Bull Volcanol (1988) 50:287–303

Bulletin of Volcanology

The Nevados de Payachata volcanic region (18 °S/69 °W, N. Chile)

I. Geological, geochemical, and isotopic observations

G Wörner[1]*, RS Harmon[2], J Davidson[3], S Moorbath[4], DL Turner[5], N McMillan[6], C Nye[5], L Lopez-Escobar[7], and H Moreno[7]

[1] Institut für Mineralogie, Postfach 102148, Ruhr Universität Bochum, D-4630 Bochum, Federal Republic of Germany
[2] Dept. of Geological Sciences, Southern Methodist University, Dallas, TX 75275, USA
[3] Department of Geological Sciences, C. C. Little Building, University of Michigan, Ann Arbor, MI 48109, USA
[4] Department of Earth Sciences, Parks Road, Oxford OX1 3PR, United Kingdom
[5] Geophysical Institute, University of Alaska, Fairbanks, AK 99755, USA
[6] Department of Geology and Geography, Eastern Illinois University, Charleston, IL 61920, USA
[7] Departamento de Geologia y Geophisica, Universidad de Chile, Casilla 13518, Santiago, Chile

Abstract. Subduction-related volcanism in the Nevados de Payachata region of the Central Andes at 18 °S comprises two temporally and geochemically distinct phases. An older period of magmatism is represented by glaciated stratocones and ignimbrite sheets of late Miocene age. The Pleistocene to Recent phase ($\leq$0.3 Ma) includes the twin stratovolcanoes Volcan Pomerape and Volcan Parinacota (the Nevados de Payachata volcanic group) and two small centers to the west (i. e., Caquena and Vilacollo). Both stratovolcanoes consist of an older dome-and-flow series capped by an andesitic cone. The younger cone, i. e., V. Parinacota, suffered a postglacial cone collapse producing a widespread debris-avalanche deposit. Subsequently, the cone reformed during a brief, second volcanic episode. A number of small, relatively mafic, satellitic cinder cones and associated flows were produced during the most recent activity at V. Parinacota. At the older cone, i. e., V. Pomerape, an early dome sequence with an overlying isolated mafic spatter cone and the cone-forming andesitic-dacitic phase (mostly flows) have been recognized. The two Nevados de Payachata stratovolcanoes display continuous major- and trace-element trends from high-K_2O basaltic andesites through rhyolites (53%–76% SiO_2) that are well defined and distinct from those of the older volcanic centers. Petrography, chemical composition, and eruptive styles at V. Parinacota differ between pre- and post-debris-avalanche lavas. Precollapse flows have abundant amphibole (at $SiO_2 > 59$ wt%) and lower Mg numbers than postcollapse lavas, which are generally less silicic and more restricted in composition. Compositional variations indicate that the magmas of the Nevados de Payachata volcanic group evolved through a combination of fractional crystallization, crustal assimilation, and intratrend magma mixing. Isotope compositions exhibit only minor variations. Pb-isotope ratios are relatively low ($^{206}Pb/^{204}Pb = 17.95$–$18.20$ and $^{208}Pb/^{204}Pb = 38.2$–38.5); $^{87}Sr/^{86}Sr$ ratios range 0.70612–0.70707, $^{143}Nd/^{144}Nd$ ratios range 0.51238–0.51230, and $\delta^{18}O_{SMOW}$ values range from +6.8‰ to +7.6‰ SMOW. A comparison with other Central Volcanic Zone centers shows that the Nevados de Payachata magmas are unusually rich in Ba (up to 1800 ppm) and Sr (up to 1700 ppm) and thus represent an unusual chemical signature in the Andean arc. These chemical and isotope variations suggest a complex petrogenetic evolution involving at least three distinct components. Primary mantle-derived melts, which are similar to those generated by subduction processes throughout the Andean arc, are modified by deep crustal interactions to produce magmas that are parental to those erupted at the surface. These magmas subsequently evolve at shallower levels through assimilation-crystallization processes involving upper crust and intratrend magma mixing which in both cases were restricted to end members of low isotopic contrast.

Introduction

Active volcanism in the Andean arc of western South America occurs in three distinct and separated regions, i. e., the Northern Volcanic Zone (NVZ) from 2 °N to 5 °S, the Central Volcanic Zone (CVZ) from 16 °S to 28 °S, and the Southern

* *Present address:* Institut für Geowissenschaften, Postfach 3980, Universität Mainz, D-6500 Mainz, Federal Republic of Germany

Offprint requests to: G. Wörner

Volcanic Zone (SVZ) from 33 °S to 46 °S (Thorpe et al. 1982). Petrologic and geochemical investigations of magma genesis in the Central Volcanic Zone generally have been restricted to either large-scale, across-arc or along-arc traverses (e.g., McNutt et al. 1975, 1979; Dostal et al. 1977; Deruelle 1982; Longstaffe et al. 1983; Barreiro and Clark 1984) or comparisons with the other two zones (e.g., Francis et al. 1977; Klerkx et al. 1977; Deruelle 1982; Harmon et al. 1981, 1984).

The CVZ is characterized by exceptionally thick continental crust (> 70 km, James 1971a, b) and a great abundance of young (Late Mesozoic–Cenozoic) volcanoes. However, because of the high altitude and general inaccessibility of the region, few individual volcanic centers have been studied in detail. Exceptions are San Pedro-San Pablo at 22 °S examined by Francis et al. (1974, 1977) and O'Callaghan and Francis (1986), Cerro Purico-Chascon at 23 °S discussed by Hawkesworth et al. (1982) and Francis et al. (1984), and the Cerro Galan caldera at 26 °S studied by (Francis et al. 1980, 1983, in press).

The Nevados de Payachata volcanic complex and surrounding volcanic centers at 18 °S, 69 °W (Fig. 1) are located between the Barroso-Arequipa region at 16 °S–17 °S in southern Peru and the Salar de Atacama region at 22 °S–25 °S of northern Chile, southwestern Bolivia, and northwestern Argentina. The 18 °S area is virtually unstudied, but particularly interesting because of its unique tectonic setting. It is situated directly east of the "Arica bend," a conspicuous 45 ° kink in the Peru-Chile trench and the Nazca plate subduction zone, and is located near the buried southern margin of the South American Precambrian craton.

This report describes the volcanic history of the Nevados de Payachata volcanic region based on field mapping and whole-rock K-Ar age dating and calls attention to unusually high Ba, Sr, and Ti contents in an otherwise typical high-K, calc-alkaline central Andean volcanic suite. Questions

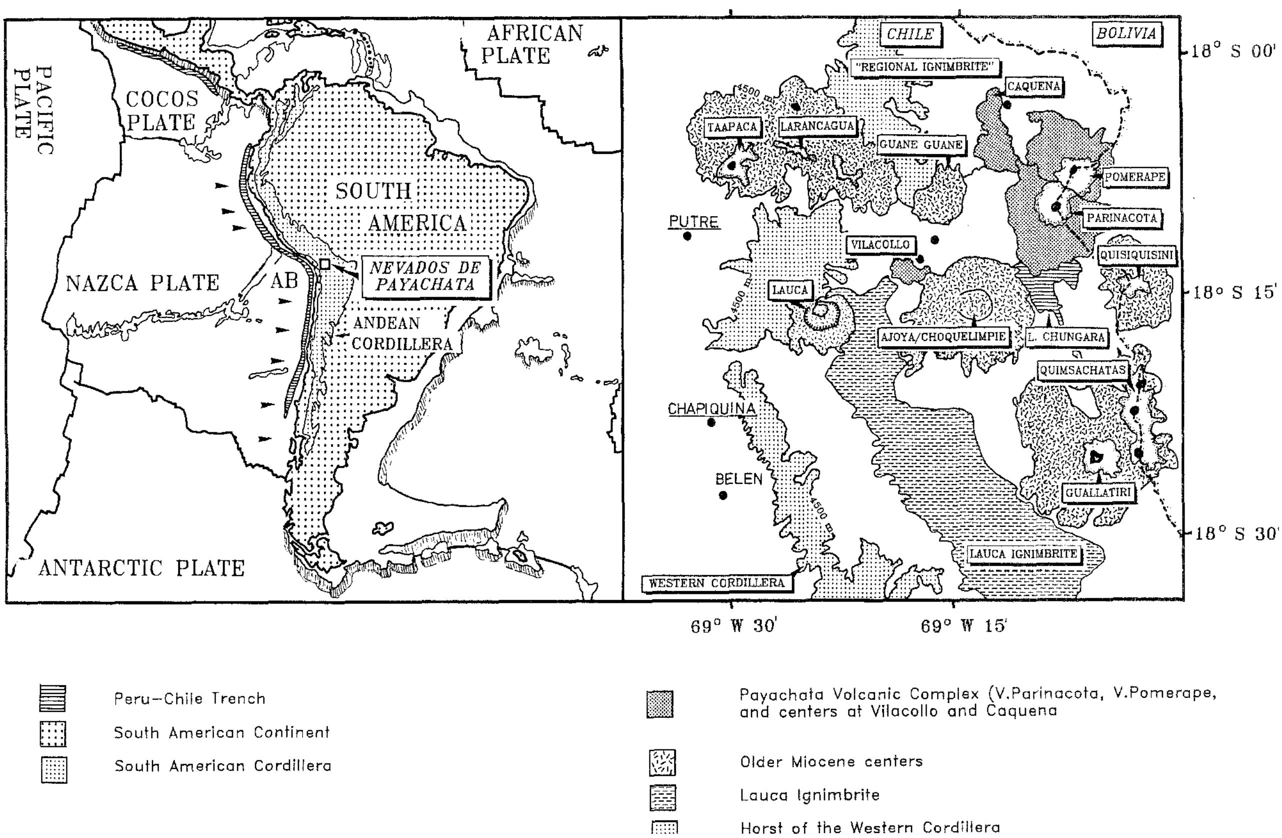

Fig. 1. a Tectonic setting of the volcanic zones in the South America Andes and location of the Nevados de Payachata volcanic group in the Central Volcanic Zone (CVZ). *Large arrows* indicate direction of movement of the Nazca plate toward the Peru-Chile trench (horizontal bar signature). *Wide dots*, South American continent; *narrow dots*, South American Cordillera (i.e., > 3000 m a.s.l.); AB, "Arica bend". **b** Sketch map of the Nevados de Payachata area and surrounding older centers. Bar in lower left = 10 km

regarding (a) the origin of this unusual chemical signature, (b) whether it is only a local and temporally recent feature, and (c) to what exent it can be traced along and/or across the Andean arc in space and time remain.

The Andean arc at 18°S

From seismic data along the Andean arc Stauder (1973, 1975) and Barazangi and Isacks (1976) recognized segments of low- and high-angle Nazca plate subduction. The high-angle segments are characterized by Benioff zones dipping about 20°-30°E and active volcanism, compared to the intervening zones where subduction is at a shallower angle (5°-10°) and Quaternary volcanism is absent. The transition from steep to shallow subduction at the northern limit of the CVZ was found by Bevis and Isacks (1984) and Grange et al. (1984) to be characterized by flexure rather than rupture of the subducted lithosphere. At 18°S the seismic zone is strongly focussed at ca. 120 km beneath the active volcanic front some 300 km inland from the trench axis (Fig. 2). To the east of the Arica bend there is a 90° sector behind the arc for which deep-seated (>120 km) earthquakes are rare (Barazangi and Isacks 1976). A "low-Q" zone is present below the base of the lithosphere (James, personal communication), implying the presence of asthenosphere within the mantle wedge.

The Peru-Chile trench outboard of the CVZ is relatively deep (ca. 7000 m) and almost devoid of sediments (Thornburg and Kulm 1987). The direction of plate convergence relative to the continental margin changes from oblique (75°) at 17°S to perpendicular at 20°S (Pilger 1981), the transition taking place at the Arica bend. The present subduction rate is about 10 cm/y (Chase 1978), but has varied between 5 and 20 cm/y during the past 70 Ma (Parado-Casas and Molnar 1987). The age of the Nazca plate at the trench ranges from ca. 45 Ma in the northern CVZ to ca. 55 Ma in the southern CVZ. Its age at the Arica bend is uncertain, but older than 55 Ma according to Wortel (1984, using data of Handschuhmacher 1976). Fast convergent rates and subduction of young lithosphere appear to be the characteristic features of the Andean active plate margin (Pardo-Casas and Molnar 1987).

The crust below the Altiplano of the CVZ reaches its maximum thickness (>75 km) in the vicinity of the Arica bend (Fig. 2). The exposed geology at 18°S largely represents the history of Nazca plate subduction and arc evolution along the western margin of central South America during the past 200 Ma. The earliest products of this magmatic cycle are submarine Early Jurassic andesitic volcanics and sediments found near the coast. These are overlain by Mesozoic igneous and marine sedimentary units that are covered by continental sediments, intruded by younger plutonic rocks, and capped by a thin veneer of Miocene to Recent volcanics. A few lenses of Precambrian basement rocks (gneisses, amphibolites, and serpentinites) of the South American craton are exposed tectonically along the western margin of the Altiplano.

The nature of the middle and lower crust is poorly defined. Geophysical evidence (Wigger 1986; Schwarz et al. 1986) shows a low-velocity zone with high electrical conductivity at midcrustal levels. This feature was interpreted by these authors as a zone of partial melting that contains numerous crustal magma chambers.

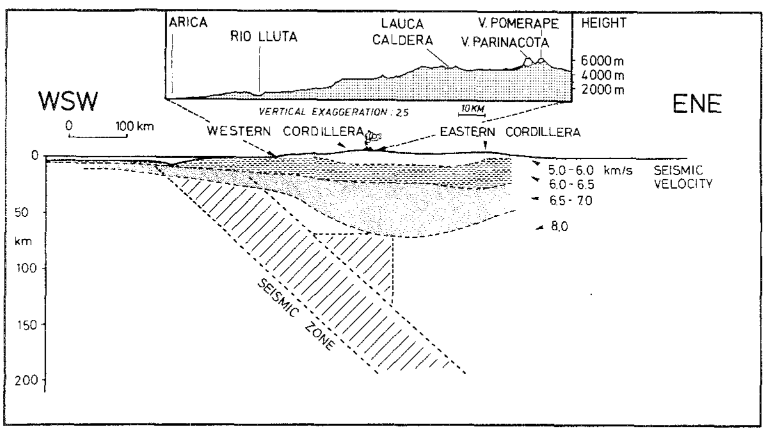

Fig. 2. Profile from the Pacific coast at Arica (18°S) to the Nevados de Payachata volcanic group on the Altiplano (based on data of James 1971a, b)

Volcanic stratigraphy at 18 °S

The Nevados de Payachata volcanic complex and surrounding older centers (Fig. 1) are located on the Altiplano of northeastern Chile and western Bolivia some 285 km east of the trench axis and about 110 km above the top of the subducted Nazca plate (Fig. 2). Two main magmatic phases are recognized in the study area (Fig. 1b): Pleistocene to Recent volcanism occurs within a zone parallel to the trench axis while the older Miocene phase defines a broader magmatic arc extending to the east and west of this active volcanic front.

Katsui and Gonzalez-Ferran (1968) have interpreted the stratigraphic relations of the Miocene to Recent volcanic centers at 18 °S. Our stratigraphic sequence and volcanologic/geologic map (Figs. 4, 5, Table 2) are similar, but contain several important modifications. The absolute ages of the volcanic centers are all documented by K-Ar dating to be older than inferred by Katsui and Gonzalez-Ferran (1968). Neither V. Guallatiri, the Quimsachata centers, or V. Taapaca have had a Holocene eruptive phase. Also, some lithologies in the Katsui and Gonzalez-Ferran (1968) geological map have been reinterpreted. The hummocky terrain west of V. Parinacota, thought by Katsui and Gonzalez-Ferran (1986) to be a lava flow, is clearly identified here and by Francis and Self (1987) as a debris-avalance deposit. New K-Ar whole-rock age determinations for the Nevados de Payachata volcanoes and older centers are presented in Table 1. Stratigraphic relations of the centers based on field data and these age determinations are shown in Table 2.

I The older volcanic series

a) Guane Guane. This feature is a topographic high (5097 m) located between the western Cordillera and V. Parinacota (Figs. 1b, 3, and 4). It consists of a series of layered, epiclastic boulder and pebble deposits containing Miocene andesite. The strata dip ca. 30 °S and are overlain uncon-

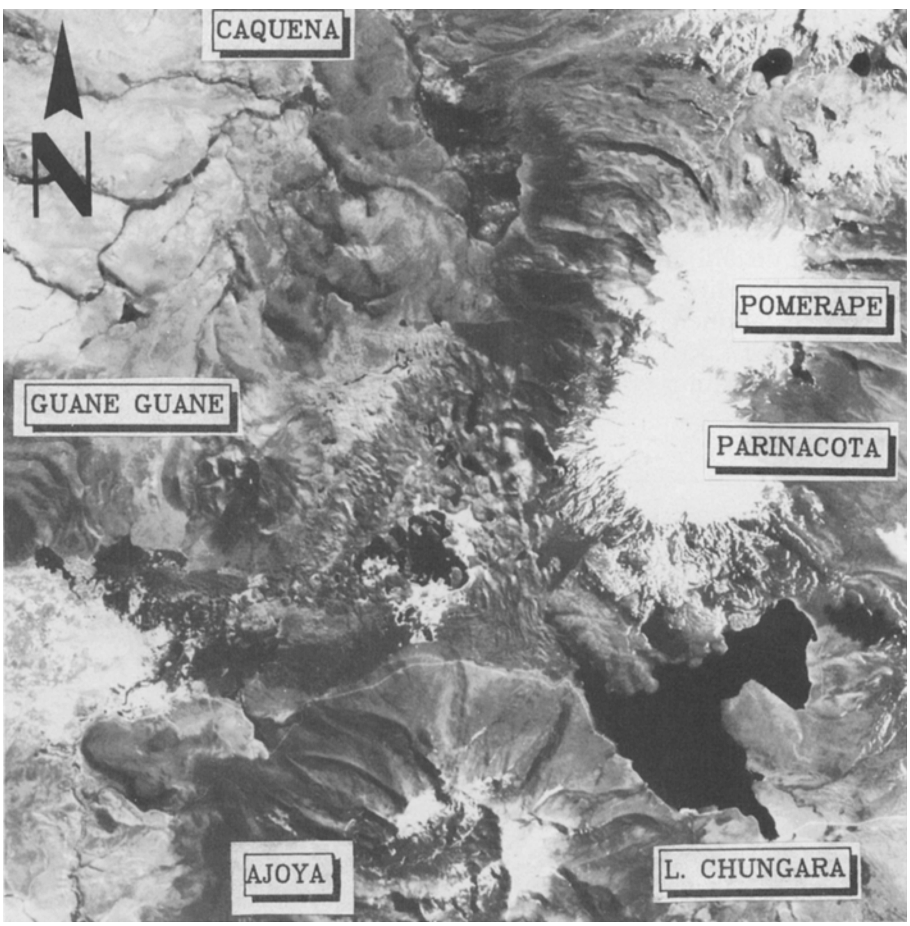

Fig. 3. Landsat image of the Nevados de Payachata volcanic group and V. Parinacota debris-avalanche deposit (courtesy of P. W. Francis, LPI). Width of the figure is ca. 30 km

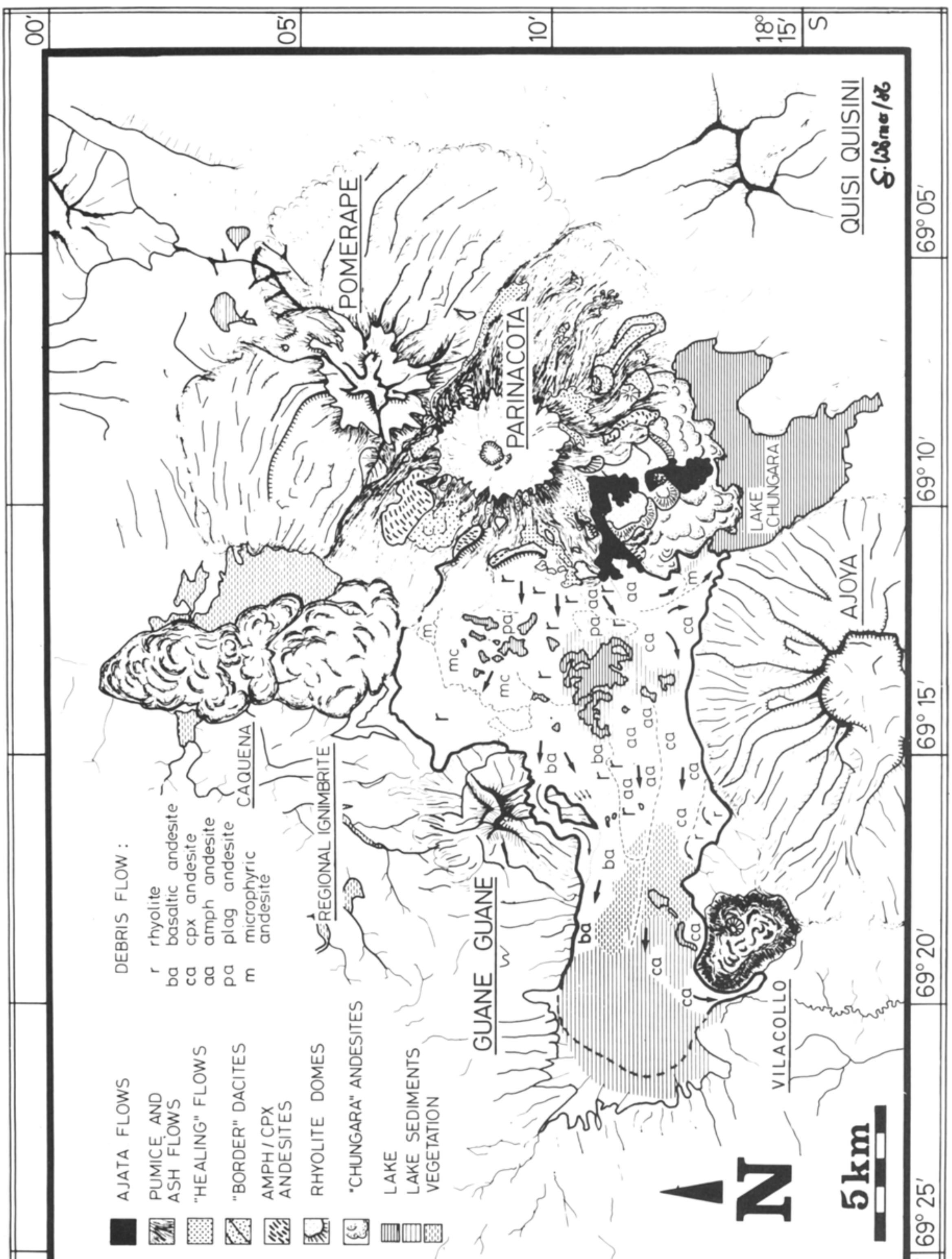

Fig. 4. Physiographic-geologic map of the Nevados de Payachata volcanic group and surrounding area. See text for discussion

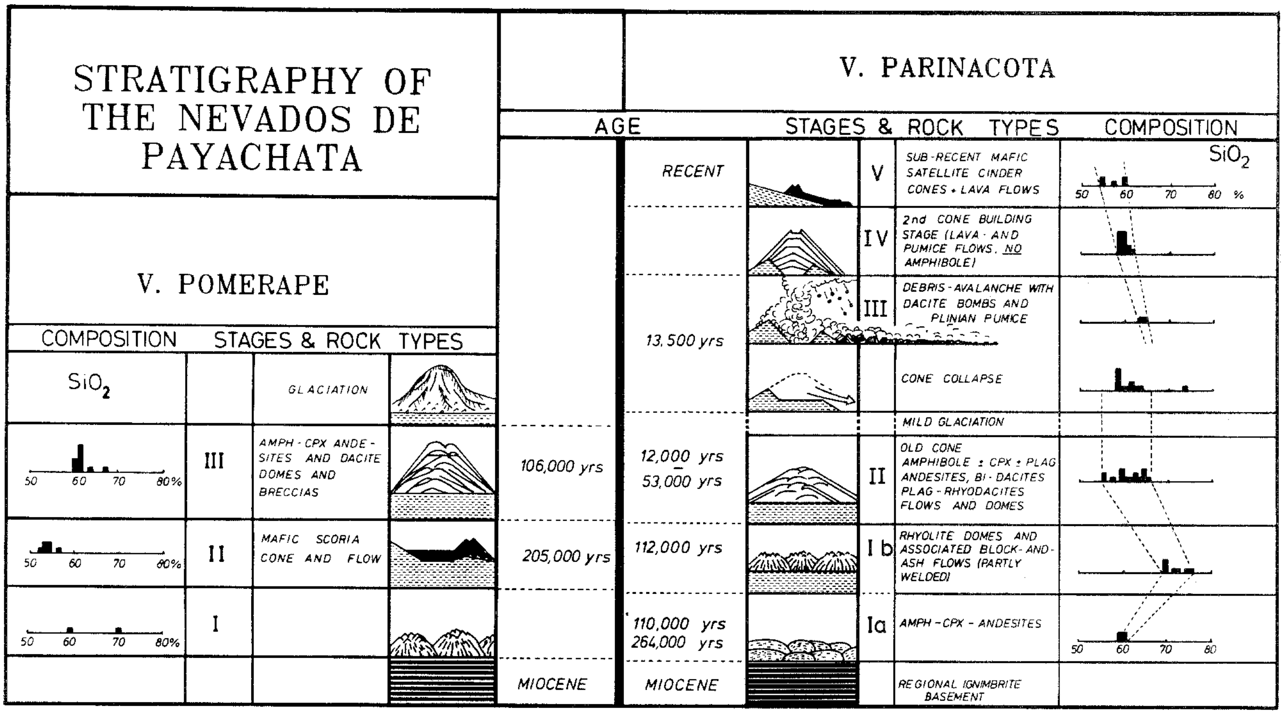

Fig. 5. Schematic diagram illustrating the volcanic history and stratigraphy of V. Pomerape and V. Parinacota

formably by the regional, Miocene rhyolitic ignimbrite. Therefore, Guane Guane suggests the occurrence of post mid-Miocene tectonic activity in the area.

b) Regional ignimbrites. A series of Miocene rhyolitic ignimbrites form the planar morphology of the Altiplano upon which the stratocones have been constructed. Several different units can be distinguished in canyons draining the Altiplano to the west. However, we have undertaken no detailed work on these ignimbrites.

c) Volcan Lauca. V. Lauca (Fig. 1b) is a collapsed andesite cone consisting of a series of outwardly dipping lava flows, a central calderalike depression, and a rhyodacitic dome. The cone-forming lavas can be separated into a lower series of altered plagioclase-amphibole andesites and a younger series of fresh, sparsely porphyritic, feldspar-rich dacites. These rocks contrast sharply with the highly porphyritic (50 vol%), biotite, amphibole, two-feldspar rhyodacite dome. K-Ar dates for the younger Lauca andesite cone lavas and dome rhyodacite are identical at 10.4 ± 0.3 Ma and 10.5 ± 0.3 Ma, respectively. The Lauca ignimbrite (Fig. 1b) is an ash-flow sheet overlying the Lauca andesite flows, which has its maximum thickness, pumice clast sizes, and degree of welding within the northern breach of the caldera. It has a dense rock equivalent volume of ca. 6–8 km^3.

d) Miocene stratocones. The late Miocene magmatic phase is represented by large, deeply dissected stratocones such as the Choquelimpie (≥ 6.60 Ma) and V. Ajoya (≥ 7.06 Ma) centers (Figs. 1b, 3). The older dacite dome series at Caquena (Fig. 1b) may also belong to this phase. V. Ajoya lavas consist of weakly to intensely altered, pyroxene-bearing andesites, containing abundant oxidized amphibole, and rare dacites. Both older volcanoes have intensely altered cores and central caldera-like depressions resulting from preferential erosion. These zones also have been sites of epithermal mineralization; low-grade silver ore is currently being quarried at Choquelimpie. Late-stage dacite dikes, dated at 6.60 ± 0.20 Ma, postdate this hydrothermal alteration.

II The younger volcanic series

a) Isolated Pleistocene centers. The Vilacollo, Caquena, and Chungara centers (Figs. 1b, 4) have produced thick, well-preserved lava flows as well as cinder cones (Vilacollo) and domes (Caquena). The Vilacollo center erupted a mafic amphibole andesite containing rare feldspar phenocrysts.

Table 1. K-Ar whole-rock age determinations

Sample no.	K_2O (wt%)	Sample weight (g)	^{40}Ar RAD (mol/g) $\times 10^{-11}$	$\frac{^{40}Ar\ Rad^2}{^{40}K * 1000}$	$\%^{40}Ar$ RAD	Age (Ma)	±sigma (Ma)
PAR 082	2.99	8.0817	0.0051	0.0007	0.38	0.012	0.015
PAR 016[a]	3.67	8.0837	0.0289	0.0032	1.28	≥0.054	0.006
PAR 016[a]	3.67	8.0837	0.0265	0.0029	1.17	≥0.050	0.011
						≥0.053	0.011[a]
POM 116[a]	3.25	7.0368	0.0493	0.0061	7.34	0.105	0.005
POM 116[a]	3.25	7.0368	0.0504	0.0063	7.51	0.108	0.009
						0.106	0.007[a]
PAR 121[a]	3.27	6.1733	0.0523	0.0065	1.88	0.111	0.008
PAR 121[a]	3.27	6.1733	0.0514	0.0063	1.85	0.109	0.030
						0.110	0.022[a]
PAR 048[a]	4.04	6.1246	0.0671	0.0067	6.38	≥0.115	0.005
PAR 048[a]	4.04	6.1246	0.0639	0.0064	6.08	≥0.110	0.004
						≥0.112	0.005[a]
PAR 074[a]	3.32	5.1515	0.0927	0.0113	2.80	0.194	0.008
PAR 074[a]	3.32	5.1515	0.0925	0.0112	2.78	0.194	0.010
						0.194	0.009[a]
POM 149[a]	1.55	6.4861	0.0494	0.0129	1.94	0.222	0.024
POM 149[a]	1.55	6.4861	0.0540	0.0141	2.12	0.243	0.024
POM 149[a]	1.55	6.4861	0.0428	0.0112	1.68	0.192	0.024
						0.219	0.024[a]
POM 152[a]	1.43	7.0783	0.0394	0.0112	3.21	0.192	0.006
POM 152[a]	1.43	7.0783	0.0410	0.0116	3.34	0.200	0.010
POM 152[a]	1.43	7.0783	0.0373	0.0106	3.04	0.182	0.013
						0.192	0.012[a]
PAR 118[a]	3.21	6.1889	0.1241	0.0156	1.81	0.269	0.017
PAR 118[a]	3.21	6.1889	0.1060	0.0133	1.55	0.229	0.013
PAR 118[a]	3.21	6.1889	0.1357	0.0171	1.98	0.294	0.019
						0.264	0.016
CAQ 001[a]	3.27	6.1832	0.1373	0.0169	1.56	0.291	0.037
CAQ 001[a]	3.27	6.1832	0.1159	0.0143	1.32	0.246	0.043
CAQ 001[a]	3.27	6.1832	0.1343	0.0166	1.53	0.285	0.038
						0.275	0.044[a]
CHU 171[a]	2.94	5.0920	0.1192	0.0164	2.51	0.282	0.031
CHU 171[a]	2.94	5.0920	0.1231	0.0169	2.59	0.291	0.053
						0.285	0.053[a]
CHO 098[a]	3.21	6.2581	3.0428	0.3823	55.99	≥6.57	0.20
CHO 098[a]	3.21	6.2581	3.0240	0.3800	55.53	≥6.53	0.20
CHO 098[a]	3.21	5.8088	3.0785	0.3868	56.52	≥6.65	0.20
						6.60	0.20[a]
AJA 177	2.36	5.1337	2.3845	0.4087	27.0	7.02	0.21
AJA 177[a]	2.36	5.1337	2.4117	0.4133	27.3	7.10	0.21
						7.06	0.21[a]
LAU 102	2.46	2.5318	3.7189	0.6105	90.6	10.5	0.3
LAU 102[a]	2.46	2.5318	3.6955	0.6067	90.2	10.4	0.3
						10.5	0.3[a]
LAU 105	3.67	2.3398	5.5663	0.6124	85.6	10.5	0.3

RAD, radiogenic; sigma, standard deviation

Constants used: Lambda ε + Lambda ε' $= 0.581 \times 10^{-10}$/years
Lambda β $= 4.92 \times 10^{-10}$/years
$^{40}K/K_{total}$ $= 1.167 \times 10^{-4}$ mol/mol

a: Replicate analyses from a single sample fusion, average result given

PAR, V. Parinacota; POM, V. Pomerape; CAQ, Caquena; CHU, Chucuyo = Vilacollo; CHO, Choquelimpie; AJA, Ajoya; LAU, Lauca

Table 2. Ages and stratigraphic relations of the Nevados de Payachata complex and surrounding older centers

Young stratocones			
Parinacota			
V	Late Holocene (Parasitic mafic centers)		
IV	Early Holocene	**Pomerape**	
III	0.0135		
II	too young to date		
	>0.053±0.011	III	0.106±0.007
Ib	0.112±0.005	II	0.205±0.024
Ia	0.110±0.022	I	?
Young local centers			
Chungara	0.194±0.009 to 0.264±0.030		
Caquena	0.275±0.044		
Vilacollo	0.285±0.053		
Old stratocones, local centers and ignimbrites			
Older Caquena	?		
Choquelimpie	>6.60±0.20		
Ajoya	>7.06±0.21		
Lauca	10.50±0.30		
Regional Ignimbrite	?		

The younger Caquena centers are characterized by microporphyritic amphibole andesites. Amphiboles in both rock types are highly oxidized. K-Ar ages (Table 1) for these centers are 0.29±0.05 Ma (Vilacollo), 0.28±0.04 Ma (Caquena), and 0.194±0.009 to 0.26±0.02 Ma (Chungara).

b) The Nevados de Payachata. Pomerape (6222 m) is young, but glacially dissected (Figs. 1b, 3, 6). Outcrops at lower elevations are limited due to extensive glacial debris cover. However, the structure and stratigraphy of the stratocone appears to be rather simple. It has been constructed upon a complex of dacitic-rhyolitic domes (Tables 1, 2, Fig. 5). These are coarsely porphyritic (up to 50 vol%), biotite, amphibole, two-feldspar rhyodacites. An isolated spatter cone and lava flow of basaltic andesite composition overlie both these domes and the northern, lower flank of V. Pomerape. They possibly postdate an older glacial phase, but also have been glacially dissected. This mafic andesite is amphibole free and contains phenocrysts of pyroxene, olivine, and plagioclase. Xenolithic inclusions of quartz-bearing plutonic rock are abundant and show reaction rims (clinopyroxene) with the surrounding host. Whole rock K-Ar dates of handpicked material (POM 149 and POM 152, Table 1) gave an average age of 0.205±0.024 Ma. The V. Pomerape stratocone consists of cone-building amphibole andesite flows (Stage II) with a cap of partly welded dacitic breccias. One andesite flow has been dated at 0.106±0.007 Ma.

Volcan Parinacota, the younger stratocone (6348 m), overlaps the southern flank of V. Pomerape (Figs. 4 and 6). Its stratigraphy is complex and well-documented in outcrop. The following five eruptive stages have been distinguished:

Stage I comprises a basal series of monotonous hornblende andesite lavas, here called the "Chungara andesites" (Stage Ia), which occur along the northern shore of Lake Chungara (Figs. 3, 4). On the basis of their age and subdued flow morphologies these lavas could also be grouped with the Vilacollo and Caquena centers. All Chungara andesites are compositionally similar; they contain abundant oxidized amphibole, and variable amounts of clinopyroxene and biotite are rarely present. A steep-sided plateau of phenocryst-rich rhyolitic to dacitic domes and associated welded and unwelded collapse breccias (Fig. 6a; Stage Ib) overlies the Chungara andesites. This coalescing dome sequence exhibits a number of textural types ranging from sparsely vitrophyric to more porphyritic, coarsely crystalline varieties. The rhyolite-dacite plateau is about 100 m thick and outcrops over a 100° sector from south to west at the base of the V. Parinacota cone (Fig. 4). The youngest stage Ia and Ib rocks are closely related in time, yielding K-Ar ages of 0.110±0.004 Ma to 0.264±0.03 and ≥0.112 Ma±0.005 Ma, respectively (Table 1).

Stage II consists of a sequence of older biotite-dacite domes and flows (e.g., "border dacite" of Fig. 4) with a minimum age of 0.053±0.011 Ma (Table 1), andesites with variable amounts of clinopyroxene and amphibole, which are too young to be dated, and an evolved feldspar-rich dacite dome. All of these lithologies form an older, mildly glaciated V. Parinacota stratocone (Fig. 4). Modal compositions of stage II lavas are highly variable and range from mafic olivine-pyroxene andesite to amphibole-rich (up to 10 vol%) andesite, plagioclase andesite, and highly porphyritic biotite-amphibole, two-feldspar rhyodacite. The latter are petrographically and chemically indistinguishable from the V. Pomerape basal rhyodacite dome series. The abundance of amphibole, even in some more mafic members of the series, and the general presence of biotite is noteworthy.

Stage III in the V. Parinacota history comprises the cone-collapse event that resulted in the deposition of a Mount St. Helens-type debris-avalanche deposit to the west of the present stratocone (Figs. 4, 5, 6), associated prismatically jointed bombs, and a thin dacitic pumice-fall deposit. The debris-avalanche deposit has a hummocky morphology with a myriad of small lakes

Fig. 6. a View of the Nevados de Payachata from the west (summit of Guana Guane, Figs. 1, 4). The summits of the two stratovolcanoes V. Pomerape (left) and V. Parinacota are approximately 5 km apart, emphasizing the close relationships of their magmatic system. Note large (up to 100 m high) tilted blocks at the base of V. Parinacota (right center) and hummocky terrain of the debris avalanche in the middle ground. **b** Details of the hummocky terrain of the debris-avalanche deposit and the newly formed Lake Chungara in the left background

and peat basins developed in the intervening depressions (Fig. 3, 6b). Lake Chungara was formed when the avalanche deposit dammed a preexisting river. Peat underlying the debris has been ^{14}C dated at ca. 13 500 B.P. (P. Francis, personal communication).

The debris-avalanche deposit (Fig. 6a, b) covers an area of approximately 110 km^2, can be traced to the west some 23 km, and has an estimated volume of ca. 5-6 km^3. Although proximal hummocks range up to 100 m in height, the average hummock size in distal portions of the deposit is about 30 m. Internally, individual hummocks commonly consist of a single large block in which the original volcanic stratigraphy may be preserved (e. g., andesite flows on rhyolite dome material or flow sequences) and a mantle of more disturbed loose material. Coherent blocks tens of meters in diameter have been encountered several kilometers from the volcano. Individual blocks comprising the intermediate to distal hummocks (> 10 km from source) are between 0.5 and 2 m in diameter. By comparison, hummocks at Mount St. Helens are often highly sheared and brecciated and contain decimeter-size blocks set in a fine matrix of shattered rock.

A series of traverses form the basis for the lithologic map of the debris-avalanche deposit shown in Fig. 4. Seven main lithologies have been distinguished, six of which can be directly correlated with in situ remnants of the old stratocone lavas (stage I and II lithologies). The irregular distribution of rock types in the proximal area (Fig. 4) is characterized by large, tilted blocks of stage Ib dome material (up to 200 m in diameter) and overlying stage II andesite flows. Central and distal portions of the avalanche deposit consist of elongated patches of monolithologic (with or without stage Ib dome rocks) zones which are oriented parallel to the direction of transport. This suggests laminar, high-velocity flow and the "smearing out" of larger rock masses during movement (see also Francis and Self 1987).

Prismatically jointed, biotite, amphibole, plagioclase dacite bombs are found in some places on the top of the avalanche deposit. These probably represent the juvenile magmatic component associated with the cone-collapse event (stage III) because this dacite is unusually fresh and quite distinct from all other dacites found on the old cone. A blast deposit similar to that at Mount St. Helens has not been recognized.

Stage IV at V. Parinacota saw the complete reconstruction of the volcanic edifice during the past 13500 years to its present form by andesite aa lava flows (here designated the "healing flows," Fig. 4) and sub-Plinian andesitic pumice and scoria flows. Some of these pumice flows are mildly welded at distances of 2 km from the summit crater. Primary, delicate pumice-flow surface morphologies (lobate flow fronts and margins, levees) are well preserved on the lower eastern flank of V. Parinacota. This eruptive activity produced the present steep-sided summit crater that is about 1 km in diameter and a thin veneer of brown andesitic ash distributed predominantly to the east of the cone. Erosion forms on the upper flanks around the volcano consist of abundant gullies. Redeposition of tephra has occurred by thin (0.2–2 m) lahars, spreading over the southern and western lower flanks.

Where stratigraphic relationships are exposed clearly, the more recent healing flows are more mafic, contain olivine phenocrysts, and are devoid of amphibole. There are a number of differences between the precollapse lavas (stage II andesites and dacites) and postcollapse lavas (stage IV healing flows) at V. Parinacota. Eruption rates appear to have been much higher for stage IV flows, as is suggested by their monotonous petrography, uniform degree of preservation, and the short duration (ca. 13500 years) of this phase. In contrast, rock types, eruption style, and degree of alteration are all much more variable on the old cone, and evidence of glacial erosion is found between different flows. Pyroclastic pumice flows are abundant in stage IV, but are not observed on the older cone. This may, however, be due in part to a preservational bias. Finally, nearly all stage IV lavas are amphibole-free, whereas most stage II lavas contain abundant amphibole.

Stage V comprises the most recent volcanic activity at V. Parinacota, which occurred at a series of satellite centers (the "Ajata" cones and aa flows, Figs. 4, 5). The most mafic compositions found at V. Parinacota and in the Nevados de Payachata area have been erupted at these small centers. Older Ajata flows are plagioclase-porphyritic, mafic andesite flows, and the youngest flows are distinctly olivine-rich (5–10 vol%), clinopyroxene-bearing basaltic andesites that lack plagioclase phenocrysts.

Geochemistry

A total of 101 samples from the Nevados de Payachata complex and older surrounding centers were analyzed for major- and trace-element contents using XRF spectroscopy of fused glass beads. Selected samples were analyzed for their Sr-, Nd-, and Pb-isotope ratios and O-isotope compositions. Representative analyses are listed in Table 3.

Major- and trace-element variations

There are well-defined, congruent geochemical trends for both V. Pomerape and V. Parinacota and the surrounding late Pleistocene centers (Figs. 7, 8) that all define a high-K, calc-alkaline andesite suite (Gill 1981). The compositional trends of the two stratocones are largely identical (Figs. 7, 8), although silicic lavas with $>70\%$ SiO_2 were not found at V. Pomerape. The Payachata lava series lacks a compositional gap. However, within individual eruptive stages, we observe (a)

Table 3. Representative chemical and isotope analyses and K-Ar whole-rock ages from the Nevados de Payachata and surrounding older centers

	PAR 011 1	PAR 162 2	PAR 016 3	PAR 082 4	PAR 048 5	PAR 118 6	POM 152 7	POM 116 8	POM 095 9	CAQ 001 10	CAQ 002 11	LAU 005 12	LAU 106 13	AJA 177 14	RIG 187 15
SiO_2	52.90	60.40	63.10	60.20	66.90	59.10	52.30	60.90	68.20	61.00	55.90	58.00	73.20	60.10	73.60
TiO_2	1.57	1.08	0.91	1.18	0.49	1.13	1.76	1.14	0.47	0.91	0.78	0.73	0.15	0.67	0.20
Al_2O_3	15.63	16.16	15.25	15.81	14.71	15.96	16.16	15.84	14.50	15.91	18.28	17.64	13.46	16.90	12.96
Fe_2O_3	8.50	5.92	4.73	6.31	2.86	6.19	10.26	6.01	2.72	4.97	7.74	7.20	1.07	6.10	1.30
MnO	0.11	0.08	0.06	0.08	0.05	0.08	0.12	0.08	0.05	0.07	0.16	0.15	0.07	0.11	0.05
MgO	4.82	2.22	1.96	3.11	1.00	2.93	5.80	2.70	0.94	2.17	3.58	2.84	0.16	2.39	0.18
CaO	7.25	4.78	3.83	5.32	2.40	5.14	8.08	4.83	2.27	4.49	7.30	6.41	0.63	5.47	0.87
Na_2O	4.02	4.19	4.23	4.22	4.10	4.04	3.65	4.09	4.07	4.38	3.41	3.48	3.74	3.59	3.78
K_2O	2.44	3.03	3.46	3.01	3.97	3.13	1.43	3.20	4.02	3.23	1.85	1.76	4.32	2.34	4.56
P_2O_5	0.73	0.40	0.35	0.43	0.17	0.42	0.45	0.40	0.16	0.39	0.21	0.22	0.04	0.22	0.05
H_2O+	0.41	—	0.75	—	1.22	—	—	—	1.07	1.21	—	—	1.32	0.52	0.59
Total	98.38	98.26	98.63	99.67	97.87	98.12	100.01	99.19	98.47	98.73	99.21	98.43	98.16	98.41	98.14
V	199	124	92	141	46	135	250	126	42	95	169	131	8	112	13
CR	54	17	37	43	13	44	184	44	15	24	11	13	4	16	15
CO	35	43	25	28	27	23	49	25	17	29	34	29	22	21	28
NI	70	29	33	43	19	44	85	43	20	34	24	22	12	23	17
CU	71	54	37	48	21	47	88	57	21	42	61	50	6	46	13
ZN	138	112	102	98	72	106	136	103	66	96	92	103	50	94	53
RB	48	86	97	75	131	84	24	96	133	84	77	50	192	68	146
SR	1714	853	895	1117	619	1075	757	966	563	1194	575	526	47	556	157
Y	21	16	11	14	5	14	18	13	8	14	18	21	11	18	8
ZR	187	219	198	184	169	218	147	208	168	221	122	147	97	141	108
NB	10	9	9	4	5	8	5	5	7	7	4	31	21	5	13
BA	1718	1165	1209	1340	1050	1409	681	1273	932	1447	742	695	58	808	296
Pb	19	20	21	16	24	18	8	18	24	22	11	13	42	14	27
$^{87}Sr/^{86}Sr$	0.70613	0.70687	0.70685	0.70670	0.70674	0.70665	0.70667	0.70638	0.70675	0.70674	0.70584	0.70665	0.70719	0.70686	0.70645
$^{143}Nd/^{144}Nd$	0.512379	0.512327	0.512293	—	—	0.512298	0.512350	0.512311	0.512309	—	—	—	—	—	—
$^{206}Pb/^{204}Pb$	18.084	18.169	18.026	17.998	17.993	18.051	18.180	18.142	17.997	18.064	18.228	18.203	17.674	18.283	17.962
$^{207}Pb/^{204}Pb$	15.614	15.612	15.613	15.601	15.612	15.602	15.612	15.619	15.605	15.601	15.610	15.615	15.560	15.619	15.616
$^{208}Pb/^{204}Pb$	38.375	38.417	38.320	38.242	38.283	38.304	38.470	38.404	38.253	38.328	38.420	38.518	37.768	38.556	38.281
	6.8	7.5	7.0	7.1	7.3	7.6	7.2	7.5	7.3	8.1	8.1	6.8	9.5	7.4	8.4
AGE (Ma)	—	—	0.053	0.012	0.112	—	0.191	0.106	—	0.275	—	> 10.5	> 10.5	7.06	> 10

1, youngest Ajata flow (Parinacota V)
2, healing flow (Parinacota IV)
3, border dacite (Parinacota II)
4, wall andesite (Parinacota II)
5, rhyolite dome (Parinacota Ib)
6, Chungara andesite (Parinacota Ia)
7, Pomerape mafic cone (Pomerape II)
8, glaciated andesite (Pomerape III)
9, rhyolite dome (Pomerape I)
10, young Caquena
11, old Caquena
12, Lauca andesite
13, Lauca rhyolite
14, Ajoya andesite
15, Miocene (regional) ignimbrite

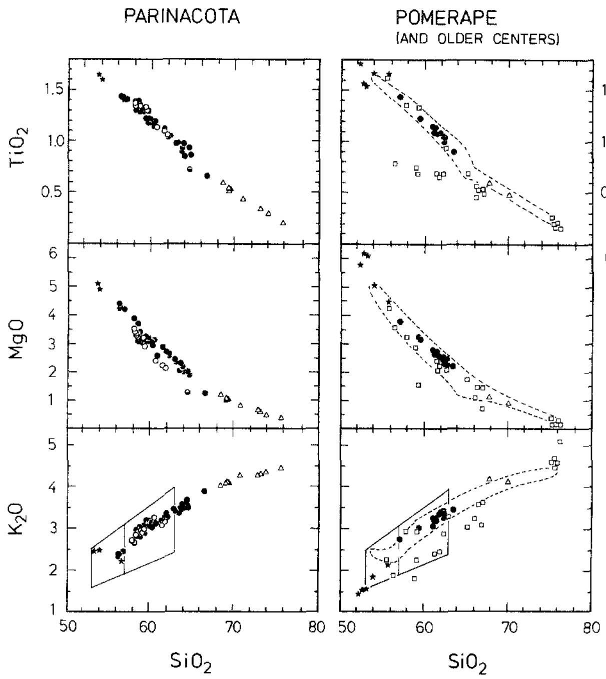

Fig. 7. Major-element variation diagrams for lavas from (a) V. Parinacota and (b) V. Pomerape and older volcanic centers in the Payachata area. V. Parinacota: ★ = recent satellite vents (V), ○ = healing flows (young cone, IV), ● = andesite and dacites (old cone-building flows and domes (II), and Chungara andesites (Ia), ◒ = stage III pumice and prismatically jointed bombs, △ = silicic domes (Ib). Pomerape: ★ = satellite vents (III), ● = cone-building andesites (II), △ = silicic domes (I). Non-Payachata centers: □ = Caquena, Vilacollo, Ajoya, Choquelimpie, Lauca. Outlined field is high-K-series of Gill (1981). Dashed field is compositional range of Parinacota

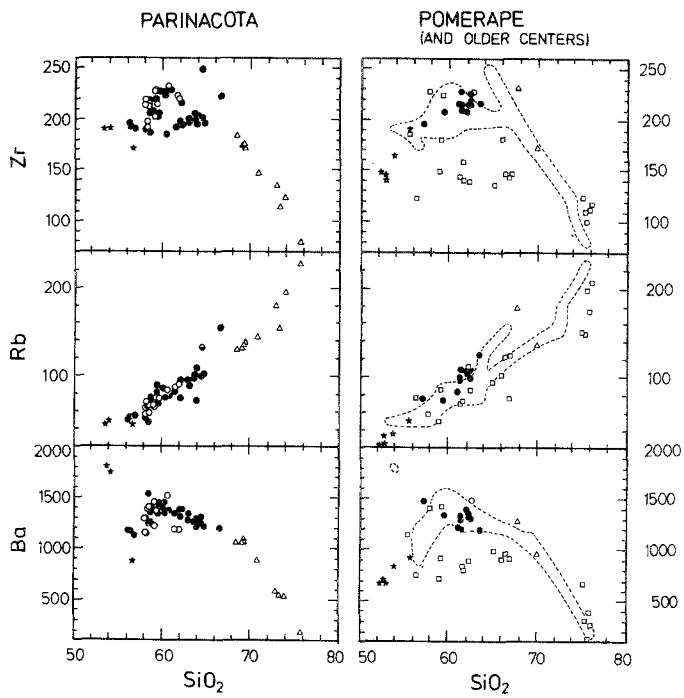

Fig. 8. Trace-element variation diagrams for the Nevados de Payachata lavas and older, non-Payachata lavas (for symbols see Fig. 7)

bimodal andesite-rhyolite associations (e.g., stage Ia, ≈60% SiO_2; stage Ib, 69%–76% SiO_2), (b) continuous ranges from mafic andesites through dacites (e.g., old cone, stages II, III, 57%–67% SiO_2), and (c) the new cone with contrasting andesite (stage IV, 58%–62% SiO_2) and mafic andesite lavas (Ajata, stage V, 53%–57% SiO_2, Fig. 5). The latter are the youngest and most mafic lavas sampled.

Precollapse (stage II) and postcollapse (stage IV) lavas also differ geochemically, in addition to the volcanologic and petrographic differences. Stage IV lavas are, on the average, less silicic than older stage II cone lavas, although they fall within the SiO_2 range of previously erupted andesite compositions. Stage IV lavas are also lower MgO, Cr, Ni, and Sr than most stage II flows at a given SiO_2 content. Prismatically jointed dacite bombs and dacite pumice tephra associated with the stage III cone-collapse event belong to the most evolved compositions erupted at the Parinacota cone. Thus, there is a notable difference in volcanologic, petrographic, and chemical character of lavas erupted at V. Parinacota before and after cone collapse. This implies a break in magma evolution resulting from a change in the subvolcanic plumbing system. Either the intensive parameters controlling differentiation (i.e., pressure and temperature) were modified, or a new batch of magma entered the magma system.

Ni-Rb variations illustrate that at least two processes, crystal fractionation and magma mixing, may have operated in the shallow, crustal portion of the Nevados de Payachata magmatic system. Data for the postcollapse mafic healing flow lavas (stage IV), the satellite centers (Ajata lavas, stage V), and the evolved rhyolites and rhyodacites (stage Ib) define a strongly curved path (long-dashed line in Fig. 9). This is characteristic of fractional crystallization or combined assimilation-fractional crystallization. Stage Ib silicic domes plot at the evolved end of this path

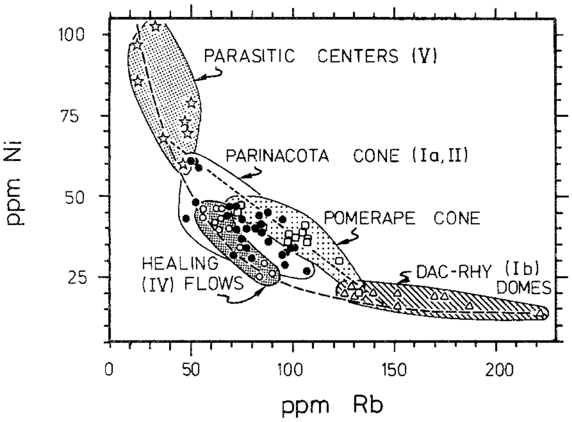

Fig. 9. Ni-Rb variation diagrams for V. Pomperape and V. Parinacota lavas. *Curved, long-dashed line* is fractional crystallization path; *straight short-dashed line* is mixing line (both schematic). Symbols as in Fig. 7; see text for discussion

and could be explained by (ca. 90%) crystal fractionation of a mafic parental magma. By contrast, most cone-building stage II andesites plot above this trend, suggestive of intratrend magma mixing

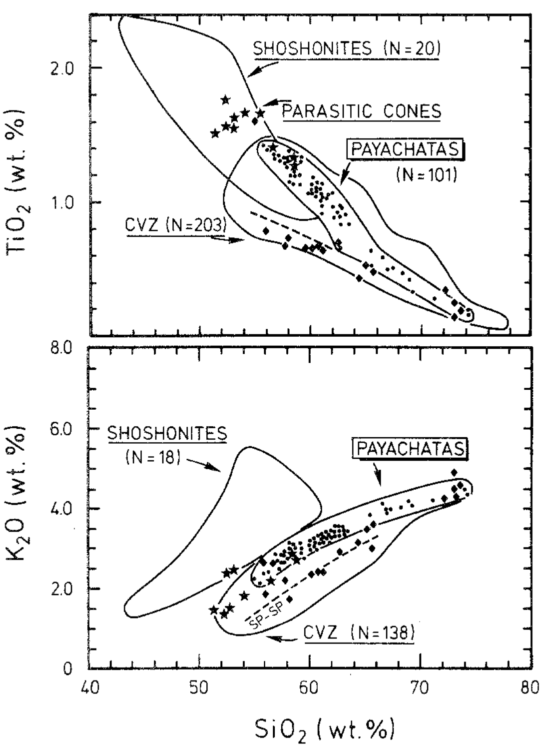

Fig. 10. Regional comparison of (·, ★) Nevados de Payachata lavas and (♦) older lavas at 18°S with literature data from the CVZ for selected major elements. *Heavy dashed line* (SP-SP), San Pedro-San Pablo trend (O'Callaghan and Francis 1986). Data from standard literature sources quoted in text and Siegers et al. (1969), Pichler and Zeil (1972), Fernandez et al. (1973), Hörmann et al. (1973), Dupuy and Lefevre (1974), James et al. (1976), Kussmaul et al. (1977), Thorpe and Francis (1976), Thorpe et al. (1976, 1979), Dupuy et al. (1977)

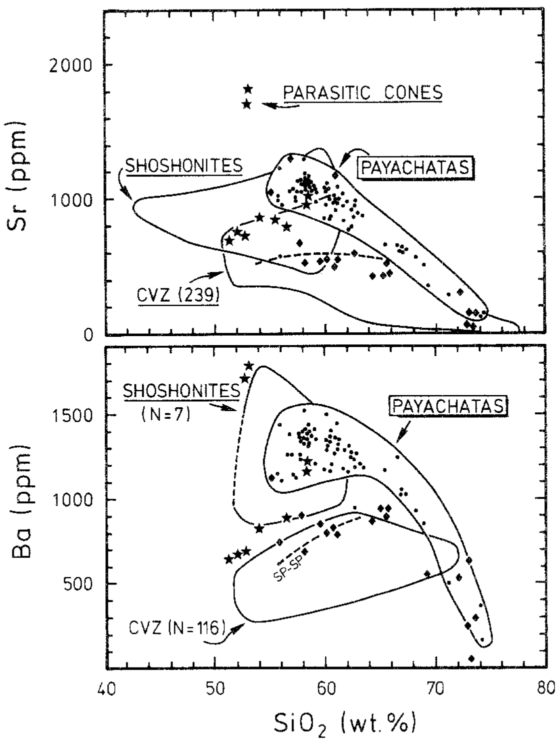

Fig. 11. Regional comparison for selected trace elements (see Fig. 9) and text for further explanation. Symbols and literature sources as Fig. 10

(short dashed line in Fig. 9). Petrographic evidence for magma mixing is rare; however, rounded and resorbed plagioclase and quartz grains as well as quench plagioclase spherulites have been observed in some samples of intermediate composition. This indicates that magma mixing resulted in complete rehomogenization of magmas and therefore was not a short-term, pre-eruptive process.

Regional comparison within the CVZ

Major- and trace-element data from the Nevados de Payachata area at 18°S are compared with published data for other CVZ volcanic centers in Figs. 10 and 11. Oxide abundances for Payachata lavas mostly fall within the ranges for other CVZ calc-alkaline magmas, whereas K_2O and TiO_2 trends for andesites fall within the uppermost part of the CVZ field (Fig. 10). Ratios of Na_2O/K_2O for the Payachata lavas are all below unity, except for a few rhyolitic rocks affected by high-temperature, vapor-phase alteration. This and the position of the complex *at* the volcanic front of the present arc imply that all Nevados de Payachata lavas are calc-alkaline, and not shoshonitic.

Contents of Sr and, in particular, Ba are much higher for all Nevados de Payachata andesites (up to ca. 68% SiO_2) than those previously documented for the CVZ (Fig. 11). Most Payachata andesites actually fall into, and some even plot beyond the field for shoshonites erupted east of the main CVZ volcanic arc. Moreover, the general trend of decreasing Ba contents with increasing SiO_2 runs contrary to the typical calc-alkaline trend (e.g., San Pedro-San Pablo in Fig. 11).

Even more unusual chemical characteristics are observed for the most mafic basaltic andesites erupted at peripheral centers (stars in Figs. 10, 11). TiO_2 values for all of these rocks plot outside the previously known range for CVZ calc-alkaline lavas. Two samples from the youngest Ajata lavas have the highest Ba and Sr contents (1800 ppm and 1700 ppm, stars in Figs. 10, 11) of any CVZ volcanic rocks. The Sr-isotope ratios of these lavas are lower than those of all other Payachata lavas (Table 3).

Similarly high Sr and Ba contents (1800 ppm and 1500 ppm, respectively) have been measured for two andesite samples ($\approx 59\%$ SiO_2) from the Miocene volcanic center at Lirima (19°46′S, 68°45′W) by Tagiri et al. 1985). We have resampled this center and our petrographic and chemical data (unpublished data) indicates that these high Sr and Ba values can be attributed to feldspar accumulation and strong hydrothermal alteration, rather than being a primary feature. Recent fieldwork and geochemical analyses of lavas from between 17°45′S and 19°45′S (unpublished data) have shown that the Nevados de Payachata lavas in fact represent the extreme peak of a broader region of Sr and Ba enrichment in the CVZ between 18°S and 19°S.

By contrast, late Miocene lavas at the Lauca caldera (ca. 10 Ma), V. Ajoya (ca. 7 Ma), and V. Choquelimpie (ca. 6.5 Ma) plot largely within the CVZ field (diamonds in Figs. 10, 11). Therefore, the unusual geochemical signature at 18°S is limited to volcanic rocks that are younger than 6 Ma.

Isotopic compositions

In spite of these large chemical variations, the Sr-, Nd-, Pb-, and O-isotope compositions (Table 3) of the Nevados de Payachata lavas exhibit relatively little variation. This contrasts with the wide ranges in isotope composition exhibited by many other CVZ centers (Francis et al. 1977; Tilton and Barreiro 1980; Hawkesworth et al. 1979, 1982; James 1982; Harmon et al. 1984; Harmon and Hoefs 1984). Except for (a) the most mafic satellite lava at V. Parinacota, which has slightly lower Sr- and higher Nd isotope ratios (0.7061 and 0.51238, respectively) than the other Payachata samples and (b) an enigmatic V. Parinacota white dacite pumice (stage III), which contains the most radiogenic Sr of the Payachata samples ($^{87}Sr/^{86}Sr = 0.7070$), the ranges of whole-rock isotope compositions are as follows: $^{87}Sr/^{86}Sr = 0.7066$–0.7069, $^{143}Nd/^{144}Nd = 0.51235$–0.51229, $^{206}Pb/^{204}Pb = 17.95$–18.20, $^{207}Pb/^{204}Pb = 15.59$–15.62, $^{208}Pb/^{204}Pb = 37.99$–38.47, and $\delta^{18}O_{SMOW}$ +6.8‰–7.6‰. The older volcanic centers of Ajoya and Lauca fall outside this range toward higher Sr-, Pb-, and O-isotope ratios. O-isotope ratios exhibit a modest, positive correlation with SiO_2 contents. No correlation is observed between Sr- and Nd-isotope and bulk chemical compositions.

The $^{143}Nd/^{144}Nd$ ratios of the lavas from 18°S are lower and $^{87}Sr/^{86}Sr$ ratios are higher than those observed in the Southern Volcanic Zone between 36° and 41°S (Hickey et al. 1986), indicating a strong contribution from a crustal protolith having a long-term time-integrated Sm/Nd and a high time-intergrated Rb/Sr ratio (Hawkesworth et al. 1982; Francis et al. 1984). O-isotope ratios significantly lower than +9‰–10‰ indicate that ^{18}O-rich upper crust has not played an important role in the evolution of the Nevados de Payachata magmas.

Pb-isotope relationships are displayed in Fig. 12. The Payachata data plot outside the fields for (a) previously analyzed CVZ volcanic rocks, (b) the field for Nazca plate oceanic lithosphere, and (c) the field for Nazca plate sediments. The Payachata field in Fig. 12 falls between the Nazca plate and southern Peru Precambrian crust fields in a sublinear array. Within this array Pb-isotope compositions are positively correlated with indices of differentiation such as silica content.

Regional comparison of the CVZ centers (Fig. 13) shows a low-$^{206}Pb/^{204}Pb$ northern sector in southern Peru (Barreiro 1984; James 1984) and a high-$^{206}Pb/^{204}Pb$ southern sector (e.g., Harmon et al. 1984). The Nevados de Payachata volcanic complex is similar to the northern sector with respect to its low $^{206}Pb/^{204}Pb$ values, but has distinctly lower $^{208}Pb/^{204}Pb$ values.

The isotope characteristics of the Payachata lavas collectively suggest a complex petrogenesis involving at least three distinct components. One is a subcrustal, slab-related component, similar to that described for the SVZ volcanic centers by Deruelle et al. (1983), Harmon et al. (1984), and

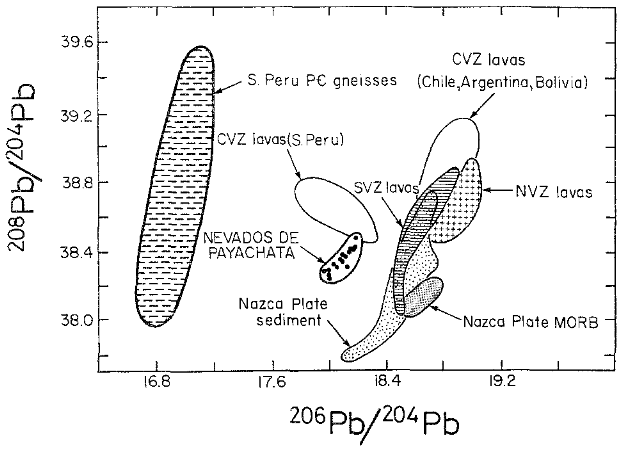

Fig. 12. $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ for Quaternary lavas of the Northern Volcanic Zone (NVZ), Central Volcanic Zone (CVZ), Southern Volcanic Zone (SVZ), and the Payachata lavas. Also included for comparison are the field for Pacific MORBs and sediments from the Nazca plate (Unruh and Tatsumotu 1976) and S. Peru Precambrian gneisses (Barreiro and Clark 1984; Tilton and Barreiro, 1980)

Hickey et al. (1984, 1986). The other components are of crustal origin. One is characterized by low, time-integrated U/Pb and Th/Pb ratios and may be similar to the Precambrian Charcani gneisses of southern Peru described by Tilton and Barreiro

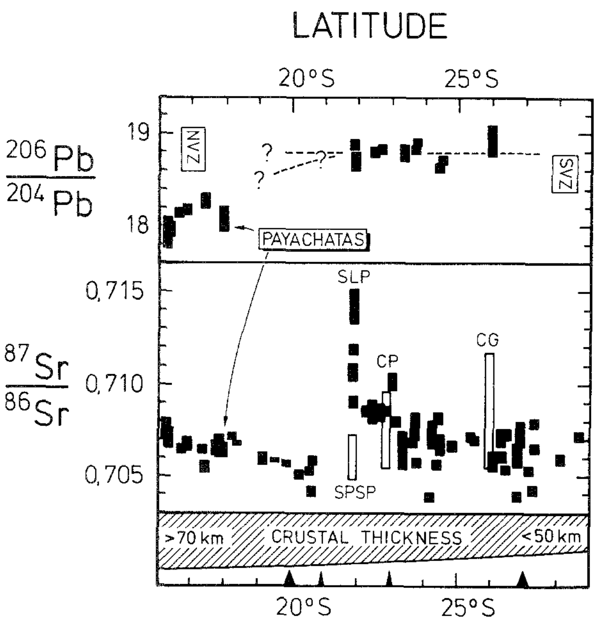

Fig. 13. Reginal variations in Pb and Sr isotope compositions along the CVZ Andean arc. Note the sampling gap between 18° and 22° for Pb isotope data. Literature sources as quoted in Fig. 9. SPSP, San Pedro-San Pablo; CG, Cerro Galan; CP, Cerro Purico; SLP, Sierra de Lipez

(1980). The other is the young continental crust of the Central Volcanic Zone enriched in radiogenic Pb, as described by Harmon et al. (1984). In a simplistic model, our data suggest that magmas parental to the Payachata system are produced by deep mixing between primary subcrustal and lower crustal components and that these parental basaltic andesite magmas differentiate further in upper crustal magma chambers through combined fractional crystallization-assimilation and magma mixing processes to produce the compositional range of lavas erupted.

Summary

In this paper we have described the geologic setting and history of the Miocene to Recent volcanism of the Nevados de Payachata region at 18°S in the Central Andes. The chemical and isotopic character of these rocks has been shown to be unusual in the context of the Central Volcanic Zone. The present discussion forms the basis for extended trace-element and isotope analyses and quantitative petrogenetic modelling that is presently in progress (Davidson et al., in preparation).

Our main conclusions are as follows:

1) The volcanic history of the Andean arc at 18°S encompasses two magmatic phases. The first produced a series of late Miocene andesitic stratocones and ignimbrite sheets (V. Lauca at 10.5 Ma, V. Ajoya at ≥7.1 Ma, and the Choquelimpie center ≥6.6 Ma). The second, Pleistocene to present phase is represented by the Nevados de Payachata complex, which consists of the V. Pomerape and V. Parinacota stratocones (0.3 Ma to Recent) and two small centers of similar age and geochemical affinity (Caquena, 0.28 Ma; Vilacollo, 0.29 Ma).

2) The volcanic history at V. Parinacota comprises five main stages and includes a major cone-collapse, debris-avalanche-forming eruption 13500 years ago. The resulting avalanche travelled up to 23 km, covered an area of 110 km^2, and emplaced a deposit with an estimated volume of 5–6 km^3.

3) Compared to other centers in the CVZ, those at 18°S are characterized by well-defined geochemical trends spanning the entire range from basalt to rhyolite. The petrographic and chemical character of the V. Parinacota lavas indicate that a major change in magma evolution occurred after the cone-collapse event. Before this event, magma evolution was dominated by fractional crystallization and magma mixing. This produced a range of

mafic andesites through rhyodacite lavas which erupted over a large time interval. After the collapse event, magma extrusion rates were higher and compositions on average were less silicic.
4) The cone-collapse event, associated change in magmatic character, and the appearance of isotopically and chemically distinct lavas may all be related to the input of new magma into the deep volcanic plumbing system.
5) Whereas Miocene lavas represent typical Andean calc-alkaline compositions, the Pleistocene to Recent centers are unusual in terms of their extremely high Ba, Sr, and, in the most recent lavas, Ti contents.

Geochemical and isotope data suggest a complex magma genesis at 18°S that is unlike that proposed elsewhere in the Central Andes: a valid petrogenetic model must explain the wide variation in bulk composition, the limited isotope variation, and the unusual Ba, Sr, and Ti contents of the Nevados de Payachata magmas.

Acknowledgements. We gratefully acknowledge help and hospitality from the CONAF personnel of Lauca National Park at Parinacota Village that facilitated the fieldwork. Mrs. G. Hulse of the British Consulate in Arica was extremely helpful in dealing with Chilean and Bolivian officials. Technical and analytical assistance has been provided by M. Bremer, Ruhr Universität Bochum (XRF), J. Borthwick, Southern Methodist University (stable isotopes), R. Goodwin, D. Foster and C. Johnson, Oxford University (radiogenic isotopes), and R. Cottrell, University of Alaska (K-Ar). H.-U. Schmincke made XRF analytical facilities freely available. P. Taylor is thanked for help and discussion. P. W. Francis made his vehicle available for our fieldwork and through the Lunar and Planetary Institute provided 'Landsat' photography that was most helpful in the field. His and W. Hildreth's critical reviews greatly improved the the manuscript. Funding for this work was provided through NSF grants EAR 8318916 to R. S. Harmon and EAR-8319766 to N. J. McMillan, a DFG-grant Wo 362/1-1 to G. Wörner, a Royal Society travel grant to S. Moorbath, an equipment grant from the Institute for the Study of Earth and Man at Southern Methodist University, and DIB (Univ. Chile) E-1703 grant to L. Lopez and H. Moreno. This work is a contribution to IGCP Project 249. "Andean Magmatism and its Tectonic Setting".

References

Barazangi M, Isacks BL (1976) Spatial distribution of earthquakes and subduction of the Nasca plate below South America. Geology 4:686–692

Barreiro BA (1984) Lead isotopes and Andean magmagenesis. Harmon RS, Barreiro BA (eds) Andean Magmatism, Chemical and Isotopic Constraints, SHIVA Publ. Nantwich, UK, p. 21–30

Barreiro BA, Clark AH (1984) Lead isotopic evidence for evolutionary changes in magma-crust interaction, Central Andes, southern Peru. Earth Planet Sci Lett 69:30–42

Bevis B, Isacks BL (1984) Hypocentral trend surface analysis: Probing the geometry of Benioff zones. J Geophys Res 89:6153–6170

Chase CG (1978) Plate kinematics: The Americas, East Africa, and the rest of the world. Earth Planet Sci Lett 37:355–368

Deruelle B (1982) Petrology of the Plio-Quaternary volcanism of the South-Central and Meridional Andes. J Volcanol Geoth Res 14:77–124

Deruelle B, Harmon RS, Moorbath S (1983) Combined Sr-O relationships and petrogenesis of Andean volcanics of South America. Nature 302:814–816

Dostal J, Dupuy C, Lefevre C (1977) Rare earth element distribution in Plio-Quarternary volcanic rocks from southern Peru. Lithos 10:173–183

Dupuy C, Lefevre C (1974) Fractionnement des elements en trace Li, Rb, Ba, Sr dans les series andesitiques et shoshonitiques du Perou. Comparison aves d'autre zones orogeniques. Contrib Mineral Petrol 46:147–157

Fernandez A, Hörmann PK, Kussmaul S, Meave J, Pichler H, Subieta T (1973) First petrologic data of young volcanic rocks of SW-Bolivia. Tscherm Mineral Petrogr Mitt 19:149–173

Francis PW, Self S (1987) Collapsing volcanoes. Scient Amer 255:90–97

Francis PW, Roobol MJ, Walker GPL, Cobbold RR, Coward M (1974) The San Pedro and San Pablo volcanoes of northern Chile and their hot avalanche deposits. Geol Rundsch 63:357–388

Francis PW, Moorbath S, Thorpe RS (1977) Strontium isotope data for recent andesites in Ecuador and North Chile. Earth Planet Sci Lett 37:197–202

Francis PW, Thorpe RS, Moorbath S, Kretzschmar GA, Hammill M (1980) Strontium isotope evidence for crustal contamination of calc-alkaline volcanic rocks from Cerro Galan, Northwest Argentina. Earth Planet Sci Lett 48:257–267

Francis PW, O'Callaghan L, Kretzschmar GA, Thorpe RS, Sparks RSJ, Page PN, de Barrio RE, Gillou G, Gonzalez OE (1983) The Cerro Galan Ignimbrite. Nature 301:51–53

Francis PW, McDonough WF, Hammill M, O'Callaghan LJ, Thorpe RS (1984) The Cerro Purico shield complex, North Chile. In Harmon RS, Barreiro BA (eds): Andean Magmatism, Chemical and Isotopic Constraints, SHIVA Publ. Nantwich, UK, p. 106–123

Gill JB (1981) Orogenic Andesites and Plate Tectonics. Springer (Berlin–New York), p. 1–390

Grange F, Hatzfeld D, Cunningham P, Molnar P, Roecker SW, Suarez G, Rodrigues A, Ocola L (1984) Tectonic implications of the microearthquake seismicity and fault plane solutions in Southern Peru. J Geophys Res 89:6139–6152

Handschuhmacher DW (1976) Post-Eocene plate tectonics of the eastern Pacific. In Sutton GH, Manghnani MH, Moberly R (eds): The Geophysics of the Pacific Ocean and its Margins. Am Geophys Union, Washington DC, p. 117–202

Harmon RS, Hoefs J (1984) Oxygen isotope ratios in Late Cenozoic Andean volcanics. 9–20

Harmon RS, Thorpe RS, Francis PW (1981) Petrogenesis of Andean andesites from combined O-Sr relationships. Nature 290:396–399

Harmon RS, Barreiro BA, Moorbath S, Hoefs J, Francis PW, Thorpe RS, Deruelle B, McHugh J, Viglino JA (1984) Regional O-, Sr- and Pb-isotope relationships in Late Cenozoic calc-alkaline lavas of the Andean Cordillera. J Geol Soc London 141:803–822

Hawkesworth CJ, Norry MJ, Roddick JC, Baker PE, Francis PW, Thorpe RS (1979) 143 Nd/144 Nd, 87 Sr/86 Sr, and incompatible element variations in calc-alkaline Andesites and Plateau lavas from S-America. Earth Planet Sci Lett 42:45–57

Hawkesworth CJ, Hammill M, Gledhill AR, van Calsteren P, Rogers G (1982) Isotope and trace element evidence for late-stage intracrustal melting in the High Andes. Earth Planet Sci Lett 51:297–308

Hickey RL, Gerlach DC, Frey FA (1984) Geochemical variations in volcanic rocks from central-south Chile (33–42°S). In Harmon RS, Barreiro BA (eds): Andean Magmatism, Chemical and Isotopic Constraints, SHIVA Publ. Nantwich, UK, p 72–95

Hickey RL, Frey FA, Gerlach DC (1986) Multiple sources for basaltic arc rocks from the Southern Volcanic Zone of the Andes (34°–41°S): Trace element and isotopic evidence for contributions from subducted oceanic crust, mantle, and continental crust. J Geophys Res 91:5963–5983

Hörmann PK, Pichler HP, Zeil W (1973) New data on the young volcanism in the Puna of NW-Argentina. Geol Rundsch 62:397–418

James DE (1971a) Plate tectonic model for the evolution of the Central Andes. Geol Soc Am Bull 82:3325–3346

James DE (1971b) Andean crustal and upper mantle structure. J Geophys Res 76:3246–3271

James DE (1982) A combined O, Sr, Nd, and Pb isotopic and trace element study of crustal contamination in central Andean lavas, I. Local geochemical vairiations. Earth Planet Sci Lett 57:47–62

James DE (1984) Quantitative models for Crustal Contamination in the Central Northern Andes. In Harmon RS, Barreiro BA (eds): Andean Magmatism, Chemical and Isotopic Constraints, SHIVA Publ. Nantwich, UK, p. 124–138

James DE, Brooks C, Cuyumbamba A (1976) Andean Cenozoic volcanism: Magma genesis in the light of Sr isotopic composition and trace element geochemistry. Geol Soc Am Bull 7:592–600

Katsui Y, Gonzalez-Ferran O (1968) Geologia del area neovolcanica de los Nevados de Payachata. Publicacion No. 29, Universidad de Chile, Facultad de Ciencas Fisicas y Matematicas, Departmento Geologia, pp 1–61 with plates

Klerkx J, Deutsch S, Pichler H, Zeil W (1977) Strontium isotopic composition and trace element data bearing on the origin of Cenozoic volcanic rocks of the central and southern Andes. J Volcanol Geoth Res 2:49–71

Kussmaul S, Hörmann PK, Ploskonka E, Subieta T (1977) Volcanism and structure of SW-Bolivia. J Volcanol Geoth Res 2:3–111

Longstaffe FJ, Clark AH, McNutt RH, Zentilli M (1983) Oxygen isotopic compositions of Central Andean plutonic and volcanic rocks, latitudes 26°–29°S. Earth Planet Sci Lett 64:9–18

McNutt RH, Crocket JH, Clark AH, Caelles JC, Farrar E, Haynes SJ, Zentilli M (1975) Initial $^{87}Sr/^{86}Sr$ ratios of plutonic and volcanic rocks of the Central Andes between latitudes 26° and 29° south. Earth Planet Sci Lett 27:305–313

McNutt RH, Clark AH, Zentilli M (1979) Lead isotope compositions of Andean igneous rocks, latitudes 26°–29°S: petrologic and metallogenic implications. Econ Geol 74:827–837

O'Callaghan LJ, Francis PW (1986) Volcanological and petrological evolution of San Pedro volcano, Provincia El Loa, North Chile. J Geol Soc London 143:275–286

Pardo-Casas F, Molnar P (1987) Relative motion of the Nazca (Farallon) and south American plates since Late Cretaceous time. Tectonics 6:233–248

Pichler H, Zeil W (1972) Paleozoic and Mesozoic ignimbrites of northern Chile. N Jb Mineral Abh 116:196–207

Pilger RH (1981) Plate reconstructions, aseismic ridges, and low angle suduction beneath the Andes. Geol Soc Am Bull 92:448–456

Schwarz G, Martinez E, Bannister J (1986) Untersuchungen zur elektrischen Leitfähigkeit in den zentralen Anden. In: Giese P (ed) Forschungsberichte aus den Zentralen Anden (21°–25°S), Berliner Geowissenschaftliche Abhandlungen 66:49–72

Siegers A, Pichler H, Zeil W (1969) Trace element abundances in the andesite formation of northern Chile. Geochim Cosmochim Acta 33:882–887

Stauder W (1973) Mechanism and spatial distribution of Chilean earthquakes with relation to subduction of the oceanic plate. J Geophys Res 78:5033–5061

Stauder W (1975) Suduction of the Nazca plate under Peru as evidenced by focal mechanisms and by seismicity. J Geophys Res 80:1053–1064

Tagiri M, Onuma N, Lahsen A, Moreno H, Takahashi M, Notsu K, Takaku Y (1985) SB systematics on the central Andes volcanic zone of northern Chile. In: Geochemical Investigation of the Southern Andes Volcanic Belt, 1982–1984. Overseas Scientific Research 59043009, Ibaraki University, Japan, 217–230

Thornburg TM, Kulm LD (1987) Sedimentation in the Chile trench: Depositional morphologies, lithofacies, and stratigraphy. Geol Soc Am Bull 98:33–52

Thorpe RS, Francis PW (1979) Variations in Andean andesite compositions and their petrogenetic significance. Tectonophysics 57:53–70

Thorpe RS, Potts PJ, Francis PW (1976) Rare earth data and petrogenesis of andesite from the north Chilean Andes. Contrib Mineral Petrol 54:65–78

Thorpe RS, Francis PW, Moorbath S (1979) Rare earth and Sr-isotope evidence concerning the petrogenesis of north Chilean ignimbrites. Earth Planet Sci Lett 42:359–367

Thorpe RS, Francis PW, Hammill M, Baker MCW (1982) The Andes. In: Thorpe RS (ed) Andesites: Orogenic Andesites and related Rocks, Wiley and Sons, New York, p 187–205

Tilton GR, Barreiro BA (1980) Origin of lead in Andean calc-alkaline lavas, southern Peru. Science 210:1245–1247

Unruh DM, Tasumoto M (1976) Lead isotopic compositions and uranium, thorium and lead concentrations in sediments and basalts from the Nasca plate. Init Rep Deep Sea Drill Project 34:341–347

Wigger P (1986) Krustenseismische Untersuchungen in Nord-Chile und Süd-Bolivien. In: Giese P (ed) Forschungsberichte aus den zentralen Anden (21°–25°S), Berliner Geowissenschaftliche Abhandlungen 66:31–48

Wortel MJR (1984) Spatial and temporal variations in the Andean subduction zone. J Geol Soc London 141:783–791

Received November 6, 1987/Accepted January 15, 1988