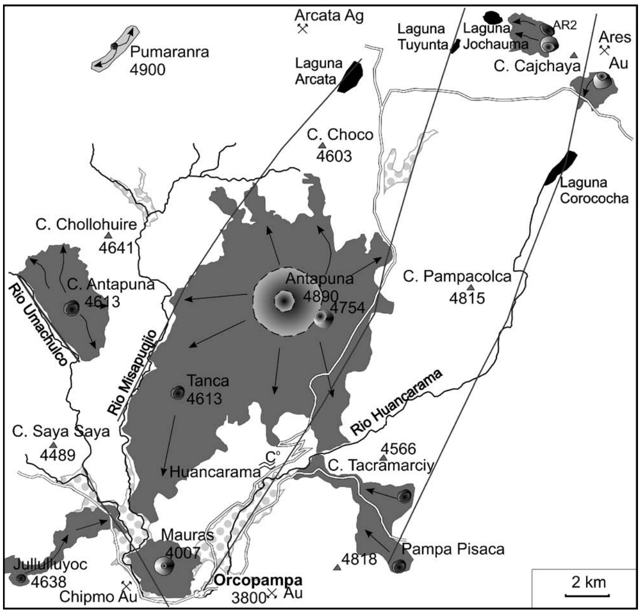

Fig. 6. Andahua Group in the Antapuna region (from Gałaś, 2008; modified). See Fig. 2 for explanation

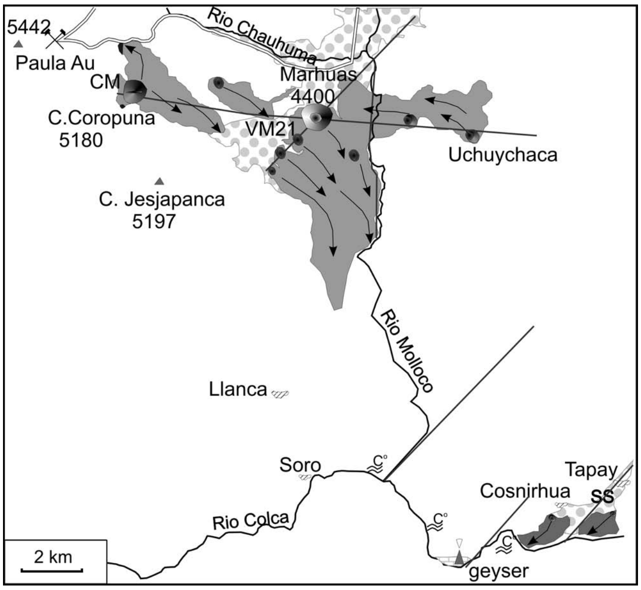

Fig. 7. Andahua Group in the Rio Mollocco region (after Gałaś, 2008; modified). See Fig. 2 for explanation

distinguished. These could have been places of lava projections above a solidified lava crust of the tumulus-type. The total length of the field is 20 km and its width varies from 1 to 6 km.

Antapuna. The Antapuna massif closes the Valley of the Volcanoes in the north (Fig. 6). The meridional Andahua–Orcopampa graben splits there into two branches: Chilcaymarca – Umachulco, trending NNW, and Huancarama, oriented NE. In the dividing, the Andahua lavas of the first generation build insular caps rising above 4,500 m a.s.l. on the edges, *i.e.* 700–1,000 m above the valley bottom. The biggest of them surrounds two summits, a relict of the Antapuna cone (4,890 m a.s.l.). The largest eruption centre – Antapuna – is elevated approximately 1,000 m above the bottom of the Valley of the Volcanoes. Due to intense glacial erosion, only fragments of a large, gently inclined cone have been preserved. Its diameter could have exceeded 4 km. Remnants of a parasitic cone can be found to the south-east of the crater. The lava was flowing radially over an almost flat surface building a shield covering an area exceeding 80 km^2. It seems likely that the southern portion of the area was also charged from the Tanca dome. Thermal springs in Huancarama, 6 km south of the Antapuna peak, are one of the post-volcanic phenomena.

Above the Huancarama valley, another lava flow outpoured from a small glacial valley of Pisaca where two small lava domes are located, being the sources of lava flowing towards the Huancarama valley.

A smaller eruption centre of the same name – Cerros Antapuna – is located more towards the west over the Umachulco valley (Fig. 6). Lavas form here a very flat cover undermined by the Umachulco River. The cover is 1.5 km wide and approximately 6 km long.

Other eruption centres are located in the vicinity of the Ares gold mine, on the slopes of Cerro Cajchaya (Fig. 6). Only one dome and two pyroclastic cones have been found there. All the landforms have been eroded by a glacier. There are also distinct glacial striations on massive lavas which poured out of the domes.

The youngest eruption centre (of the third generation), the Pumaranra lava dome, is located west of the Arcata silver mine. Lavas that extend from the base of the dome flowed both north-east and south-west. The flows are 100 m thick and they are composed of *aa* lava and block lava.

Rio Molloco. It is a relatively small area where the Andahua Group occurs, but it is interesting due to variety of landforms. Volcanic forms in this area have been classified as belonging to the second generation, despite some features proving glacial erosion. They occur near the current snow line and are well preserved. The main lava field covers the bottom of the Molloco valley (Fig. 7). There are four small lava domes there, discharging lava flowing towards the Colca Canyon. Above them, a pyroclastic cone Marhuas occurs whose relative height is 120 m. It is accompanied in the east by the Uchuychaca lava flow with a distinct *levée*. The other lava flow outpoured from a small glacial valley where two small lava craters are located.

A similar valley is situated on the western side of the Molloco Valley and it is partly filled with the Andahua lavas. The Paula gold mine is located in the upper part of the valley. The Andahua eruption centres are located in the bottom of the valley (below the mine) and lavas flowed towards the Molloco Valley. The largest of the observed lava domes of the Andahua Group, Cerro Coropuna (Fig. 8), attains a relative height of 250 m. Its jagged summit rises at 5,180 m a.s.l. (Gałaś, 2008). The dome is exceptionally steep and it is entirely built of large blocks of dacitic lava. It could have been an extrusive Peléean dome.

Smaller lava domes occur 3 km towards the east. Flows of block lava poured out from them. The thickness of the lava cover in the valley slightly exceeds 10 m and lengths of the flows vary from 1 to 3 km.

Fig. 8. Cerro Coropuna (5,180 m a.s.l.) lava dome. Sabancaya and Ampato stratovolcanoes seen at the horizon

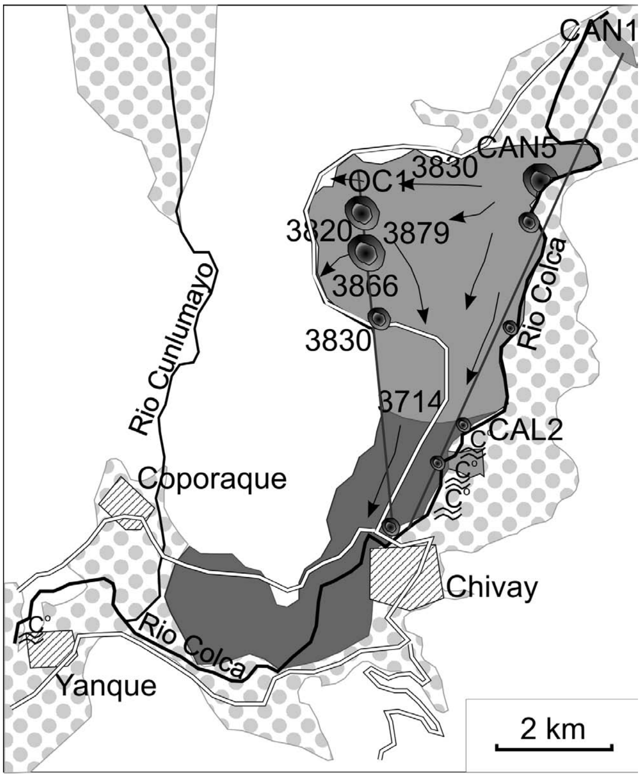

Fig. 9. Andahua Group in the Rio Colca Valley region. See Fig. 2 for explanation

Remnants of two small lava flows can also be found in the Canyon, below Tapay and between Tapay and Coshnirhua (Fig. 7). Rocks lying below the lava on the canyon walls rising from the Colca River are covered with native sulphur. In the Colca Canyon, towards the west, a dormant geyser and a slope built of travertine occur.

Laguna Parihuana. A mountain upland area occurs inside a Miocene caldera located south of Caylloma (Fig. 1). Single, isolated cones built of pyroclastic deposit and lava rocks typical for the Andahua Group can be found there. Their names are: Antaymarca, Saigua, Challpo, Andallullo, Antacollo and Sani (Table 2). Despite severe climate conditions at an altitude of approximately 4,500 m a.s.l., the cones are partly covered with vegetation and therefore they are assigned into the first or at least the second generation. The Antaymarca volcano, which has been thoroughly investigated, is 140 m high and has a relatively flat summit, 100 m in diameter. The crater is not visible. Abundant vesicular lavas, pumice, scoria and volcanic bombs and also small amounts of pahoehoe lavas can be found on the top.

Rio Colca Valley. The lavas belong to two age generations: the first (older) and second (middle) ones (Fig. 9). The older lavas cover the bottom and the northern edge of the Rio Colca Valley in the vicinity of Chivay. The Rio Colca carved a several dozens metres deep canyon in these lavas, which are 230–400 ka in age (Quispesivana & Navarro, 2001). The field was fed by at least 3 lava domes, which are located about 3 km north of Chivay and close to the bridge. Lavas in this part of the field are 20 to 90 m thick. The fields are covered with vegetation.

The younger lava field is situated north of the domes occurring below Canocota village. The lavas (90 ka) were flowing from 10 domes towards Chivay. On the east, the Colca River flows around the village in a canyon, which was cut in the lavas. It separated parts of the flow near Calera village. There are thermal springs in Calera, which charge leisure pools. Outflows of thermal water and hydrogen sulphide frequently occur up and down the river.

A small lava dome with a short flow has been discovered on the Rio Colca, below Lari and west of Madrigal.

Jarán. It is an area located on the southern side of the Colca Canyon (Fig. 10). It is almost uninhabited due to very few water sources. Lavas and tephra in this area belong to the oldest (first) generation.

Three lava fields in the vicinity of Gloriahuasi hacienda have been classified as the oldest ones due to their high level of erosion. The oldest eruptions occurred on the slopes of Cerro Gloriahuasi. Currently, only fragments of two domes and remnants of a small pyroclastic cone, as well as lava flows in the form of narrow rims on strongly eroded ridges can be observed there. The walls of the crater are built of red scoria and blocks. Granitoid xenoliths have been found in the agglutinate below the crater.

The Timar flow probably had two eruption centres. One of them is hidden under colluvial deposits on the Cerro Timar slope and a fragment of the second one – a lava dome – can be seen on the edge of a steep threshold over the Gloriahuasi stream valley. The field ends sharply (400 m high scarp) when the Sutanay and the Gloriahuasi valleys join each other. Opposite the structure a large Gloriahuasi volcano occurs, whose relative height is 450 m (Fig. 11). It is the only one stratovolcano belonging to the Andahua Group.

There are two pyroclastic cones, Honda and San Cristobal, in the Luceria field (Smoll *et al.*, 1997), which were probably formed in the final phase of the lava domes eruption. Lavas were flowing towards the Colca Canyon.

Rocks in the steep canyon, at the source of the Gloriahuasi spring, are covered with a thin layer of native sulphur being an effect of post-volcanic processes.

Jarán is the largest lava field in this region, which covers 75 km^2. 13 eruption centres have been distinguished in

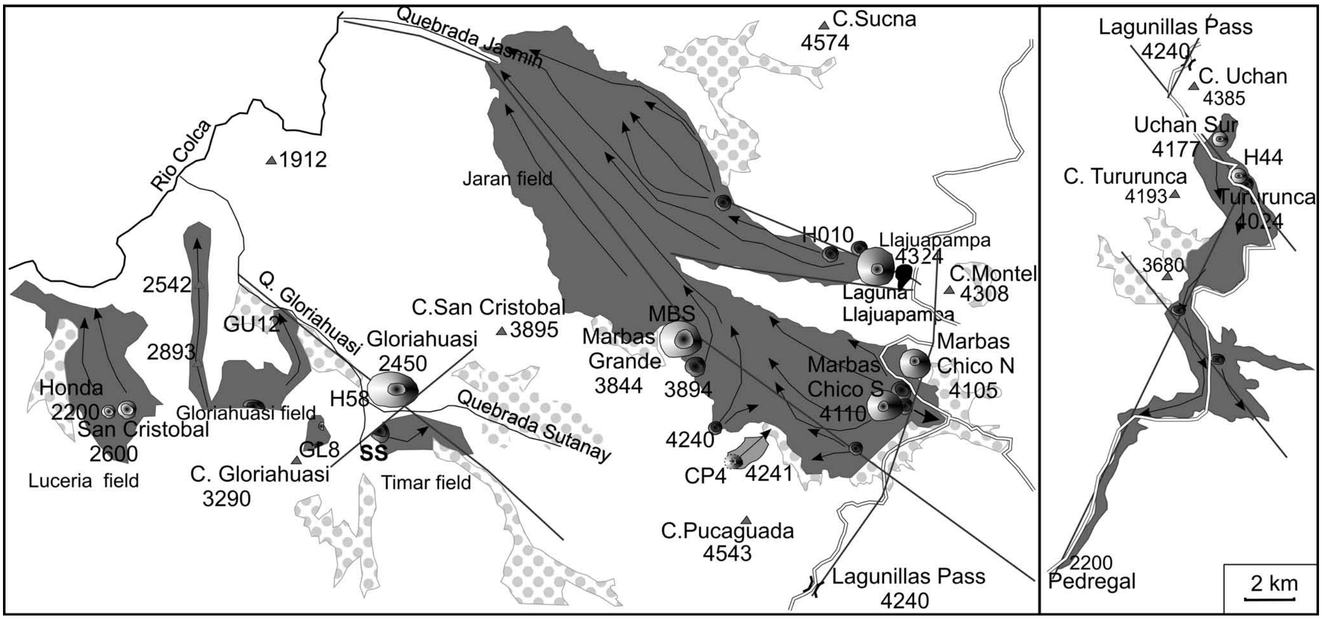

Fig. 10. Andahua Group in the Jarán region. See Fig. 2 for explanation

this area (Fig. 10). Lavas were flowing from the upper part of the Rio Jarán valley on its edges and in branches and finally united into one, single field. As a result, the whole length of the 19 km long valley became covered with lava and the width of the lava field reaches 6 km. The Jarán Valley is hanging above the Colca Canyon. When the eruption ceased, the Jarán River cut the lavas forming gorges and deposited gravel terrace covers on the banks. The thickness of black massif lava exposed in gorges is between 15 and 35 m.

Following the effusion, some centres were still ejecting pyroclastic material, which formed cones. The highest one is the Llajuapampa volcano (4,324 m a.s.l.), whose relative height attains 170 m. The Marbas Chico Sur and Norte, and also Marbas Grande volcanoes are much lower. The Marbas Chico Norte cone is 139 m high and its slope inclination attains 35° (Gałaś, 2008). There is one more cone on the slope of Cerro Pucaguada, 400 m above the bottom of the valley, which seems to be a bit younger (belonging to the second generation). Initially, lava flowed from the centre and ran down along the slope to the alluvia. The second centre located on the same slope, approximately 1 km to the NW, emitted lava which joined the lava field at the bottom of the Jarán valley.

The Uchan field is the southernmost field situated along the road from Huambo to Pedregal (Fig. 10). Lavas from the field form a 10-km-long narrow flow running to the SW. Two pyroclastic cones are located there: Uchan Sur (4,177 m a.s.l.) and Tururunca (4,024 m a.s.l.). On the southern slope of Uchan Sur white pumice is dominant.

Huambo. Four lava fields were mapped in this region: Mojonpampa, Uncapampa, and two small fields Jajacuchu and Toyapampacuchu. Most of the eruption centres are situated on a vast plateau (3,400–4,300 m a.s.l.), the border of which is formed by the southern edge of the Colca Canyon. The oldest eruption took place NE of the Chinini village. Lavas flowed from several domes with relative height from several dozens to 100 m. Most of the lavas formed a cascade down the Chinini valley and the rest spread to the northern vast plateau. Other eruptions occurred more to the north, along the faults parallel to the course of the Colca Canyon (SWW–NEE; Fig. 12). Eruptions occurred on the western slope of Hualca Hualca stratovulcano.

Fig. 11. Gloriahuasi stratovolcano

The eastern part of the lava field is a little younger. The edges of the flows and the eruption centres are better preserved. It is possible to distinguish there at least three domes wherefrom lava flows started moving towards the west and the north overlapping the western lava field. The latter flows reached the Canyon forming a cascade down to its bottom. The longest flow is 14 km long. These flows are also cut by the above mentioned faults. The youngest volcanic landform in the lava field is the Keyoc volcano, which occurs on an old lava dome. The lava fields in this region cover an area of approximately 100 km^2 (Gałaś, 2008).

The Uncapampa lava field forms a plateau between the Rio Huambo and Rio Colca rivers. It is separated from the previously described field by an almost 600 m high ridge

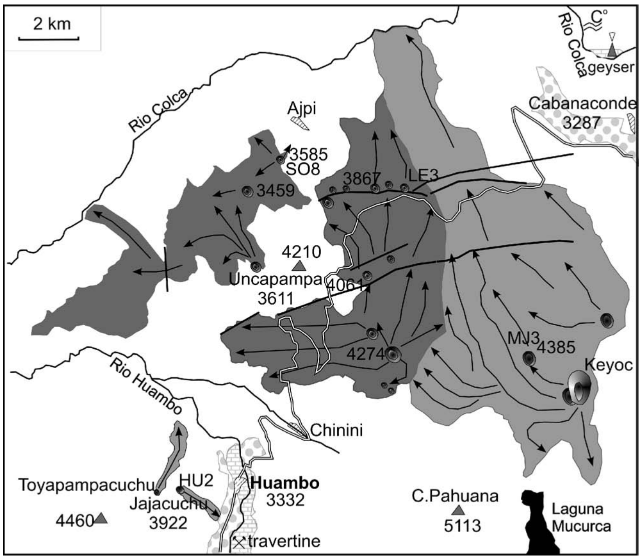

Fig. 12. Andahua Group in the Huambo region (after Gałaś, 2008; modified). See Fig. 2 for explanation

(4,210 m a.s.l.; Fig. 12) built of folded quartzite (Yura group, Jurassic/Cretaceous), crowned by Neogene dacite intrusion. The age of the field is assigned into the first generation. The eruption centres are strongly damaged by erosion and the courses of the flows are hard to determine. The edges of the lava field are eroded. Three eruption centres have been distinguished. A lava dome with a crater – Uncapampa (3,611 m a.s.l.) – occurs at the foot of the ridge, and an eroded dome (3459 m a.s.l.) is placed the centre of the field. A small dome (3,585 m a.s.l.) is located on the edge of the secondary ridge above Ajpi. Lava was flowing from this dome on both sides of the ridge.

Other eruptions in the region had a smaller extent. Two centres are located on the secondary ridges; Toyapampacuchu and Jajacuchu, west of Huambo. The lava flows ran from the ridges and nearly reached the bottom of the Huambo Valley. Part of the Huambo Valley at the altitude of 3,830 – 3,200 m a.s.l. is filled with a thick cap of travertine, being probably the result of volcanic activity.

RELATIONS BETWEEN VOLCANIC ACTIVITY AND TECTONICS

The subduction of oceanic crust under the Arequipa segment of the South American continent is supposed to have been active since the Palaeozoic (Golonka & Ford, 2000; Golonka, 2007). The Peruvian phase (Late Cretaceous/Palaeogene) is considered to be the main compression phase in this part of the Andes accompanied by rapid growth of magmatic arc and crustal thickening (Sempere & Jacay, 2008). Numerous folds, thrusts and faults oriented NW–SE were formed then. Later, the compression axis became rotated (Sébrier & Soler, 1991) and the structures were transformed into perpendicular ones (NE–SW) under the influence of the compression in the next phases. The NE structures were formed in the Early Miocene and NEE ones in the Late Miocene, while at the Miocene/Pliocene boundary they were already oriented W–E (Soulas, 1977). The orogeny still lasted in the Neogene and volcanic eruptions culminated in Miocene time, forming several calderas within a long-lived volcanic arc of Puquio–Calloma and resulting also in hydrothermal ore veins (Noble *et al.*, 2003; Paulo, 2008).

The Andahua Group eruption centres concentrate in tectonic basins, which originated due to regional tension along faults and pre-existing compression features. According to Caldas (1993), the deep crustal fractures reached magma chambers causing a decrease of pressure and rising of magma.

The lava fields in the central part of the Valley of the Volcanoes seem to fill the depression. The identified eruption centres are aligned along faults controlling the graben and crossing the valley. However, the eruption centres occur not only within the Valley of the Volcanoes but also on horsts. This is exemplified by the Antapuna centre above Orcopampa (Fig. 6), numerous centres near Shila, Paula and Ares mines – all above 4,800 m a.s.l. – as well as some flows situated on a ridge near Huambo: Jajacuchu and Toyapampacuchu (Fig. 12).

Faults observed in the Valley of the Volcanoes in the Mesozoic bedrock continue into Quaternary colluvial deposits and also in lavas of the Andahua Group. For example, SW from Laguna de Pumajallo, the Andahua River is squeezed between the lava cover and the eastern bank of the valley built of Mesozoic sedimentary formations (Fig. 3). The edge of the valley built of Jurassic sandstone follows an active faults oriented N150°. In the period of 2003–2010 the river incised 4 to 5 m into the alluvium. This is indicated by a damaged concrete bridge (built in 2000), whose abutments moved back causing breaking of the structure and its collapse into the river.

According to tectonic studies of Sébrier and Soler (1991), the stress regime in this part of the Andes is typified by N–S extension and E–W compression associated with the convergent oceanic Nazca plate. The extension axis in the Arequipa region is aligned NE–SW (Mering *et al.*, 1996).

New investigations (Żaba & Małolepszy, 2008) concluded that some horsts and grabens in Quaternary deposits of the Colca Valley developed on the first generation of faults oriented N–S. The next generation is oriented NE–SW and NW–SE. Tectonic discontinuities in the Maca–Pinchollo sector (part of the Colca Valley) are based on WNW–ESE and NE–SW trending faults (Żaba & Małolepszy, 2008).

Four systems of faults can be distinguished in the mentioned area: (1) gravitational faults running N–S and causing displacement of the northern and southern parts of the Valley of the Volcanoes; (2) steep, gravitational faults running NW–SE and WNW–ESE, which close the Valley of the Volcanoes in the vicinity of Orcopampa and Ayo and also cut the Andahua lava flows in the central part of the valley (Figs 2, 3); (3) sinistral strike-slip faults, approximately oriented NE–SW, developed in the central part of the Valley of the Volcanoes; (4) W–E oriented faults observed on the surface of the Andahua lavas at Mojonpampa (Fig. 12).

The system (1) can be observed at the borders of the Valley of the Volcanoes: Chipchane–Santa Rosa and along Panahua–Cerro Mauras (Fig. 2). Lava domes and pyroclastic cones of the Andahua Group are aligned mainly along the systems (2), (3) and (4). The second system follows the line Ticsho–Cochapampa–Jenchana–Ucuha and also A6–Chico–Chilcayoc–Chilcayoc Grande (Figs 2, 3). The third system is represented by eruptive centres along the line Jenchańa–Ninamama and also Cerro Toruyoc–Sucna (Fig. 3). This is a transverse system in the Valley of the Volcanoes which forms structural steps. The fourth system is parallel to the orientation of the Colca Canyon and the eruption centres on the Mojonpampa aligning it in the region of Huambo (Fig. 12).

PETROGRAPHIC AND GEOCHEMICAL CHARACTERISTICS OF THE ANDAHUA VOLCANIC ROCKS

The Andahua lavas are dark grey or black and reddish on weathered surfaces in the zone below 3,000 m a.s.l. because of higher external temperatures. Tephra from volcanic cones is mostly black, only close to craters, agglomerates of bombs cemented with lava and scoria become red. Ashes are black, sometimes with white layers of clay minerals. Porosity of all lavas is 10–20%, while scoria from pyroclastic cones shows porosity of 40 to 70%. Block lavas squeezed out of the domes are significantly less porous, sometimes becoming megascopically massive near eruptive vents or in internal parts of lava flows.

Hypocrystalline-porphyritic rocks with generally low content of phenocrysts (up to 15%; exceptionally to 70%; sample VO2) are most common among the Andahua Group. Aphyric-felsitic rocks are also abundant. The groundmass is of hyalopilitic, felsitic or microcrystalline texture. The rocks are porous, rarely dense, their fabric irregular or fluidal. Phenocrysts are represented by plagioclase, pyroxene, hornblende, olivine or rarely biotite and alkali feldspar.

Phenocrysts of the plagioclase reach the size of 2 to 6 mm in different lava flows. They are usually corroded to a variable extent; they dominate also among microlites and microcrysts. Composition of this generation is just slightly more acid than that of the phenocrysts. I found lavas with significant domination of plagioclase phenocrysts in domes in the region of Huambo (Fig. 12, sample LE3) and Cerro Coropuna (Fig. 7, sample CM).

Investigation of phenocrysts by means of an electron microprobe (Delacour, 2002) proved the occurrence of zonal plagioclase An_{63-72} in basalt and An_{29-49} in dacite. Intermediate elements like labradorite-andesine occur more frequently in andesite. Zones rich in glass inclusions have been found in phenocrysts of the plagioclase (Delacour, 2002).

Pyroxene, after plagioclase, is a typical phenocryst mineral in many samples from the Andahua Group. Augite is in majority among pyroxene; enstatite is also present in some lavas. Ortho- and clinopyroxenes are usually significantly pickled and changed. They become a component of the groundmass in some samples. Exceptionally large (4 mm) phenocrysts of pyroxene occur in the lavas of the southern part of the Mojonpampa lava field (sample H015b). Pyroxenes are present, as dominant phenocrysts, in lavas occurring near Cerro Ticlla (Fig. 5, sample A14) and Cerro Cajchaya (Fig. 6, sample AR2).

I also observed rocks where amphiboles represented by oxyhornblende (basaltic hornblende) were dominating phenocrysts. They occur in various forms starting from complete crystals to such forms where they are partly or totally replaced by glass or microlites. Quite frequently, opacite rims are well developed (Fig. 12, HU2). Numerous crystals of oxyhornblende occur in the Rio Tambo valley (Fig. 2, sample DK3), in the Rio Sora valley (MS1), and in the lava field between Ticsho and Yanamauras volcanoes.

Olivine is represented by forsterite-rich members containing large admixtures of Cr and Ni. Its phenocrysts are sometimes strongly mechanically damaged (protoclase) with corrosion holes, or appear in the form of skeletal crystals. The phenocrysts of olivine from Cerro Uchan volcano in Gloriahuasi zone (Fig. 10, sample H44) bear envelopes of iddingsite, inclusions of ore-bearing minerals and show protoclase and corrosion. Olivine occurs in a few samples collected by the author in the study regions (Fig. 1), but they are dominant in the lavas from Cerro Nicholson (near Arequipa) which were classified as the Andahua Group by Delacour *et. al.* (2007).

Felsitic, microfelsitic and hyalopilitc ground mass is built mainly of various amounts of plagioclase, pyroxene and glass. Olivine, quartz and ore minerals (titanomagnetite and Fe oxides) occur there as accessory minerals.

Chemical analyses have proved high content of alkalis, with sodium prevailing over potasium. The contents of SiO_2 published by Weibel and Fejér (1977) are 54–63% and those analysed by Delacour *et al.* (2007) 52.1–68.1% , but the second authors presented results up to 64.9 % only. My samples showed a wide range of silica contents: 52.4 to 67.9 %, and in the majority of the rocks within the range of 54–62%. The content of K_2O was equal to 1.4–3.3% and that of Na_2O 3.4–5.4% (Table 3) with total alkalis of 5.2–8.1 %. Contents of alumina, iron and calcium were close to average contents in the spectrum of trachyandesites and latites (Le Maitre, 1976).

Projection points of the analysed lavas from the Andahua Group on the TAS diagram of chemical classification of volcanic rocks (Le Maitre *et al.*, 1989) concentrate in the lower part of the trachyandesite field, entering also the basaltic trachyandesite or trachyte/trachydacite fields (Fig. 13). Therefore, they show a slightly alkaline affinity. Single samples are located in the basalt and andesite fields. Taking into consideration additional criteria, the analysed lavas correspond mainly to three types of rocks: benmoreite, latite and mugearite. The lavas from Cerro Nicholson investigated by Delacour *et al.* (2007) belong to shoshonites. The lavas coming from Cerro Coropuna near Paula gold mine are much more silic and appear on the diagram at the same position as trachydacite, close to the dacite and rhyolite fields. Lavas from the Chipchane lava dome appear on the diagram at the intermediate position between trachyandesite and trachydacite, but they are classified as trachyte.

Table 3

Major elements composition of igneous rocks from Andahua Group
(ICP-OES at Activation Laboratories Ltd. – ACTLABS (Canada))

Region	A. Valley of the Volcanoes													B	C	
Sample	MS1	YM1	DK3	VCO	ARCH1	C1A	AC3	J1	CH2S	AS1	AYO5	MAM3	A14	AR2	CM	VM21
[wt.%]																
SiO_2	59.51	58.50	60.21	57.24	61.76	57.79	58.83	59.13	57.75	60.30	61.09	58.61	54.36	55.28	67.00	59.60
TiO_2	1.30	1.30	0.98	1.31	1.00	1.27	1.14	1.16	1.34	1.09	1.05	1.21	1.50	1.43	0.53	1.19
Al_2O_3	16.96	16.88	15.95	16.66	15.90	16.93	16.75	16.74	17.04	16.19	16.41	16.81	16.98	17.09	14.73	16.65
Fe_2O_3	6.15	6.92	5.82	7.17	5.42	6.64	6.20	6.05	6.75	6.44	5.64	6.63	8.01	7.56	3.02	5.92
MnO	0.07	0.08	0.08	0.09	0.08	0.08	0.07	0.08	0.08	0.08	0.07	0.08	0.10	0.10	0.05	0.07
MgO	2.39	2.72	2.75	3.60	2.23	2.69	2.39	2.37	2.85	3.03	2.35	2.90	4.00	3.36	1.11	2.39
CaO	5.16	5.90	5.44	6.60	4.66	6.08	5.40	5.39	6.16	5.28	5.37	5.93	6.92	6.50	2.89	5.29
Na_2O	4.83	4.71	4.26	4.39	4.91	4.49	4.94	4.51	5.43	3.99	4.63	4.57	4.80	5.16	4.40	5.15
K_2O	3.13	2.57	2.56	1.80	3.02	2.44	3.02	2.58	2.52	2.91	2.90	2.64	1.78	2.05	3.51	2.87
P_2O_5	0.65	0.61	0.45	0.47	0.47	0.51	0.64	0.47	0.65	0.39	0.50	0.57	0.54	0.61	0.20	0.58
LOI	0.61	0.33	2.04	1.38	0.21	0.56	0.20	-0.01	0.10	0.75	0.13	0.49	0.17	0.29	1.33	0.27
Total	100.80	100.50	100.50	100.70	99.65	99.50	99.59	98.47	100.70	100.40	100.10	100.40	99.15	99.43	98.77	99.98

Region	D	E. Rio Colca Valley				F. Jaran							G. Huambo			
Sample	HT1	OC1	CAN5	CAN1	CAL2	LAR12	H010	MBS	CP4	GU12	H58	H44	GL8	SO8	HU2	MJ3	LE3
[wt.%]																	
SiO_2	54.51	59.21	59.78	58.4	57.35	57.41	57.66	55.72	58.89	53.51	55.55	52.35	52.13	58.78	55.39	58.69	59.57
TiO_2	1.51	1.19	1.18	1.17	1.36	0.97	1.27	1.43	1.15	1.57	1.63	1.40	1.97	0.99	1.21	1.02	0.98
Al_2O_3	16.34	16.66	16.76	16.65	16.36	15.82	16.73	16.71	16.54	16.14	16.62	17.2	15.97	16.2	16.25	16.46	16.19
Fe_2O_3	8.11	6.15	6.19	6.20	6.68	5.69	6.38	7.51	5.82	7.14	7.37	8.22	9.04	6.20	6.82	7.09	6.24
MnO	0.11	0.08	0.07	0.07	0.08	0.07	0.08	0.09	0.07	0.09	0.08	0.11	0.11	0.10	0.08	0.09	0.09
MgO	4.32	2.61	2.44	2.39	2.52	2.21	2.51	3.35	2.34	2.84	2.98	3.69	3.91	2.78	3.31	3.06	2.98
CaO	6.81	5.38	5.30	5.19	5.78	5.18	5.52	6.64	5.80	6.72	6.46	7.38	7.12	5.40	7.28	5.49	5.73
Na_2O	4.39	4.64	4.84	4.70	4.74	4.53	5.18	4.21	5.06	4.84	5.23	4.57	4.01	3.66	3.27	3.57	3.98
K_2O	2.09	2.75	3.05	2.83	2.60	2.95	2.97	1.94	2.94	2.45	2.33	2.11	2.02	3.34	1.73	2.98	3.29
P_2O_5	0.63	0.59	0.59	0.59	0.71	0.48	0.66	0.66	0.59	0.84	0.80	0.56	1.06	0.34	0.55	0.33	0.32
LOI	0.52	0.39	0.00	0.20	-0.01	0.18	0.49	1.30	1.70	0.10	0.33	1.40	0.60	1.00	3.53	1.41	1.38
Total	99.35	99.65	100.2	98.4	98.19	95.50	99.44	99.56	100.90	96.23	99.38	98.99	97.94	98.82	99.43	100.20	100.80

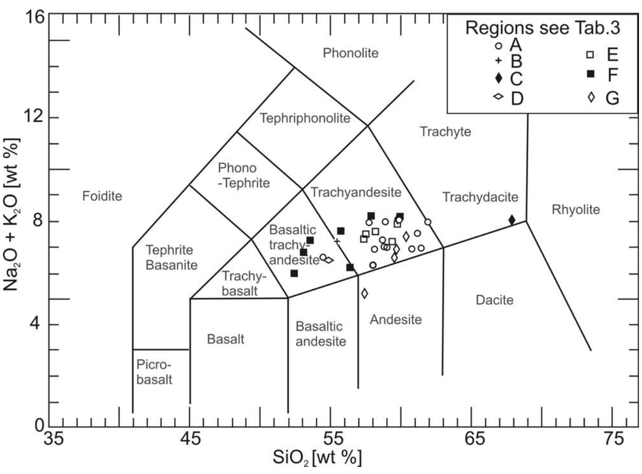

Fig. 13. Position of the Andahua volcanic rocks from regions A-G on the TAS diagram

Lavas in the vicinity of Andagua contain numerous xenoliths of white quartzite of the Yura Group (Caldas, 1993). Quartzite layers are ubiquitous in the Valley of the Volcanoes and most probably occur also in the graben filled with lava.

My analysis of spatial variations of lava chemistry gives the following results:

– benmoreite dominates in the northern and central parts of the Valley of the Volcanoes including the Rio Sora valley (Yana Mauras, Cochapampa, Fig. 2);

– latite is in majority in the central and southern parts of the Valley of the Volcanoes (Ucuya, Jechapita and Sucna, Fig. 3), and dominates south of the Colca Canyon in Huambo region (MJ3, SO8, Fig. 12);

– benmoreite (Llajuapampa, CP4) and mugearite (Marbas Grande, GL8) are represented by lavas from the region of Jarán (Fig. 10);

– latite and benmoreite occur in the Chivay region (Fig. 9);

– andesite bearing the mean content of potassium typical for calc-alkali volcanism appears in a crater located on the Cerro Jajacuchu ridge (Fig. 12).

According to my observations, the oldest lavas (of the first generation) corresponding to trachyandesite from the central part of the Valley of the Volcanoes are dominant (Ucuya, VCO, Rio Tambo; Figs 2, 3) also in all other regions. The lava from the Colca Valley (OC1, CAN1, Fig. 9) and from Huambo regions (LE3, Fig.12) are represented by latite. Mugearite is dominant in the region of Gloriahuasi (GL8, GU12, Fig. 10) and it is common in the lava field in the Shila sector (A14, Fig. 5).

The second generation is more varied and it occurs in all regions. It represents all classes subdivided on the TAS diagram. The samples from Cerro Tururunca (H44, Fig. 10) and Cerro Coropuna (CM, Fig. 7) are most outstanding among all Andahua volcanic rocks. Mugearite from C. Tururunca has the lowest content of SiO_2 and the highest amount of CaO. This volcano is nearest to the Pacific coast line (92 km) from all volcanic centres of the Andahua Group. On the contrary, the trachidacite from Cerro Coropuna has the highest contents of SiO_2, K_2O and the lowest amount of CaO. Cerro Coropuna is 142 km far from the Pacific coast. In the Valley of the Volcanoes, characteristic is trachite from the Puca Mauras volcano.

The youngest lavas erupted in the Valley of the Volcanoes and in the Antapuna region (Pumaranra, Fig. 6) only. On the TAS diagram, they are projected exactly in the field of trachyandesites, like benmoreites and latites.

DISCUSSION OF RESULTS

The Andahua Group is one of the youngest and the least investigated volcanic groups in South America. The latest investigations (Delacour *et al.*, 2002; Thouret *et al.*, 2002; Ruprecht & Wörner, 2007; Sørensen & Holm, 2008) have proved that it is characterised by a relatively varied mineral and chemical composition.

My studies emphasise the importance of the fact that volcanic activity of the group was spread in time and space. The oldest eruptions probably took place in the Middle Pleistocene in the areas of Gloriahuasi and Antapuna and also in the Valley of the Volcanoes. The youngest effusive activity took place in the Valley of the Volcanoes along the Jenchana–Ninamama fault. An active fumarole was observed near Ninamama vent in 2003. Recent activity of many centres suggests that future eruptions may be expected.

Eruption centres and lavas of the Andahua Group occur in the area whose dimensions are 110 by 110 kilometres. I distinguished six lava fields and identified 118 lava domes, craters, and 47 pyroclastic cones (Table 2). It means that the Andahua Group can be classified as a large basalt volcanic field (Connor & Conway, 2000). Despite significant distances between the eruption centres, their styles of activity were usually similar. The interpreted eruption styles were of Hawaiian type at domes and fissures and Stromboli or rarely Vulcano type at scoria cones. The only dome of acid lava (Cerro Coropuna – trachydacite) might have bought disastrous explosions but glacial erosion removed their traces, if any.

Lava effusions have been dominating over pyroclastic ejections. Lava flows when running down the slopes obstructed valley systems changing courses of river beds and formed lakes. Lavas are the main product of the Andahua volcanoes. The average thickness of individual flows is usually 15–80 m, however, in some fields it may accumulate up to 120 m.

The catalogue of eruption centres and maps of ranges in particular fields show the author's attempt to determine the discussed volcanic activity in time and space and becomes a base of output data for the discussion on the question what should be called the Andahua Group and which criteria allow to determine the newly discovered eruption centres as the members of the group. For example, the Santo Tomas Group described by Moncayo (1994) and located in the valley of the same name, about 70 km north of Caylloma, is probably a lithostratigraphic equivalent of the Andahua Group. It is of similar form, age (only of the first generation) and petrographic character and located about 70 km northeast of the Pumaranra Andahua lava dome.

Lavas from the Cerro Nicholson volcano near Arequipa are also assigned to the Andahua Group by Delacour *et al.* (2007) despite the fact that the distance from it to the Valley of the Volcanoes exceeds 100 km and the nearest Andahua eruptive centre is approximately 80 km away. Chemical composition (Delacour *et al.*, 2007) shows that the rocks are a little bit too alkaline (shoshonites), which appear slightly aside on the TAS diagram when compared to the other lavas from the group. However, their form and eruption style are analogous those of the Andahua Group, *i.e.* represent a monogenetic cone with a short lava flow. Similar forms but much more distant can be observed near Cusco/Sicuani, where the Quimsachata volcanic rocks also are classified as shoshonites (Delacour *et al.*, 2007), and in the Pancaurani volcanic rocks in the Tacna region (Caldas, 1993).

It hardly possible that Holocene lava flows originating underneath the ice cap on the summit of the Coropuna stratovolcano (*i.e.* at an altitude of at least 5,500 m a.s.l.) also belong to the Andahua Group. They cover glacial sediments, the age of which is approximately 10,000 years BP. The chemical and petrographic characteristics of the Coropuna and Andahua Group lavas show different origin (Venturelli *et al.*, 1978).

CONCLUSIONS

Five seasons of field studies made it possible to define the areal extent, centres of eruption and approximate age of the Andahua Group. The Andahua lavas stretch out at intervals in an area that is at least 110 km long and 110 km wide. Seven volcanic regions bearing centres of eruption have been distinguished, namely: the Valley of the Volcanoes, Antapuna, Rio Molloco, Laguna Parihuana, the Rio Colca Valley, Jaran and Huambo. Each region contains several lava fields composed of single or sequential lava flows, pyroclastic cones and many centres of lava effusion, including domes and fissures (Table 1). The Valley of the Volcanoes is the largest region where volcanic products are most common.

The total number of centres amounts to 165. A typical centre of eruption is a small lava dome aligned most probably along the feeding fissures. Eruption style is of the Hawaiian type. The second group of centres are scoria cones showing the Stromboli style of eruption.

Some fields can be classified as monogenetic, but the Andahua Group corresponds rather to basaltic volcanic fields. There occur clusters or polygenetic volcanoes which have erupted many times.

The lavas of the Andahua Group belong mainly to trachyandesites, entering also the basaltic trachyandesite or trachyte/trachydacite fields.

Eruptive centres of the Andahua Group are aligned mainly along the fault systems trending NW–SE and NE–SW. This is adequate to the inter-mountain graben in the Valley of the Volcanoes that continues to the Gloriahuasi region at the opposite bank of the Colca Canyon. There are so many proofs of quite recent activity of the numerous centres that future eruptions may be expected.

Acknowledgements

I am is grateful to Prof. A. Paulo and Dr. M. Muszyński for constructive comments on the first draft of this paper. Financial support was provided by the AGH University of Science and Technology statutory funds no. 11.11.140.560.

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