Geochronology ($^{40}Ar/^{39}Ar$, K-Ar and He-exposure ages) of Cenozoic magmatic rocks from Northern Chile (18-22°S): implications for magmatism and tectonic evolution of the central Andes

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ABSTRACT

K-Ar and Ar/Ar ages from magmatic rocks of northern Chile (18-22°S) describe duration and extent of the Tertiary and Quaternary magmatic evolution and date major tectonic events in northernmost Chile. This paper summarizes new K-Ar and Ar-Ar mineral and whole rock ages for intrusive rocks from the Precordillera, Tertiary ignimbrites and andesitic stratovolcanoes from the Western Andean Escarpment at 18°S (WARP) and the volcanic front. Intrusive rocks of the Precordillera (Quebrada Paguana, Quebrada Blanca, Quebrada Choja, Quebrada Guatacondo, Cerro Chandacolla) represent the Cretaceous to Eocene magmatic arc system and gave ages between 45 and 35 Ma. Younger ages on intrusive rocks are invariably caused by deuteric alteration. Ignimbrites of the Putani and Oxaya formations gave Ar-Ar sanidine ages around 24.2 to 24.8 Ma and 22.8 to 19.4 Ma, respectively. Andesitic stratovolcanoes, which directly overlie Oxaya ignimbrites east of the Western Cordillera gave ages of 20.3 Ma (Cordon Quevilque) to 9.0 Ma (Cerro Margarita). Samples from the Miocene to Pleistocene arc system on the Chilean Altiplano underlying the volcanoes of the active volcanic front have been dated between 10.5 to ~3 Ma. A widespread ignimbrite can be correlated from the Lauca basin to the Pacific coast and to the east to occurrences of near Pérez. Repeated Ar-Ar sanidine dating of the Lauca-Pérez-ignimbrite resulted in highly concordant ages of 2.71±0.25 Ma, 2.72 Ma±0.01 Ma, and 2.73±0.11 Ma. Rocks from the active chain (Volcanic Cordillera) gave ages younger than 0.9 Ma (Volcán Irruputuncu, Volcán Olca, Volcán Aucanquilcha, Volcán Ollagüe, Volcán Poruñita). These new data are used to constrain Miocene stratigraphy and tectonic movements as well as the timing of uplift and sedimentary response at the Western Andean Escarpment within the framework of the tectonic evolution of the Central Andes.

Key words: Geochronology, Volcanism, Cenozoic, Northern Chile.

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RESUMEN

Geocronología ($^{40}Ar/^{39}Ar$, K-Ar y edades He de exposición) de rocas cenozoicas del norte de Chile (18-22°S): implicancias para el magmatismo y la evolución tectónica de los Andes centrales. Las edades K-Ar y Ar/Ar de rocas magmáticas del norte de Chile (18-22°S) describen la duración y extensión de la evolución magmática terciaria y cuaternaria, y datan los eventos tectónicos mayores en esta región. Este trabajo resume nuevas edades K-Ar y Ar/Ar en minerales y roca total para intrusivos de la Precordillera, ignimbritas cenozoicas y estratovolcanes andesíticos del Escarpe Andino Occidental a los 18°S, y del frente volcánico. Las rocas intrusivas de la Precordillera (Quebrada Paguana, Quebrada Blanca, Quebrada Choja, Quebrada Guatacondo, Cerro Chandacolla) representan el sistema de arco magmático cretácico a Eoceno, y dieron edades entre 45 y 35 Ma. Edades menores en rocas intrusivas son invariablemente causadas por alteración deutérica. Las ignimbritas de las formaciones Putani y Oxaya dieron edades Ar-Ar en sanidina alrededor de 24.2 a 24.8 Ma y 22.8 a 19.4 Ma, respectivamente. Los estratovolcanes andesíticos que sobreyacen directamente a las ignimbritas de Oxaya al norte de la Cordillera Occidental, dieron edades de 20.3Ma (Cordón Quevilque) a 9.0 Ma (Cordón Margarita). Las muestras del Sistema de Arco Mioceno a Pleistoceno en el altiplano chileno que infrayacen a los volcanes del frente volcánico activo, han sido datadas entre 10.5 y *ca.* 3 Ma. Una ignimbrita de extensa distribución areal puede ser corelacionada desde la cuenca de Lauca hasta la costa del Pacífico, y hacia el este con ocurencias vecinas a Pérez. Dataciones repetidas por el método Ar-Ar en sanidina de la ignimbrita Lauca-Pérez dieron resultados concordantes de 2.7±0.25 Ma, 2.72±0.01 Ma y 2.73±0.01 Ma. Rocas del arco actual (Cordillera Volcánica) dieron edades más jóvenes que 0. 9 Ma (volcanes, Irruputuncu, Olca, Aucanquilcha, Ollagüe, Poruñita). Estos nuevos datos se usan para constreñir la estratigrafía miocena, los movimientos tectónicos y la cronología de alzamiento y respuesta sedimentaria en el Escarpe Andino Occidental en el marco de la evolución tectónica de los Andes centrales.

Palabras claves: Geocronología, Volcanismo, Cenozoico, Norte de Chile.

INTRODUCTION

Unraveling the magmatic and tectonic history of the Central Andes based on stratigraphy (Lahsen, 1982) depends on reliable absolute age dating. In particular, the estimation of magma production rates along the arc (*e.g.*, Francis and Hawkesworth, 1994) relies strongly on absolutely dated volcanic rocks. In addition, uplift history, tectonic deformation rates and landscape evolution can only be assessed when volcanic marker horizons are well-dated (Isacks, 1988; Allmendinger *et al.*, 1997; Seyfried *et al.*, 2000; Uhlig, 2000).

K-Ar whole rock ages are known to be prone to analytical problems and to be easily affected by sample alteration. K-Ar mineral data are more reliable. The most reliable age information comes from concordant Ar-Ar plateau ages, isochron ages and total degassing ages on sanidine and biotite mineral separates. These ages are combined with additional ages on the same unit and/or other samples, for which the stratigraphic correlations are well known to provide the most reliable age constraint.

Nevertheless, even K-Ar ages may still provide valuable information in the form of minimum ages when possible sources of uncertainty are considered and taken into account.

There is a relative scarcity of geochronological data in the area of northern Chile (between 17 and 22°S) compared to the region of the Salar de Atacama or the Maricunga Belt (see compilation by Kay *et al.*, 1999). The present contribution summarizes our K-Ar and Ar-Ar ages for a suite of intrusive and volcanic rocks from the Western Andean slope, Pre-Cordillera and the Miocene to Recent volcanic chains on the Chilean Altiplano between 17 and 22°S (Fig. 1). These data are combined with other data previously reported in abstract form only (Horn *et al.*, 1992, Walfort *et al.*, 1995) and evaluated to better constrain the magmatic and tectonic evolution of the Central Andes in Cenozoic times.

GEOLOGICAL SETTING

The active western continental margin of central South America is characterized by subduction of the Farallon-Nazca plate and arc magmatism since Jurassic times. Convergence rates have been variable between 5 cm/a at around 60 and 30 Ma and up to 15 cm/a from 50 to 40 Ma and around 20 cm/a to 10 Ma. At the same time, the convergence angle changed from continent-parallel around 60 Ma to almost orthogonal at present (Pardo-Casas and Molnar, 1987). The dip of the subducting Nazca plate today varies from less than 10° in the shallow subducting regions between the volcanic zones to 20-30° within the volcanic zones, *e.g.*, in the Central Andes (Thorpe, 1984; Kay and Abruzzi, 1996). No magmatism occurs in areas of present-day flat-slab subduction in the north and south of the Central Andes. The geological record of magmatism through space and time suggests that flat-slab subduction also occurred in the geological past.

Proterozoic basement rocks and overlying Permian (?) marine sediments (Wörner *et al.*, in press) are exposed in the area of Belén and Tignamar in northern Chile. Mesozoic tholeiitic rocks of the La Negra Formation and Jurassic to Lower Cretaceous marine back arc sediments comprise the uplifted Coastal Cordillera and Central Depression (Longitudinal Valley). A glassy sample from a mafic andesite pillow at the Morro at Arica has been dated here at 133.1±4 Ma (APT-011). This age should be considered a minimum age because of the possibility that slight devitrification could have affected the K-Ar system. Magmatism shifted some 100 km from a western position in the Jurassic to the present Western Cordillera in Oligocene times (Scheuber, 1994) suggesting the combined effect of continued tectonic erosion at the leading edge of the South American plate and variable slab dip. Upper Cretaceous to Lower Tertiary volcanic, volcaniclastic, sedimentary, and intrusive rocks have been folded, uplifted and eroded in Late Eocene times (Hammerschmidt *et al.*, 1992). The general evolution is that of an evolving and east-migrating arc system that changed in Early Creataceous time from a marine arc and backarc environment to terrestrial in Middle Cretaceous times.

Prior to the last 30 Ma, the area of northernmost Chile was characterized by continental sedimentation, andesitic volcanism, and abundant reworked volcaniclastic sediment and sedimentary rocks (Lupica Formation). These sedimentary rocks and volcanic structures indicate low elevations and abundant water. However, stratigraphic data of Naranjo and Pascoff, 1985; Salas *et al.*, 1966, Vogel and Vila, 1980) suggest that large volumes of coarse gravel (Azapa Formation, Salas *et al.*, 1966) started to accumulate since about 25 Ma in the area of the present Longitudinal Valley (Figs. 1, 2). These sediments indicate the initiation of Andean uplift at that time when abundant water was still available. Pollen and the sedimentary record of Miocene lake sediments and underlying red gravels on the present Altiplano (Kött *et al.*, 1995; Gaupp *et al.*, 1999) suggest that the present extremely arid climate and high elevations (>3000 m) existed since the last 6 Ma.

The topography of the Western Andean Escarpment (WARP) at 18°S is shown in figure 2 and comprises the Coastal Cordillera, Longitudinal Valley, Western Andean Escarpment, active Volcanic front, and Altiplano as it evolved in the past 30 Ma (Mpodozis and Ramos, 1990; Lamb *et al.*, 1997; Allmendinger *et al.*, 1997).

SAMPLE DESCRIPTION AND GEOCHRONOLOGICAL DATA

We will describe (from south to north) briefly each sample locality to facilitate the discussion and use of the new age data. In the later paragraphs the geological implication of the new data are discussed. The location (coordinates), petrographic and stratigraphic information on the samples dated as well as the measured age data are given in table 1, the samples are located on the maps in figures 3, 4, 5, 6, 7 and 8. More detailed information on the samples, sampling site, their geochemical composition and geological surroundings can be found in thesis form by Horn (1992), Heuman (1993), Anthes (1993),

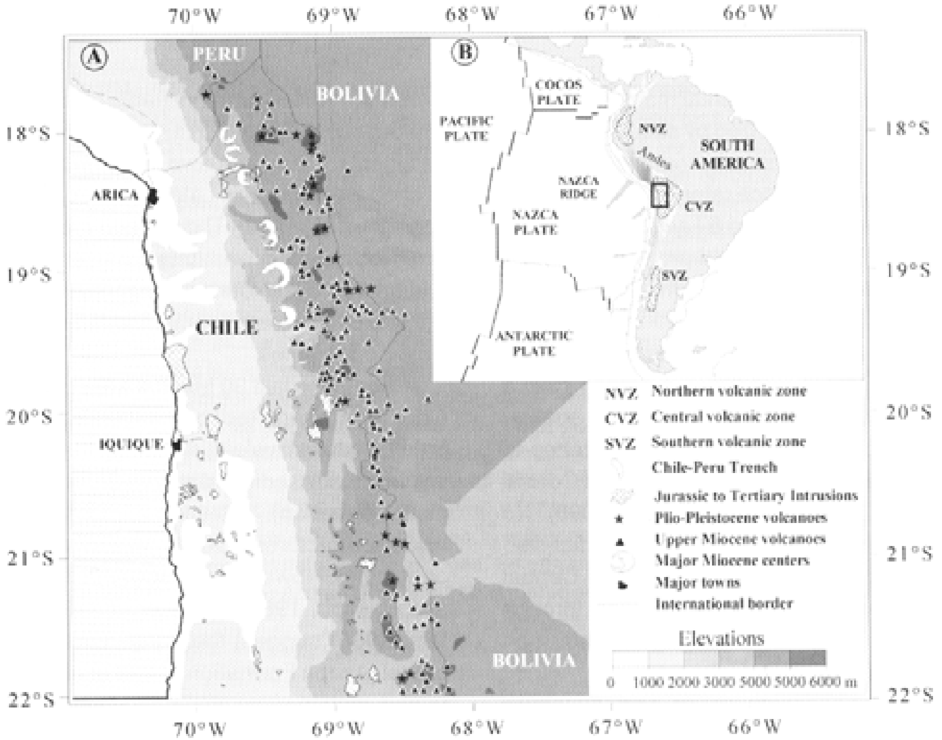


FIG. 1. Morphological map of the area studied in the central Andes between 22 and 26°S, with Plio-Pleistoceno and Miocene volcanic centers, and outcrop areas of intrusive rocks.

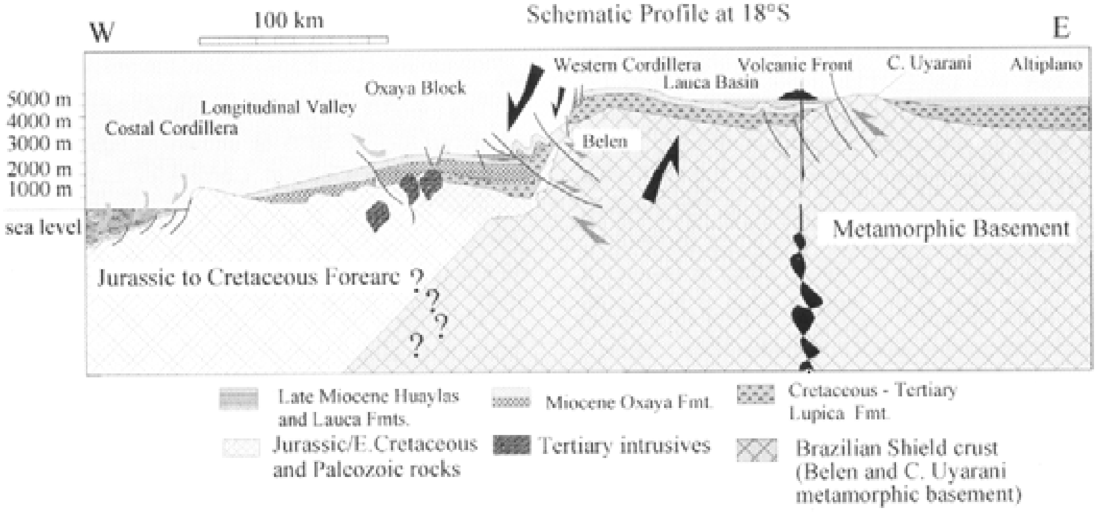


FIG. 2. Schematic east-west profile slightly modified after Wörner *et al.* (2000a), from the coast to the Altiplano (at about 18°S).

TABLE 1. Ar-Ar AND K-Ar DATA OF VOLCANOES, IGNIMBRITES AND INTRUSIVES IN THE CVZ.

Sample	Locality	Description/Formation	Rock type	Method	Mineral (K wt.%)	% $^{40}Ar_{rad}$	Age (Ma ± 2σ)	Comments	Data source
Intrusive rocks									
Quebrada Blanca									
BLA 21	21°01'04"S 68°50'10"W	Intrusion	Granodiorite	K-Ar	Bi (6.6)	88.9	17.5 ± 0.5	Disturbed, not reliable	(1)
BLA 21	21°01'04"S 68°50'10"W	Replicate	Granodiorite	K-Ar		93.1	35.0 ± 1.0		(1)
BLA 21	21°01'04"S 68°50'10"W	Replicate	Granodiorite	K-Ar		78.1	36.1 ± 1.0		(1)
Quebrada Choja									(1)
CHJ 04	21°05'00"S 68°52'25"W	Intrusion	Granodiorite	K-Ar	Bi (6.5)	93.7	34.2 ± 1.0		(1)
Quebrada Guatacondo									
GUA 01	20°55'30"S 68°54'00"W	Intrusion	Granodiorite	K-Ar	Bi (6.7)	89.5	33.3 ± 0.9	First intrusive outcrop, km 46 from Panamericana	(1)
GTC 02	20°59'20"S 68°53'10"W	Intrusion	Granite	K-Ar	Bi (6.4)	95.1	34.3 ± 1.0		(1)
GTC 02	20°59'20"S 68°53'10"W	Replicate	Granite	K-Ar		89	34.8 ± 1.0		(1)
GTC 02	20°59'20"S 68°53'10"W	Replicate	Granite	K-Ar		82.1	43.7 ± 1.2		(1)
GTC 02	20°59'20"S 68°53'10"W	Replicate	Granite	K-Ar		79.2	44.1 ± 1.3		(1)
Cerro Chandacolla									
HUA 01	19°52'45"S 68°57'20"W	Intrusion	Granodiorite	K-Ar	Bi (7.1)	9.9	28.0 ± 6.0	Disturbed, not reliable	(1)
HUA 01	19°52'45"S 68°57'20"W	Replicate	Granodiorite	K-Ar		73.6	34.3 ± 1.0		(1)
Cerro Colorado									
COL - A	-	Intrusion	Syeno-granodiorite	Ar-Ar	Biotite	-	68.08 ± 0.36	Plateau age	(2)
COL - B	-	Intrusion	Akali gabbro	Ar-Ar	Biotite	-	67.99 ± 0.36	Plateau age	(2)
Volcanic rocks of the north-south transect									
Porquesa Ignimbrite									
POR 03	19°59'00"S 68°45'40"W	Thin local ignimbrite from Porquesa	Rhyo. ignimbrite	K-Ar	Bi (5.6)	1.7	0.15 +0.20/-0.15	No reliable age	(1)
POR 03	19°59'00"S 68°45'40"W	Thin local ignimbrite from Porquesa	Rhyo. ignimbrite	K-Ar	Fsp. (1.1)	1.4	0.29 +0.45/-0.29	No reliable age	(1)
Isluga									
IS3-045	19°09'00"S 68°51'22"W	Glaciated flows of Isluga IIId	Dacite	K-Ar	WR (3.185)	7.49	0.096 ± 0.006		(3)
IS3-045	19°09'00"S 68°51'22"W	Glaciated flows of Isluga IIId, replicate	Dacite	K-Ar	WR (3.190)	7.45	0.096 ± 0.006		(3)
IQM-003	19°06'55"S 68°50'35"W	from older dissected Quimsachata	Andesite	K-Ar	WR (2.97)	24.2	0.566 ± 0.017		(3)
Cerro de Nappa 20°30'40"S 68°39'45"W									
NAP 01	20°30'05"S 68°40'00"W	Px. andesite		K-Ar	WR (1.7)	5.8	1.38 ± 0.50		(1)
Volcán Irruputuncu 20°44'00"S 68°33'55"W									(1)
IRU 10	20°43'30"S 68°34'20"W	Lower flow on W base of cone	Andesite flow	K-Ar	Bi (4.9)	2.7	0.45 ± 0.40		(1)
IRU 10	20°43'30"S 68°34'20"W	Replicate	Andesite flow	K-Ar		1.7	0.07 ± 0.08	No reliable age	(1)
IRU 11	20°43'20"S 68°34'15"W	Younger upper flow on W slope	Andesite	K-Ar	Bi (4.1)	1.5	0.14 ± 0.04		(1)
IRU 15	20°46'S 68°37'W	Ignimbrite on Pampa Irruputuncu	Rhyo. ignimbrite	K-Ar	Bi (3.9)	2.9	0.32 ± 0.25		(1)

Sample	Locality	Description/Formation	Rock type	Method	Mineral (K wt.%)	% $^{40}Ar_{rad}$	Age (Ma ± 2 σ)	Comments	Data source
Volcán El Rojo Sur 20°46'20''S 68°36'00''W									
ELR S	20°46'20''S 68°36'00''W	Isolated scoria cone	Glas. aph. bas. and.	K-Ar	WR (2.1)	37.1	2.93 ± 0.13		(1)
ELR S	20°46'20''S 68°36'00''W	Replicate	Glas. aph. bas. and.	K-Ar		45.4	3.23 ± 0.12		(1)
Volcán Olca 20°55'50''S 68°29'35''W									
OLC 01	20°56'36''S 68°32'35''W	Old distal flow at base W of summit	Andesite	K-Ar	WR (2.3)	2.1	0.43 ± 0.50	No reliable age	(1)
OLC 05	20°55'55''S 68°30'10''W	Flow on upper SW slope	Hbl. andesite	K-Ar	WR (2.3)	0.2	0.005 ± 0.350	No reliable age	(1)
OLC 05	20°55'55''S 68°30'10''W	Replicate	Hbl. andesite	K-Ar		3.7	-0.08 ± 0.04		(1)
Volcán Aucanquilcha 21°12'30''S 68°28'00''W									
AUC 01	21°11'25''S 68°27'10''W	Thick leveed flow near pass	Dacite	K-Ar	Fsp. (0.5)	12.5	0.78 ± 0.12		(1)
AUC 07	21°13'45''S 68°30'20''W	Thick domes/flows on SW slope	and-dacite	K-Ar	WR (2.4)	7.9	0.52 ± 0.12		(1)
AUC 07	21°13'45''S 68°30'20''W	Replicate		K-Ar		4.1	0.40 ± 0.20		(1)
Volcán Mino 21°11'30''S 68°35'20''W									
MIN 02	21°10'20''S 68°33'20''W	Older cone 2.5 km E of Mino	Basaltic andesite	K-Ar	WR (2.3)	60.1	3.59 ± 0.11		(1)
MIN 07	21°10'30''S 68°35'15''W	Flows from N slope El Mino	Amph. andesite	K-Ar	WR (1.9)	15.8	3.27 ± 0.40		(1)
Volcán Ollagüe 21°18'10''S 68°11'00''W									
OLA 10	21°16'10''S 68°16'10''W	Isolated younger dome NW of Ollague	Rhyodacite	K-Ar	Bi (6.7)	2.6	0.47 ± 0.50	No reliable age	(1)
OLA 10	21°16'10''S 68°16'10''W	Replicate	Rhyodacite	K-Ar	4.7		0.34 ± 0.15		(1)
OLA 10	21°16'10''S 68°16'10''W		Rhyodacite	K-Ar	Fsp (0.7)	2.6	0.81 ± 0.50		(1)
OLA 11	21°18'55''S 68°10'05''W	Glaciated ridge, E of sulfur mine-	Andesite	K-Ar	WR (2.8)	10	0.41 ± 0.08		(1)
OLA 13	21°18'50''S 68°10'30''W	Younger flow from summit	Glassy dacite flow	K-Ar	Bi (6.6)	6.3	0.13 ± 0.04		(1)
OLA 13	21°18'50''S 68°10'30''W	Replicate	Glassy dacite flow	K-Ar		6.9	0.21 ± 0.06		(1)
OLA 13	21°18'50''S 68°10'30''W	Glassy dacite flow		K-Ar	Fsp (0.6)	6.9	0.89 ± 0.25		(1)
OLA 23	21°18'20''S 68°11'15''W	Older series flow at upper w flank	Dacite flow	K-Ar	WR (2.3)	7.3	0.68 ± 0.18		(1)
OLA 25	21°17'15''S 68°11'15''W	Glaciated flows NW slope	Andesite	K-Ar	Bi (3.9)	10.4	0.91 ± 0.17		(1)
OLA 27	21°17'05''S 68°12'05''W	Thick older series flow NW	Andesite	K-Ar	Bi (5.6)	16.2	0.75 ± 0.08		(1)
OLA 27	21°17'05''S 68°12'05''W	Replicate	Andesite	K-Ar		14.8	0.97 ± 0.07		(1)
OLA 31	21°16'00''S 68°11'35''W	Isolated older domes	Rhyodacite	K-Ar	Fsp (0.8)	1.6	0.62 ± 0.90	No reliable age	(1)
OLA 31	21°16'00''S 68°11'35''W		Rhyodacite	K-Ar	Bi (5.5)	8.6	0.45 ± 0.10		(1)
Volcán Poruñita 21°16'40''S 68°17'30''W									
PORU 02 (dense bomb)	21°17'40''S 68°15'35''W	Phreatomagmatic cone	Bas. and., aph.	K-Ar	WR (1.9)	4.3	0.42 ± 0.20		(1)
PORU 02	21°17'40''S 68°15'35''W	Replicate	Bas. and., aph.	K-Ar		5.8	0.65 ± 0.20		(1)
PORU 02	21°17'40''S 68°15'35''W	Replicate	Bas. and., aph.-	K-Ar		6.3	0.68 ± 0.20		(1)
Cerro Chela 21°24'00''S 68°29'40''W									
CHE 07	21°25'30''S 68°25'50''W	Flows from base	Andesite flow	K-Ar	WR (2.3)	13.4	3.75 ± 0.50		(1)
CHE 08	21°24'20''S 68°27'00''W	Dense spatter from flow at base	Bomb	K-Ar	WR (1.5)	28.5	4.11 ± 0.25		(1)

(table 1 continued)

Sample	Locality	Description/Formation	Rock type	Method	Mineral (K wt. %)	% $^{40}Ar_{rad}$	Age (Ma ± 2 σ)	Comments	Data source
Cerro Carcote 21°26'10"S 68°23'10'W									
CAR 01	21°26'10"S 68°23'10"W	Small isolated scoria cone	Bas. andesite	K-Ar	WR (1.9)	43	3.34 ± 0.13		(1)
CAR 01	21°26'10"S 68°23'10"W	Small isolated scoria cone replicate		K-Ar		41.4	2.82 ± 0.11		(1)
Cerro Palpana 21°33'0"S 68°31'40"W									
PAL 01	21°33'55"S 68°29'55"W	Flows from ESE ridge	Fsp. cpx. andesite	K-Ar	WR (1.7)	23.1	3.65 ± 0.30		(1)
PAL 04	21°34'00"S 68°29'40" W	Flows from ESE ridge	Bio. mphy. maf. and.	K-Ar	WR (1.8)	22.3	3.81 ± 0.30		(1)
Cerro de las Cuevas 21°35'15"S 68°29'20"W									
CUEV 04	21°34'25"S 68°29'30" W	Isolated spatter cone near pass	Ol. basalt	K-Ar	WR (1.7)	34.6	3.15 ± 0.15		(1)
CUEV 04	21°34'25"S 68°29'30" W	Replicate	Ol. basalt	K-Ar	WR (1.7)	42.1	3.36 ± 0.13		(1)
Nevados de Payachata Complex									
Parinacota									
PAR-082	18°11'10"S 69°10'10"W	Old cone flow ('wall andesite')	Amph. andesite	K-Ar	WR	0.38	0.012 ± 0.015	Too young to be reliably dated	(4)
PAR-016	18°12'00"S 69°06'15"W	old cone border dacite	Dacite	K-Ar	WR	1.23	•0.053 ± 0.011	Too young to be reliably dated	(4)
PAR-048	18°10'55"S 69°10'35"W	basal domes	Rhyodacite	K-Ar	WR	6.23	•0.112 ± 0.005	Too young to be reliably dated	(4)
PAR-121	18°12'05"S 69°09'00"W	Lago Chungará andesite	Amph. andesite	K-Ar	WR	1.87	0.110 ± 0.022		(4)
PAR-074	18°11'55"S 69°09'08"W	Lago Chungará andesite	Amph. andesite	K-Ar	WR	2.79	0.194 ± 0.0.009		(4)
PAR-118	18°12'55"S 69°08'12"W	Lago Chungará andesite	Amph. andesite	K-Ar	WR	1.78	0.264 ± 0.016		(4)
Chucuyo									
CHU-171	18°13'50"S 69°18'15"W	Chucuyo mafic andesite center	Cpx andesite	K-Ar	WR	2.55	0.285 ± 0.053		(4)
Caquena domes									
CAQ-001	18°03'45"S 69°13'05"W	Caquena dome/flow complex	Amph andesite	K-Ar	WR	1.47	0.275 ± 0.045		(4)
Pomerape									
POM-116	18°04'40"S 69°08"10"W	Glaciated flow on NWN slope	Cpx andesite	K-Ar	WR	7.43	0.106 ± 0.007		(4)
POM-149	18°05'10"S 69°06'25"W	Isolated glaciated scoria cone	Mafic ol-andesite	K-Ar	WR	1.91	0.219 ± 0.024		(4)
POM-152	18°05'10"S 69°06'25"W	Isolated glaciated scoria cone	Mafic ol-andesite	K-Ar	WR	3.20	0.192 ± 0.012		(4)
Quaternary volcanoes of the active volcanic front									
LLU 91 016	17°58'35"S 69°38'20"W	Taapacá, at road 4 km E of Alcerreca	Dacite	Ar-Ar	Sanidine (8.9)	81.8	1.27± 0.04*	Old Taapacá block and ash flow, Quebrada Allane	(5)
TAP-001	18°09'30"S 69°28'20"W	Taapacá, 5 km W of Las Cuevas	Dacite	K-Ar	WR (2.69)	6.43	0.096± 0.04	Taapacá block and ash flow	(3)
TAP-001	18°09'30"S 69°28'20"W	Taapacá, 5 km W of Las Cuevas	Dacite	K-Ar		5.86	0.078± 0.04	Replicate	(3)
TAP-97-MC	18°07'45"S 69°30'55"W	Taapacá, short flow S of summit	sanidine	Ar-Ar	Sanidine (<10)		0.0386± 0.0026	Megacryst, average of 4 analyses	(8)
TAC-004	17°42'55"S 69°44'00"W	Base of V. Tacora	Andesite	K-Ar	WR (2.55)	16.51	0.499 ± 0.015	Flow at base of volcano	(3)
SUP-025	18°45'50"S 68°58'18"W	Surire-Puquintiqua	Andesite	K-Ar	WR (2.38)	14.85	0.496 ± 0.015	Glassy dacite from base of S-directed cirque	(3)
SUA-006	18°46'50"S 69°04'00"W	Surire-Arintiqua	Andesite	K-Ar	WR (3.07)	19.72	0.637 ± 0.019	Columnar jointed bomb at S. flank	(3)
ELRN	18°28'05"S 69°11'45"W	El Rojo Norte Cinder cone	Mafic andesite	K-Ar	WR	73.73	3.05 ± 0.19	Dense bombs	(1)
ELRN	18°28'05"S 69°11'45"W	Replicate	Mafic andesite	K-Ar		76.02	3.35 ± 0.22	Dense bombs	(1)

(table 1 continued)

Sample	Locality	Description/Formation	Rock type	Method	Mineral (K wt. %)	% $^{40}Ar_{rad}$	Age (Ma ± 2 σ)	Comments	Data source
ELRN	18°28'05"S 69°11'45"W	Replicate	Mafic andesite	K-Ar		75.42	2.34 ± 0.16	Dense bombs	(1)
LAU-91-071	18°33'20"S 69°11'05"W	Tuff in Lauca Sediments	Fine dacitic ash	K-Ar	Biotite	56.30	5.38 ± 0.21	Biotite separated from ash (Kött *et al.*, 1993)	(1)
LAU-91-116	18°33'55"S 69°09'03"W	Tuff in Lauca Sediments	Fine dacitic ash	K-Ar	Biotite	62.20	6.04 ± 0.27	Biotite separated from ash	(1)
LAU-91-117	18°34'50"S 69°08'30"W	Tuff in Lauca Sediments	Fine dacitic ash	K-Ar	Biotite	57.10	6.20 ± 0.24	Biotite separated from ash	(1)
LAU-91-117	18°34'50"S 69°08'30"W	Replicate	Fine dacitic ash	K-Ar		47.10	5.52 ± 0.19	Biotite separated from ash	(1)
Miocene Shield volcanoes and isolated volcanic deposits									
CHO-098	18°17'25"S 69°15'35"S	Dike at Choquelimpe mine	Quartz porphyry dike	K-Ar	WR	55	6.60 ± 0.20		(4)
AJA-177	18°14'00"S 69°13'00"W	N flank Ajoya	amph. andesite flow	K-Ar	WR	27	7.06 ± 0.21		(4)
LAU-102	18°15'50"S 69°23'25"S	Cerro Tejene eroded cone	Andesite flow	K-Ar	WR	90	10.5 ± 0.3		(4)
LAU-105	18°15'55"S 69°24'10"W	Dome remnant centered at Tejene	Rhyodacite	K-Ar	WR	87	10.5 ± 0.4		(4)
CMA-10	18°42'25"S 69°24'05"W	Cerro Márquez Zapahuira Fm.	Amph-andesite	Ar-Ar	amph		9.18 ± 0.33**	One of two degassing stages (small sample)	(7)
HUY-94-165	18°04'00"S 69°41'00"	Cerro Huaylias, S. Alcerreca, Zapahuira Fm.	Andesite	Ar-Ar	amph		20.33 ± 0.38	Total gas age	(7)
COP-94-216	18°S23'40" 69°35'45"W	Cerro Copaquilla, Zapahuira Fm.	Andesite	Ar-Ar	WR		15.07 ± 0.12	Slightly disturbed spectrum, total gas age	(7)
ZAP 01	18°18'15"S 69°37'55"W	Cordón Quevilque Zapahuira Fm.	Andesite	Ar-Ar	Amph		20.12 ± 0.76	Not leached	(7)
ZAP 01	18°18'15"S 69°37'55"W	Replicate Zapahuira Fm.	Andesite	Ar-Ar			20.02 ± 0.32	Leached sample in 5% HF	(7)
ZAP 03	18°16'20"S 69°35'55"W	Cordón Quevilque, Zapahuira Fm.	Hbl. andesite	Ar-Ar	Hbl (0.35)	47.4	18.70± 0.80 **	Cordón Quevilque, near Zapahuira	(5)
LAU-94-174	18°34'50"S 69°01'35"W	Tilted volcanic rocks at Lauca gorge Putana Fm.	Ignimbrite	Ar-Ar	Biotite		24.23 ± 0.13	Plateau age, small sample	(7)
LAU-94-11	18°34'50"S 69°01'35"W	Tiltedvolcanic rocks at Lauca gorge Putana Fm.	Block and ash flow	Ar-Ar	Plagioclase		24.8 ± 2.1		
								Total gas age	(7)
LAU-94-118	18°34'50"S 69°01'35"W	Tilted volcanic rocks at Lauca gorge Putana Fm.	Block and ash flow	Ar-Ar	Biotite		24.17 ± 0.13	Isochrone age, excess argon	(7)
Ignimbrites									
Canal-Ignimbrite below Parinacota collapse									
LAU 2/1	18°14'20"S 69°17'00"W	At Lauca canal, 2 km S Chucullu	Ignimbrite	K-Ar	glass (3.9)	1.6	< 0.485 Ma	Too young to date by K-Ar	(1)
LAU 2/1	18°14'20"S 69°17'00"W	At Lauca canal, 2 km S Chucullu	Ignimbrite	K-Ar	glass (3.9)		< 0.346 Ma	Too young to date by K-Ar	(1)
Lauca-Pérez-Ignimbrite									(1)
LLU 91 014	17°58'40"S 69°38'20"WN	Near road, 5 km E Alcerreca-Lauca Fm.	Ignimbrite	Ar-Ar	Sanidine (6.0)	74.7	2.71± 0.25*	Upper coarse of Río Lluta	(5)
LLU 91 017	17°58'40"S 69°38'20"W	Near road, 5 km E Alcerreca-Lauca Fm.	Ignimbrite	Ar-Ar	Sanidine (4.6)	63.5	2.73± 0.11*	Upper coarse of Río Lluta	(5)
ZAP 181	18°22'15"S 69°38'20"W	At international road near Pucará-Lauca Fm.	Ignimbrite	Ar-Ar	Sanidine (6.7)	67.2	2.72± 0.01*	Near Zapahuira	(5)
LAB 16/32	18°30'25"S 69°12'50"W	Lauca Basin (Kött *et al.*, 1995), Lauca Fm.	Ignimbrite	K-Ar	Fspar (2.77)	81.5	2.67± 0.25	Lauca Basin	(1)
LAB 19/30	18°30'15"S 69°15'45"W	Lauca Basin (Kött *et al.*, 1995), Lauca Fm.	Ignimbrite	K-Ar	Fspar (4.24)	78.1	2.32± 0.18	Lauca Basin	(1)
LAB 19/30	18°30'15"S 69°15'45"W	Lauca Basin (Kött *et al.*, 1995), Lauca Fm.	Ignimbrite	K-Ar	Fspar (4.24)	63.2	2.88± 0.13	Lauca Basin	(1)

(table 1 continued)

Sample	Locality	Description/Formation	Rock type	Method	Mineral (K wt. %)	% $^{40}Ar_{rad}$	Age (Ma ± 2 σ)	Comments	Data source
LAB 6/39	18°26'10"S 69°13'05"W	Lauca Basin (Kött *et al.*, 1995), Lauca Fm	Ignimbrite	K-Ar	Fspar (3.99)	88.5	2.01± 0.32	Lauca Basin	(1)
Tignamar Ignimbrite									
TIG-94-106	18°35'40"S 69°28'55"W	In tilted sediments of Jorcane Formation	Ignimbrite	Ar-Ar	Biotite		10.55 ± 0.07	Good plateau age	(7)
Chucal Ignimbrites									
SUR-94-113	18°43'05"S 69°05'55"W	Top ignimbrite of Chucal sequence Chucal Fm.	Ignimbrite	Ar-Ar	Plagioclase		11.49 ± 0.35	Isochrone age	(7)
CHC-94-116	18°44'05"S 69°06'00"W	Basal ignimbrite of Chucal sequence Chucal Fm.	Ignimbrite	Ar-Ar	Sanidine		18.79 ± 0.11	Plateau age	(7)
Oxaya/Condoriri-Ignimbrites									
LAU 91 023	18°34'30"S 69°14'00"W	West. Cord., W margin Lauca Basin, Oxaya Fm.	Top ignimbrite	Ar-Ar	Sanidine (6.0)	92.8	19.72± 0.90*	Below Lauca basin sediments	(5)
ZAP 182	18°22'15"S 69°38'20"W	At international road near Pucara Oxaya Fm.	Top ignimbrite	Ar-Ar	Sanidine (6.4)	94.3	19.38± 0.20*	Top Oxaya ignimbrite near Cordon Quevilque	(5)
BEL-94-159	18°23'40"S 69°29'02"W	Quebrada Pachama at 5100 m Oxaya Fm.	Ignimbrite vitrophyre	Ar-Ar	Biotite	95.89	19.94 ± 0.12	Isochrone age, slightly disturbed spectrum	(7)
BEL-94-198	18°27'20"S 69°31'55"W	5 km N of Belén Oxaya Fm.	Middle ignimbrite	Ar-Ar	Sanidine	99.99	19.72 ± 0.11	Plateau age, discord. Ignimbr. on Lupica Fm.	(6)
LUP-94-105	18°29'05"S 69°31'08"W	Tilted ignimbrite near Lupica Oxaya Fm.	Ignimbrite	Ar-Ar	Biotite		19.44 ± 0.05	Isochrone age	(7)
LUP-94-105	18°29'05"S 69°31'08"W	Tilted ignimbrite near Lupica Oxaya Fm.	Ignimbrite	Ar-Ar	Fspar		18.6 ± 0.7	Total gas age	(7)
POC94-135	18°27'40"S 70°04'25"W	Lowermost Oxaya Ignimbrite Oxaya Fm.	Lower ignimbrite	Ar-Ar	Biotite		21.83 ± 0.11	Plateau age, Lluta valley at Poconchile	(7)
LLU-102	18°22'00"S 69°55'35"W	Lowermost Oxaya Ignimbrite Oxaya Fm.	Lower ignimbrite	Ar-Ar	Sanidine	98.9	22.72 ± 0.15	Plateau age, Lluta Valley at Molinos	(6)
Morro Pillows from Coastal Cordillera									
APT-011	18°28'45"S 70°S19'20"	Morro, Arica	Andesite pillow	K-Ar	Glass	41.3	133.1± 4.0	Fresh glass collected after earthquake collapse	(3)

$K/^{40}K$ = 0.0001167 (Steiger and Jäger, 1977).
Decay constants: ^{40}K = 5.543* 10-10/years, ^{37}Ar = 0.0197477 /days, ^{39}Ar = 0.72* 10-5/days.
* = Ar-Ar plateau age.

Data sources

(1) Horn *et al.* (1992), NERC (U.K.).
(2) Heumann *et al.* (in prep.) (Frije Universiteit, Amsterdam).
(3) D. Turner, Fairbanks (U.S.A.).
(4) Wörner *et al.* (1988), D. Turner, Fairbanks (U.S.A.).
(5) Walfort *et al.* (1995) (FU-Berlin).
(6) Lezaun/Henjes-Kunst (BGR).
(7) Henjes-Kunst (BGR).
(8) Singer (Geneva, Unpublished).

Kött (1994), Walfort (1995), Eutsterhues (1994), Lezaun, 1997). These theses are available from SERNAGEOMIN in Santiago. Analytical details are given in Walfort (1995), and Hammerschmidt *et al.* (1992). The majority of the Ar-Ar ages reported here were determined in the laboratory of the German Geological Survey (BGR) in Hannover. Therefore, the procedure of analysis in this particular laboratory is briefly outlined here. Details can be found in Faryad and Henjes-Kunst (1997).

MINERAL SEPARATION

Rocks were selected by checking for datable amphiboles, biotite, plagioclase or, preferentially, sanidine in thin-sections and hand-specimen. The material of the selected rocks was crushed and sieved to gain the appropriate grain sizes (between 500 and 125 μm for different rocks). This material, representing between 2 and 10 kg, was pre-enriched on a Wilfley-table. Mineral separation was done in a processing sequence consisting of gravity precipitation in bromoform and di-iodine-methane, separation in a magnetic-separator and finally handpicking.

ANALYTICAL PROCEDURE FOR $^{40}Ar/^{39}Ar$ ANALYSIS

Separated minerals were placed in a vacuum sealed quartz vial, alternating with the biotite standard HD-B1 (K-Ar age 24.21 Ma) as irradiation monitor to obtain the J-curve (Dalrymple and Duffield 1988), irradiation of the samples was done in the FRG-2 GKSS Geesthacht reactor.

$^{40}Ar/^{39}Ar$ analysis were carried out at the BGR, Hannover with the laser probe consisting of a Fisons VG 3600 mass spectrometer fitted with a 12 W Nd:YAG IR-laser system (Baasel Lasertech), a low volume ultra high vacuum inlet line, and a Johnston secondary electron multiplier. The IR laser (= 1064nm) was operated in continuous mode with a beam diameter of 200 μm. Argon gas was released by stepwise heating with de-focussed laser or by total fusion of several minerals. Due to low Ar contents of certain samples it was necessary to fuse several grains at once. Sample gas purification was achieved by letting the gas pass a cold trap (dry ice/ alcohol) and two Zr-Al getter elements (350°C, SAES).

Analyses of amphibole separates were also done in a conventional step-heating apparatus with resistance furnace. Gas cleaning stage and measurement in the mass spectrometer (VG 1200) are comparable to the above-described technique; the only major difference is the argon extraction technique. In a resistance furnace, the sample is degassed in discrete intervals of 30 min duration at successively higher temperatures between 600° and 1550°C.

ANALYTICAL PROCEDURE FOR He-EXPOSURE AGE DATING

Our experimental approach took advantage of the fact that magmatic helium is predominantly located in fluid inclusions in mafic phenocrysts whereas cosmogenic helium resides in the crystal lattice. The two components can be separated by crushing - a process, which liberates the gases from the inclusions, and by subsequent melting to extract the cosmogenic helium from the crystal lattice. Therefore, phenocryst-bearing whole rock samples were separated by crushing, sieving, and hand-picking under microscope. To avoid any contamination from dust or weathering the mineral surfaces were mildly etched. Then helium and neon were extracted from olivine and pyroxene by off-line crushing to liberate trapped (magmatic) volatiles from inclusions. Hilton *et al.* (1993) have demonstrated that crushing times longer than 30 sec can contaminate the magmatic gases with matrix-derived cosmogenic or radiogenic helium; therefore, the authors reduced the crushing time for all samples to a minimum. But when the gas concentration released by crushing was below the detection limit, the authors prolonged their crushing time by up to 1 min, and therefore in some cases the amount of gas released from the matrix dominates the magmatic signal. Before and after crushing samples, blank measurements were carried out to check for low He blank.

Prior to melting, the crushed samples were sieved to diameters <105 μm and exposed to a resistance furnace and heated to 2,050°C for total fusion. The purification of the extracted volatiles followed a procedure described by Hilton *et al.*, 1993.

Ion beam intensities of ^4He and ^3He were extrapolated to the time of gas inlet and the $^3He/^4He$ ratio were normalized to the $^3He/^4He$ ratio of the atmosphere ($Ra=1.4x10^{-6}$) or to a ^3He-enriched secondary standard (14 Ra). Helium concentrations

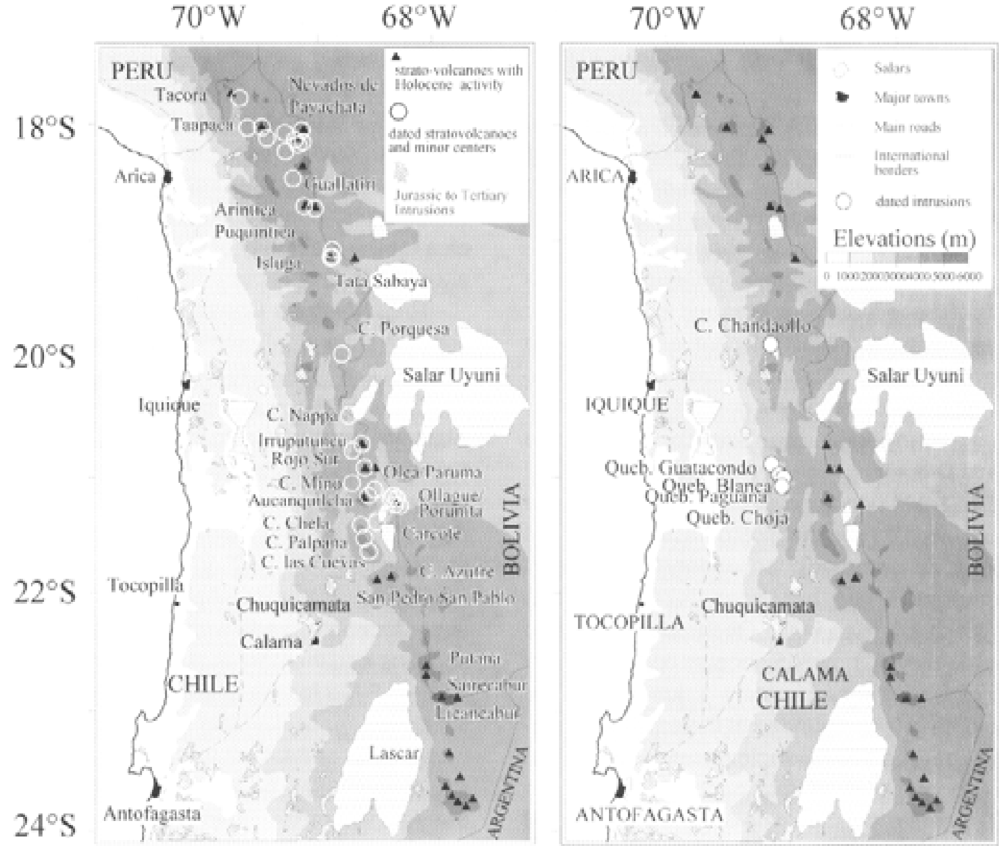


FIG. 3. Location map of dated samples for volcanic and intrusive rocks. Volcanoes dated here are circled in white, locations for intrusive rocks are indicated by white dots. For age data, see table 1).

were determined by peak height comparison with a known volume of either atmospheric gas or a secondary standard gas introduced to the extraction system via a pipette system purified and processed in the same manner as the sample gases.

RESULTS

INTRUSIVE ROCKS

K-Ar dates measured on biotite from Cerro Colorado were reported by Huete *et al.* (1977) for the Cerro Colorado (62.2±2.4 and 65.1±1.8). Heumann *et al.* (in prep.) obtained two Ar-Ar-plateau ages of 67.98 ±0.36 Ma and 68.08 ± 0.36 from an evolved granitoid and a mafic alkali-gabbro, respectively. These ages were obtained in Amsterdam by incremental step heating of biotite separates (20 mg with 200-400 μm grain sizes) according to the analytical procedure of Koppers *et al.* (1988). The age difference between K-Ar and Ar-Ar plateau ages is typically a few Ma and the difference observed here is within that range. The small age difference suggests that emplacement and partial opening due to alteration were closely related in time. Cerro Ceucis was dated by Huete *et al.* (1977) at an age of 59.4±1.2 Ma (whole rock) on a porphyritic granodiorite. The El Abra intrusion yielded ages of 33.5 and 35.4 Ma on hydrothermal biotites and of 36.9±0.7 Ma for the youngest intrusive phase

(Pajonal diorite; Ambrus, 1977). These few examples show typical ages for intrusive rocks of the northern Chilean Precordillera to fall into the range of 30 to 65 Ma

We dated a few more intrusive rocks from this suite. Their location is shown in figure 3 and details on the field relations can be found in thesis form (Heumann, 1993; Anthes, 1993).

In the upper course of Quebrada Blanca (BLA-21), a small multiple intrusion at Cerro Caracoles consists of granodiorites, diorites and mafic gabbroic rafts near the top. A similar multiple quartz-monzonite intrusion at nearby Quebrada Blanca is known to host a high-grade porphyry copper deposit. K-Ar ages have been obtained on a single biotite separate and gave two almost concordant ages of 35.0±1.0 and 36.1±1.0 Ma and one erroneous young age of 17.5±0.5 Ma. Clearly, the biotite fraction giving the younger age is disturbed by secondary chloritization.

Sample CHJ 04 has been taken from the granodioritic intrusion in the Quebrada Choja. The intrusion forms a narrow N-S oriented body of several km length and approximately 1 km wide. The granodiorite is fault-bounded at the east to coarse-grained, red-colored conglomerates and is in intrusive contact with andesitic country rocks in the west. The biotite K-Ar age date obtained is 34.2±1.0 Ma and agrees within uncertainty with the Quebrada Blanca diorite.

A granite, which intruded into a tectonic assemblage of marine Late Jurassic, terrestrial Cretaceous sediments and Oligocene andesites was sampled in the valley of Quebrada Guatacondo (GUA-01). Its K-Ar biotite date of 33.3 ±0.9 Ma is again similar to the age for intrusions in the Quebradas Blanca and Choja.

In the upper course of Quebrada Paguana, a small (3-4 km^2) intrusion shows a northern granodiorite and a southern diorite part (GTC-2). The diorite contains up to 20% well-rounded amphibole-rich xenoliths probably from underlying basement amphibolites as exposed in the Quebrada Choja. The intrusion is emplaced in the transition zone from Eocene andesites to the Cretaceous sedimentary sequences of Quebrada Guatacondo and is probably directly related to the fault that thrusted the Choja basement over these Cretaceous sediments. A biotite separate has been replicated three times, giving two distinct K-Ar dates around 34 Ma (34.3±1.0, 34.8±1.0) and 44 Ma (43.7±1.2, 44.1±1.3). The two older dates may be more reliable, because of a higher proportion of radiogenic Ar (c. 80 %) in these measurements. The younger ages probably result from alteration and chloritization of the sample, and thus loss of Ar and heterogeneous distribution of K. This alteration age corresponds closely to the intrusive activity in that area around 35 Ma (see above) and thus could be the result of contact metamorphic heating. Such results are good examples for the ambiguity of K-Ar dates on biotite from altered intrusive rocks.

The Quebrada Chandacolla (HUA 01) sample comes from a small dioritic intrusion into andesites of upper Cretaceous to lower Tertiary age. Quebrada Chandacolla is located 10 km south of Cerro Alantaya and near Cerro Pichuna. The younger age (28.0±6.0 Ma) is clearly unreliable (only 9.9 % radiogenic Ar and large uncertainty) while the older date (34.3±1.0 Ma) represents a minimum age for the intrusion.

Granitoids from the Azapa and Lluta valleys are unconformably overlain on an erosional surface by Miocene sedimentary rocks. K-Ar whole rock gave 61.2 ±1.5 Ma for the Lluta intrusion (Kohler, 1999) which is identical within uncertainty to the K-Ar biotite date of 64.4 ±2.0 Ma given by Muñoz and Charrier (1996). The K-Ar- age of 92.7± 2.3 Ma for the Azapa granite (Kohler, 1999) represents the oldest magmatic activity of the Precordillera region in the study area.

Agemar *et al.* (1999) showed that Tertiary intrusive rocks of the Chilean Precordillera have variably suffered deuteric alteration as shown by mineral stable isotope composition as well as chloritization of biotite, uralitization of pyroxenes and replacement of magmatic amphiboles by actinolite. Because the stable isotope systematics suggest an alteration by magmatic fluids, such alteration likely occurred shortly after intrusion (Agemar *et al.*, 1999). Considering this alteration and the variable dates for some samples, it is only safe to say that the geological age of these intrusion should be within ± 5 Ma of the measured K-Ar date. Considering the typical shift between K-Ar dates and Ar-Ar plateau ages of 3 Ma (see Cerro Colorado), the authors would argue that all K-Ar dates on intrusives reported here and in the literature are minimum values. The likely intrusion age is probably up to 5 Ma older.

Earlier compilations of age data on volcanic and intrusive rocks in northern Chile have shown a period of volcanic quiescence between about 35 and 25 Ma (*e.g.*, Scheuber, 1994; Kay *et al.*, 1999). Our new data also show this prominent magmatic lull: youngest reliable ages for intrusive rocks are around 35 Ma while renewed volcanic activity dates at around 24 Ma (see below). This volcanic gap is also shown in southern Perú, however, it ended at around 35 Ma, thus at a slightly earlier time (James and Sacks, 1999).

MIOCENE IGNIMBRITES ON THE WESTERN ANDEAN ESCARPMENT NEAR 18°S

Two series of Early to Middle Miocene pyroclastic rocks are observed in the working area and which have now been reasonably well dated. Tilted silicic and andesitic pyroclastic flows and breccias have been sampled along the Lauca River just at the border between Chile and Bolivia. Two samples give consistent plagioclase and biotite Ar-Ar mineral dates with two biotites yielding most reliable, concordant ages of 24.23±0.13 and 24.17±0.13 Ma. Uncertainties of the plagioclase separates are invariably larger. This age correlates with the proposed age for the Putani Formation (Salas *et al.*, 1966; Muñoz *et al.*, 1994). Formations of similar type and age occur in southern Perú (Moquegua Formation, Tosdal *et al.*, 1985) and northern Chile (Riccardi, 1988).

A most reliable stratigraphic marker in northernmost Chile is a series of three larger and on smaller ignimbrite exposed in the Lluta and Azapa valleys. These Oxaya Ignimbrites form the gentle slope declining from the southernmost Peruvian and northernmost Chilean Altiplano and reach a maximum thickness of 1,120 m. Ignimbrites of the same type, age, and composition have been found on the Chilean Altiplano at Lago Chungará and further north (Condoriri Ignimbrite of Salas *et al.*, 1966) underlying the Lauca basin sediments and forming the eastern side of the Western Cordillera (Kött *et al.*, 1995). The three thick ignimbrites display classical examples of compound cooling units superimposed on a series of flow units (Smith, 1963). From base to top, welding changes systematically: the lower meter is unwelded because of cooling from the substratum. Then a basal vitrophyr of 1 to 2 m grades into the strongly welded, brown-colored lower $^2/_3$ of the flow. The upper third is less welded and shows a typical pink color. The top is enriched in pumices and only slightly reworked. Fluvial intercalations are only found in the distal sections, suggesting little time between the three flows. These flows have an individual thickness of up to 300 m. The distinct color change from the strongly welded lower part to the pink upper part has been taken as signifying individual flows. Detailed meter-by-meter sections and comparison with similar thick ignimbrite flows as described in the literature (Smith, 1963) have clearly shown that this is not the case. Consequently, these three major ignimbrite events represent large volumes of rhyodacite, which were erupted in a short period of time. Only the lowermost, smaller ignimbrite is separated from the upper three main units by an interlayer of fluvial sediments only 20 m thick.

Oxaya-Ignimbrites can thus be traced in east-west direction over a distance of 140 km from the Lago Chungará) to the coast. Towards the coast and more distal, the ignimbrites are less welded but still reach 300 m near Arica. Oxaya ignimbrites correlate to the north to southern Perú (~17°S), where they are equivalent to the Huaylillas Formation (Tosdal *et al.*, 1981, 1985). Further south in Chile, we traced Oxaya Ignimbrites beyond the Camarones valley to ~20°S. Thus, the minimum north-south extent is about 300 km. The total area covered and measured thickness suggest total volume of the Oxaya ignimbrites well in excess of 3.000 km^3 (Schröder and Wörner, 1996).

An age of these ignimbrites around 19 Ma has been known for some time (Naranjo and Paskoff, 1985), but a range from 18 to 25 Ma has been reported from northernmost Chile (Muñoz and Charrier, 1996) and southernmost Peru (Tosdal *et al.*, 1981). We present in table 1 Ar-Ar sanidine and biotite plateau ages from several occurrences of Oxaya ignimbrites. The upper members of the four Oxaya ignimbrites consistently give ages of about 19.4 Ma from occurrences on the Altiplano and the Western Andean slope with the most precise and reliable age of 19.38±0.02 Ma (ZAP-182). This date correlates to that of Naranjo and Paskoff (1985), but has a significantly smaller uncertainty. The lowermost ignimbrite is exposed near the bottom of the Lluta valley close to the village of Poconchile and further up the valley near Molinos. It gave a sanidine plateau age of 22.72± 0.15 Ma (LLU-102), consistent with stratigraphy. A biotite Ar-Ar age of the same ignimbrite from a different location gave a date of 21.83±0.11 Ma (POC-94-135), significantly younger probably because of partial opening of the K-Ar system in the biotite. Biotite Ar-Ar ages (and more so biotite K-Ar ages) on ignimbrites apparently are less reliable than Ar-Ar- sanidine plateau ages. This is because biotite in welded ignimbrites very often is found transformed by high-T alteration to oxibiotite. During oxidation Ar may be lost from the crystal lattice.

Oxaya ignimbrites within this age range from 22.7 to 19.4 Ma have been dated here from various occurrences: silicified ignimbrites from the crest of the Western Cordillera near Belén where they unconformably overlie tilted rocks of the Lupica Formation at 4,800 m to 5,200 m elevation gave 19.94±0.12 Ma (BEL 94-159). An identical age was obtained from a sample from the Chilean Altiplano on the eastern side of the Western Cordillera (LAU 91-023: 19.72±0.90). Strongly folded ignimbrites (BEL 94-198) giving Oxaya ages (19.72±0.11 Ma) are found also to be thrusted upon fluvial sediments of the Huaylas Formation (García *et al.*, 1996) near Belén and to overlie rocks of the Lupica Formation between Belén and Lupica (LUP 94-105: 18.6±0.7, 19.44±0.1 Ma).

An age of 18.79±0.11 Ma (CHC 94-116) is obtained from a sanidine Ar-Ar from an ignimbrite at the base of the sedimentary Chucal Formation (Muñoz *et al.*, 1994; Charrier *et al.*, 1994) on the Chilean Altiplano. This age from the base of the unit is consistent with a younger Ar-Ar feldspar age of 11.49±0.35 Ma (SUR 94-113) from an ignimbrite overlying the Chucal sediments on an unconformity. The age of the basal ignimbrite is similar to that of the Oxaya ignimbrites to which it may be correlated. These results place the Chucal Formation between *ca.* 19 and 12 Ma, as already pointed out by Kohler (1999). Muñoz *et al.* (1994) and Charrier *et al.* (1994) initially assigned an age between 20 and 25 Ma to the Chucal Formation. Charrier *et al.* (1999) gave it an age of 11 to 21 Ma, in accordance with our data.

Field aspects of Oxaya ignimbrites can thus be quite variable depending on original thickness and degree of welding, degree of alteration and/or silicification, and deformation. Precise Ar-Ar mineral ages, however, allow unambiguous correlations between these different occurrences.

A tilted ignimbrite (TIG-94-106) occurs within the lower section of fluvial sediments overlying Oxaya Ignimbrites between the antithetically rotated Oxaya Block and the upper Western Andean Escarpment. It gave an Ar-Ar biotite date of 10.55±0.07 Ma. This places the time of sediment accumulation at mainly <10.6 Ma and thus the rotation of the Oxaya Block to be older than 10.6 Ma. This correlates very well with the age of the tilted lava flow at Pampa Toro Muerte dated by García *et al.*, 1996 at 11.4±0.3 Ma) on the Oxaya Block. At face value, these ages would argue for a rotation of the Oxaya block between 10.6 and 11.4±0.3 Ma, which is surprisingly short for such large a movement.

MIOCENE STRATOVOLCANOES ON THE WESTERN ANDEAN ESCARPMENT

Extreme aridity in the Central Andes results in preservation of volcanic structures with only limited erosion in the interior of stratocones. Erosion typically cuts into the core of the structure weakened by hydrothermal alteration. Stratocones of up to 20 Ma in age may then still form circular shield-like or amphitheater-shaped structures; their central depression often erroneously interpreted as caldera collapse. Andesite shield volcanoes of such morphology are observed over some 250 km north-south on the western slope of the Andes between 17 and 20°S.

One of the most prominent and the southernmost of the Miocene stratovolcanoes is represented by the Chusmiza complex at 19°40'S. It is comprised of a flat shield of rather monotonous, poorly phyric andesites representing a total volume of about 400 km³. This volcano has not been dated. From its state of erosion it falls into the Miocene group of stratovolcanoes and represents its largest example.

Cerro Mamuta further north was dated at 8.8±0.5 Ma, 9.1±0.6 Ma by Mortimer *et al.*, 1974 (whole rocks) and 14.5 Ma (K-Ar pyroxene, Seguel *et al.*, 1991). The latter age on pyroxene could be biased by inherited Ar for which clinopyroxene is known to be sensitive. The younger ages for Cerro Mamuta are therefore considered more reliable. Similar large andesite shields also occur further north between cerros Mamuta and Margarita (cerros Achecalane/Colorado) These, however, have not yet been dated. Judging from their morphology, they should fall in the same age range of 10 to 15 Ma.

We dated a series of lavas from this chain of Miocene volcanoes located to the west of the presently active front in the Arica region (Table 1): Cerro Copaquilla (Ar-Ar whole rock age: COP 94-216: 15.07±0.12), Cordón Quevilque (ZAP-01: 20.0±

0.3 Ar-Ar amphibole total degassing age, 20.2 ± 0.6, replicate measurement, ZAP-03: 18.70±0.80 Ar-Ar amphibole plateau age), Cerro Huaylas (HUY 94-165: 20.33±0.38 Ma, Ar-Ar amphibole). Clearly, the 20.0 ± 0.3 and 20.33±0.38 dates are inconsistent with the youngest age for the upper ignimbrite (19.38 ± 0.02) because both stratovolcanoes gave older dates, but overlie the Oxaya ignimbrite. This age inconsistency is about 0.6 Ma and could either result from inherited Ar in the older samples or partial leaking of Ar from the dated sanidines (which is very unlikely considering the very good Ar-A age plateaus for these samples, see Lezaun, 1997). The sanidine data, therefore, are considered more reliable because they also have consistently reproduced the same ages at 19.x Ma for the upper Oxaya ignimbrite. Regarding our ages for the Cordon Quevilque andesite shield, is concluded, that the 20 Ma whole rock dates for Cordon Quevilque and Cerro Huaylas are slightly too old because whole rock geochronology (even for Ar-Ar) may be affected by alteration or leakage of Ar from the system. The younger 18.70±0.80 Ar-Ar amphibole plateau date is considered the best age. All age results and direct field observations of stratigraphic relations, thus clearly indicate that mafic andesite volcanism immediately succeeded Oxaya ignimbrites. This example also re-emphasizes the fact, that for high-resolution stratigraphy (within ±0.3 Ma), whole rock by Ar-Ar as well as K-Ar methods may be insufficient.

For the same group of eroded stratovolcanoes in this area, Garcia *et al.* (1996) reported K-Ar whole rock ages for Cerro Copaquilla of 11.4±1.3, 12.7±0.1, 15.1±0.1 Ma. The latter age is identical to our Ar-Ar date and probably the most reliable age for this center. Our youngest age for a volcano to the West of the Western Cordillera comes from Cerro Marquez/Cerro Margarita giving a reliable amphibole Ar-Ar plateau age of 9.18±0.33 Ma (CMA-10). Wörner *et al.* (1988) dated two andesites from the Cerro Tejene shield andesite volcano on the westernmost Chilean Altiplano near Portezuelo Chapiquiña and reported two concordant K-Ar whole rock dates of 10.5±0.3 (LAU-102) and 10.5±0.4 (LAU-105).

Younger ages were obtained by K-Ar whole rock dating (Wörner *et al.*, 1988) only from the Altiplano region: from Volcán Ajoya (AJA-177: 7.06±0.21) and Choquelimpe (CHO-098: 6.60±0.20 Ma) and from three biotites in tuffs from the Lauca Basin (LAU 91-071, LAU 91-116, LAU 91-117: 6.20±0.24 to 5.38±0.21 Ma). These latter samples were taken from tuff horizons that occur in the deepest parts of the basin's sediment section (Kött *et al.*, 1995). The horizons are well-sorted fine-grained layers of white and grey fallout ash with abundant biotite. Replicate measurements from the tuff samples gave conflicting results with deviations (considering uncertainties) of up to 0.25 Ma. This shows that dates on biotites from tuffs intercalated with sediments have to be interpreted with care.

THE LAUCA-PEREZ IGNIMBRITE

A younger post-uplift ignimbrite on top of the Huaylas-Formation and intercalated into the upper part of the Lauca Formation (Kött *et al.*, 1995) gave Ar-Ar sanidine ages of 2.72±0.01 Ma, 2.73±0.11 and 2.71±0.25 Ma from different localities on the Chilean altiplano near Alcerreca, from within the Lauca Basin and from occurrences near Copaquilla halfway down to the coast (ZAP-181, LAU 91-014, LAU 91-017). These ages are identical and similar to ignimbrites of the 'Pérez-Formation' which covers wide areas in western Bolivia (Marshall *et al.*, 1992). The Lauca-Pérez ignimbrite also correlates to the Sencca ignimbrite of southern Perú. Concordant ages as well as field and geochemical correlations thus clearly indicate that this ignimbrite represents one eruptive and depositional event, although with two flow units. Recent paleomagnetic data (Tapia *et al.*, 2000) also suggest that there exists only one single ignimbrite in northern Chile of this age (2.71 Ma).

Four additional K-Ar mineral dates on the same ignimbrite range from 2.01±0.32 to 2.88±0.13 Ma (LAB 16/32, LAB 19/30, LAB 6/39). This again shows that K-Ar ages on biotite from such young rocks are not reliable and not useful for high-resolution stratigraphic correlation. Biotite oxidation in ignimbrites may result in younger ages due to Ar-loss, whereas contamination by xenocrystic biotite in the pyroclastic rocks could yield mixed older ages.

The total areal extent of the Lauca-Pérez Ignimbrite (Fig. 4) is estimated at about 15.000-20.000 km^2. The maximum distance traveled is ~130 km^2 the bulk magma volume erupted is estimated to be 775 km^3 (Schröder and Wörner, 1996). The Lauca-Pérez ignimbrite flowed radially from its source encountering the flat-lying Altiplano only to the

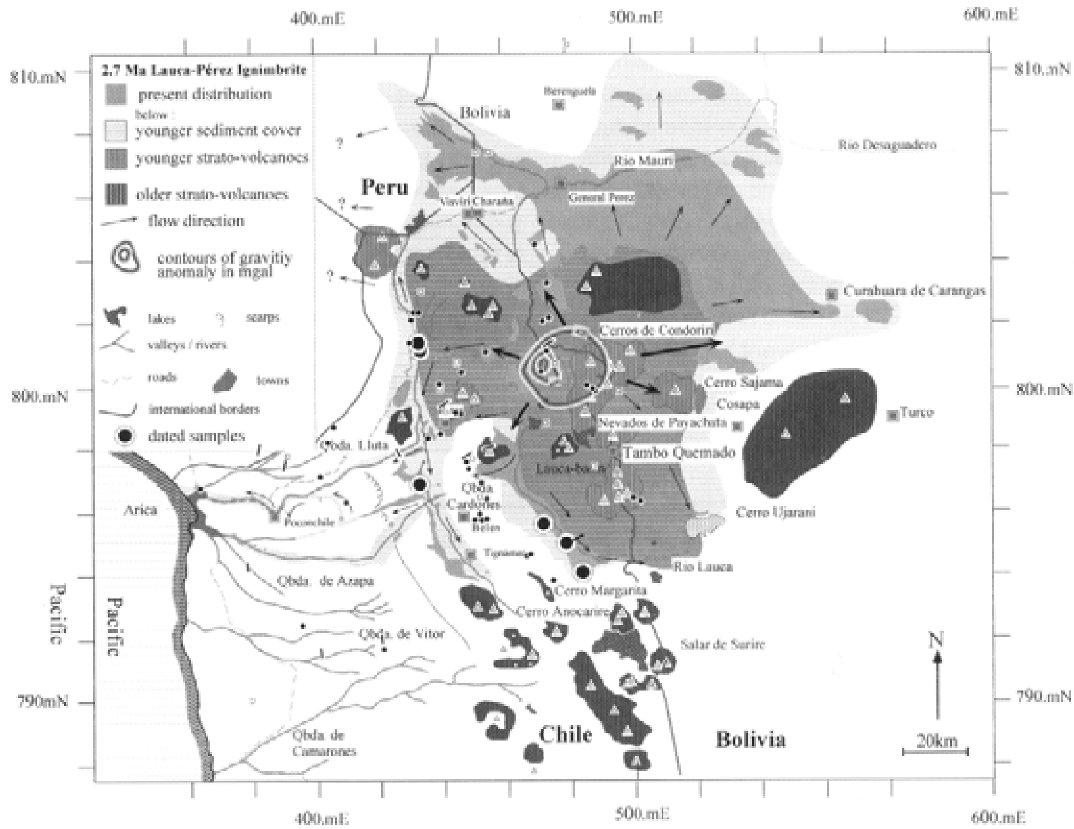


FIG. 4. Map of distribution of the Lauca-Pérez Ignimbrite in western Bolivia and northern Chile, modified after Schröder and Wörner (1996), with location of dated samples indicated, see table 1).

north, west and south. This resulted in the widespread distribution of the Lauca-Pérez-ignimbrite on the Bolivian Altiplano. A major portion, however, flowed to the west and filled depressions between the volcanic front and the Western Cordillera. One large part of the flow continued south over 80 km into the Lauca-Basin (Kött *et al.*, 1995). Another part of the flow started its descent to the coast after passing through narrow valleys and passes cutting through the Western Cordillera. The ignimbrite descended the extreme morphology from 4.500 m to abcut 3000 m a.s.l. onto the Pampa de Oxaya block where the flow again separated into different lobes. One lobe followed the half-graben along the Pampa de Oxaya 70 km to the south reaching Cerro Margarita. Several other flows concentrated into several valleys (Lluta-, Cardones-, Diablo- and Azapa) continuing 90 km to the Pacific Ocean near Arica. The different lobes have slightly but distinctly different pumice compositions suggesting that different lobes represent different times during the course of eruption from a zoned magma chamber.

The Lauca-Pérez ignimbrite suffered only minor, mostly normal faulting indicating that since about at least 2.7 Ma there was no major tectonic activity in the area.

Naranjo and Paskoff (1985) dated the same ignimbrite by the K-Ar method from one of the locations for which we have an Ar-Ar sanidine age. Unfortunately, the two ages do not agree. Our age is 2.72±0.01 Ma while their ages are 4.8±0.31 and 4.4±0.3 Ma. The Lauca-Pérez ignimbrite is characterized in its more distal parts by two flow units comprising a compound cooling unit. Both units are thus identical in age and accordingly our Ar-Ar sanidine ages from the lower and the upper flow unit give concordant sanidine plateau ages (2.73±0.11

Ma and 2.71±0.25).The occurrence of two flow units thus cannot explain this age difference. Furthermore, we correlated both flow units over a large area (Fig. 4) using pumice compositions and microprobe analyses of phenocrysts (Schröder and Wörner, 1996). Therefore,we argue that the Lauca-Pérez Ignimbrite represents one eruptive event that occurred about 2.72 Ma ago. This conclusion is rather important, because the Lauca-Pérez Ignimbrite serves as a reliable morphological and stratigraphic marker in northernmost Chile and western Bolivia.

PLIO-PLEISTOCENE TO RECENT VOLCANOES OF THE VOLCANIC FRONT BETWEEN 17 AND 21°S

Considerable age data exist to the south and within region around the Atacama Basin further south. Here we document additional, mostly K-Ar whole-rock data on Plio-Pleistocene volcanoes along a north-south transect from *ca.* 21 to 17°S (Fig. 3). Geochemical data and brief geological descriptions of volcanoes sampled and dated here are given in Wörner *et al.* (1988, 1992, 1994), maps of the volcanoes with the exact locality of the samples are given in Horn (1992). We cannot attempt to present a full account on all ages and temporal evolution on these volcanoes. Also, K-Ar on such young (whole) rocks has large uncertainties. These have been marked 'too young to date' in table 1. Taken together however, our data provide useful constraints on timing and duration of volcanism and evolution of volcano-magmatic systems along the present active front and provide age data along this north-south transect to the north of region of the Atacama Basin.

In the following, we give brief descriptions of the center's data, from south to north. Two more dates on single lava flows were obtained by He exposure dating from centers further south. These are the La Poruña flow to the west of the San Pedro San Pablo twin volcanoes. Olivine from a juvenile exposed block gave a He-age of 103±1.2 ka, which is surprisingly old for the youthful appearance of that center.

A second exposure age from the front of a lava flow from Lascar volcano in the Quebrada Talabre gave 7,170±1,250 years, also surprisingly old considering its youthful morphology.

VOLCAN LAS CUEVAS

Cerro de las Cuevas is a compound cone and lava complex and represents the youngest center of a north-south trending chain of volcanoes trending north-south from Cerro Palpana in the north to Cerro Cebollar in the south. The volcano consists of a central andesite dome surrounded by extensive and thick clinopyroxene-olivine andesite lava flows. The whole rock dates (CUEV 04) of 3.15±0.15 Ma and 3.36±0.13 Ma are close to concordant. The sample comes from a young spatter cone overlying the northeastern flank of Cerro de las Cuevas. The Las Cuevas volcano, therefore, must be largely but not much older than 3 Ma.

VOLCAN PALPANA

It is a rather monotonous mafic andesite stratovolcano with relatively little erosion on its regularly sloping flanks. Two samples have been dated, a pyroxene andesite lava flow (PAL 1) and scoria (PAL 4) on the southeastern slope of Cerro Palpana, giving ages of 3.65±0.15 and 3.81±0.30 Ma. The uniform shape and monotonous mafic andesite composition of Volcán Palpana suggests a rather rapid evolution with little erosion and times of magmatic differentiation. Therefore the entire volcano is believed to be not much older than its present lava flows at the surface.

CERRO CARCOTE

Cerro Carcote (CAR-01) is a small monogentic cinder cone overlying the Carcote ignimbrite to the southeast of Cerro Chela. A fresh dense bomb of andesite has been dated from the top of the cone at 3.34±0.30 Ma; the replicate measurement of the same sample gave 2.82±0.11 Ma. Both dates are similar, but different outside analytical uncertainty. This again emphasizes potential problems with K-Ar whole rock dating for high-resolution volcanic stratigraphy.

VOLCAN CHELA

This volcano is very similar in shape and composition to Volcán Palpana (and Volcán Miño, see below). Sample CHE 07 has been taken from one of the lava flows at the base south east of Cerro Chela. CHE 8 is a scoria bomb from the top of another lava flow. The Cerro Chela volcán lies on top of the Carcote ignimbrite, which has been dated by Baker and Francis (1978) at 5.4±0.3 Ma. Our ages of 3.75±0.5 Ma and 4.11±0.25 Ma or rocks from Volcán Chela are entirely consistent.

VOLCAN MIÑO

Volcán Miño is identical in shape, structure and lava composition to the cones of Palpana and Chela. Two samples (MIN-02, MIN-07) are from lava flows from the north and northeast flank. Their age of 3.59±0.11 Ma and 3.27±0.40 Ma is also very similar to Palpana, Chela, Carcote, and Las Cuevas all lying on the same north-south lineament.

Apparently, the Miño-Las Cuevas volcanic chain is very similar in age, eruptive style, and composition.

VOLCAN OLLAGUE AND PORUÑITA SPATTER CONE

Volcán Ollague is a composite cone which clearly has an extended evolution as shown by distinct eruptive phases and lava compositions (Wörner *et al.*, 1992, 1994; Feeley *et al.*, 1993). The base is built by an old cone with remnants of old lava flows on the eastern flank. The western flank collapsed and produced the hummocky terrain of a debris avalanche towards the west. After the collapse, the scarp was filled by younger andesitic to dacitic flows. Samples OLA 11 and 13 were taken from these young lavas near the old crater rim and are the youngest dated from Ollague (0.13±0.04 and 0.41±0.08 Ma). The replicate measurement on OLA-13 biotite gave the same age, whereas the plagioclase separate gave an erroneously old date (0.89±0.25 Ma). These data place the most recent activity at Volcan Ollagüe close to the Holocene. Samples from the older Ollagüe structure (OLA 23, -25, -27) were taken from a lava flow in the northern and northwestern part of the volcano and gave ages between 0.68±0.18 and 0.97±0.07 Ma. Samples OLA 10 and OLA 31 are from two isolated dacitic domes in the north of volcán Ollague and were dated here at 0.45±0.10 Ma and 0.34±0.15 Ma. Again, feldspar K-Ar dates are identical but have much larger uncertainties compared to those on biotite separates.

Volcán Poruñita (PORU) to the west of Ollagüe is a monogenetic spatter cone of about 700 meter in diameter. The deposits are phreatomagmatic in character and overlie the Ollagüe debris avalanche. Our Sample PORU-2 (K-Ar- whole rock) gave dates of 0.42±0.20 Ma, 0.65±0.20 Ma, and 0.68±0.20 Ma. These ages are all identical within uncertainty and entirely consistent with the Francis and Rundle (1976) age of 0.8 Ma for the underlying debris avalanche event.

VOLCAN AUCANQUILCHA

Aucanquilcha, Olca, and Paroma form a west-east volcanic chain just to the north of the older north-south Miño-Las Cuevas chain. Aucanquilcha is a large and complex andesite-dacite flow and dome complex. We sampled the youngest flows of Aucanquilcha on the northeast side and southwest slope (AUC 01, AUC 07) giving K-Ar ages of 0.78±0.12 Ma (feldspar), 0.52±0.12 Ma and 0.40±0.20 Ma (whole rock and replicate measurement). These ages are surprisingly old considering that Aucanquilcha is presently in fumarolic activity and the dated samples overlie an older structure for which Baker and Francis (1978) found ages of 3 to 8 Ma. This argues for an extended lifetime of magma production, differentiation and eruption over probably several Ma.

VOLCAN OLCA

Volcán Olca comprises a west-east elongated complex of andesitic and dacitic flows with a chain of small craters and active fumaroles. Two samples (OLC-01, OLC-05) were taken from a blocky lava flow of amphibole andesite at the southwestern base of the chain and from a young flow near the western summit. Both dates have large uncertainties and a very small proportion of radiogenic Ar and are thus not reliable (Table 1). However, a Pleistocene age is indicated. The eastern part and Volcán Paroma does not have flows with such relatively youthful morphologies, suggesting an older age.

Taken together, our limited ages and morphological preservation of the Aucanquilcha-Olca-Paroma west-east chain does not indicate a systematic shift in volcanic activity, but rather argues for a chain of long-lived volcanism quite contrary to the Miño-Chela-Palpana-Las Cuevas north-south chain.

ROJO SUR

Volcán El Rojo Sur (ELR-S) is a small isolated scoria cone just to the north of Volcán Pabellon del Inca with an associated mafic andesite lava flow. This cone is only about 100 m high, several hundred m wide and characterized by a smoothed cone shape and red oxidized scoria. Such small monogenetic cones are rare within the volcanic front; other examples are Cerro Carcote and El Rojo Norte in the Lauca Basin. The whole rock sample is a fresh mafic andesite from a dense bomb and gave two dates of 2.93±0.13 and 3.23±0.12 Ma (replicate measurements). These dates, although discordant, are rather close and suggest an eruption close to 3 Ma. Baker and Francis (1978) also reported a 3.4±0.4 Ma whole rock K-Ar age from the same locality. We note in passing that this age is identical to the Cerro Carcote and El Rojo Norte ages and only somewhat younger than the Miño-Chela-Palpana-Las Quevas chain of mafic andesites.

VOLCAN IRRUPUTUNCU

Irruputuncu is a relatively small cone comprised of thick viscous flows and associated block-and-ash flows. Its present crater is in fumarolic state. Two silicic andesites (IRU-10, IRU-11) were dated. IRU-11 is from a rather pristine younger flow overlying IRU-10. Only the older flow is covered by pliniain tephra, which could possibly correlate to a subplinianic rhyolitic ignimbrite some kilometer southwest of Irruputuncu (IRU-15). All measurements on biotite separates have the problem of only a small proportion of radiogenic Ar. Therefore, the dates have large uncertainty and are not reliable. The poor dates for the different eruptions, at least, suggest an activity of Volcan Irrupuntunco in the latest Quaternary, consistent with pristine lava flow morphologies.

PICA GAP

Between Volcán Irruputuncu at 20°43'S and Volcan Isluga at 19°09'S there are no known and dated volcanoes with associated Upper Pleistocene activity ('Pica Gap', Wörner *et al.*, 1992, 1994) except for the Cerro Porquesa dome and a small volume Porquesa ignimbrite (see below). All other volcanoes are deeply dissected by glacial valleys. These older volcanoes are practically identical in erosion morphology (and thus age) to Miocene volcanoes at 18°S dated at 6 to 10 Ma see above). The only other ages known from this region are those of Baker and Francis (1978) who document whole rock and biotite K-Ar ages ranging from 3.3±0.2 to 11.7±2.7 Ma.

Cerro Nappa is one of the few morphologically well-preserved stratovolcanoes in the 'Pica Gap'. Sample NAP-01 has been taken from a debris avalanche deposit and dated at 1.38±0.50 Ma consistent with its good morphological preservation. Other volcanic structures in the Pica gap of similar morphology (smooth cone shapes) are Cerro Cariquima (19°32'S/68°40'W) and Cerro Tatjachura (19°30'S/ 69°06'W). They have not been dated but may also have a Lower Pliocene age.

The significance of the Pica gap is enigmatic. It is located in the northeast extension of the Iquique rise on the Nazca Plate. If the subduction of this minor feature on the downgoing slab could cause cessation of volcanism of such a wide area is unclear (Isacks, 1992). There are a number of other particular features of Andean geology, which also have a spatial association with the Pica gap:

- Wörner *et al.* (1992) postulated a major crustal domain boundary in this area, based on the composition of Pb isotopes , which they interpreted to reflect the nature of the crustal basement.
- Gephardt (1994) found a first order geometrical symmetry plane for the Andean orogen and underlying slab which traces through the Pica gap.
- The Arica Bend, often cited as marking the deflection of the Andean orogen is in fact only a coastal feature, rather related to subduction erosion of the forearc than marking the culmination of the orocline. The bend is in fact further south, at the Pica latitude (Gephardt, 1994, see James and Sacks, 1999 for a discussion and more references).
- The Altiplano region just behind the Pica gap is characterized by the large (and long-lived?) depression of the Salar de Uyuni.

While these are interesting observation, they may be coincidental and a full discussion is beyond the scope of this paper.

PORQUESA DOME AND IGNIMBRITE

The Porquesa mega-dome, the only Quaternary center within the Pica gap, rises some 800 m over its base and comprises several pulses of rhyodacite eruptions. A small-volume sub-plinian ignimbrite of identical composition (POR 03) is observed in the valley towards the south and has been dated here at 0.15 +0.20/-0.15 Ma (biotite) and 0.29 +0.45/-0.29 Ma (feldspar). Baker and Francis (1976) gave two K-Ar biotite dates (0.73±0.16 and 0.63 +0.92/-0.63 Ma) for this deposit. All ages are rather imprecise and not very reliable. The authors consider their younger ages more reasonable because they are more consistent with the observation that the Porquesa ignimbrite fills young valleys and therefore should be Upper Pleistocene in age.

VOLCAN ISLUGA

Volcán Isluga is a large elongated volcanic complex, which presently shows fumarolic activity. Phreatomagmatic eruptions rather recently covered the area around the active crater by surge deposits. Holocene flows cover the northernmost ridge of the volcanic complex. We dated an older glaciated dacite flow (IS3-045) from the northwest side at 0.096±0.006 Ma. Lavas from Isluga overlie rocks from a dissected volcano (Quimsachatas) to the north and northeast. An andesite flow (IQM-003) from this older structure gave an age of 0.566±0.017 Ma, consistent with field observation.

ARINTIQUA-PUQUINTICA

Arintiqua-Puquintiqua are two eroded volcanic structures north and northeast of Salar Surire which gave whole rock ages of 0.637±0.019 and 0.486±0.015 Ma (SUP-026, SUP-006), consistent with morphology. DeSilva and Francis (1991) proposed that Arintiqua has been active in Holocene times. From the type and elevation of this volcano, we argue that the summit may not have been glaciated during the last glaciation. Consequently, the pristine flow morphology near the summit may not necessarily be indicative of Holocene activity.

EL ROJO NORTE

This scoria cone is almost identical to El Rojo Sur: it is a reddish scoria cone about 150 m high with an associated lava flow of mafic andesite composition and gave a date of around 3 Ma. Two of three whole rock K-Ar measurements are identical within uncertainty (ELRN: 3.05±0.22 Ma and 3.35±0.16 Ma) while a third replicate measurement gave a conflicting date of 2.34±0.16 Ma. There is no reason (*e.g.,* low proportion of radiogenic Ar) to discard either age determination. The El Rojo Norte scoria cone is overlain by the well-dated 2.72 Ma old Lauca-Pérez ignimbrite (Ar-Ar sanidine plateau ages, see above) suggesting that the older two K-Ar ages on the scoria cone are more likely to be correct and the younger age must be erroneous for reasons unknown. This again shows that andesite whole rock K-Ar ages need to be interpreted with great care.

VOLCAN TAAPACA

VolcánTaapacá (Nevados de Putre) is a compound dacite dome complex comprised of three extrusive stages and associated block-and-ash flows. Two ages have been obtained. One dacititc block-and-ash flow (TAP-001) filling a Quaternary valley was dated by whole rock K-Ar at 0.086±0.04 and 0.078±0.04 Ma (replicate measurement). A viscous flow from the youngest eruptive phase gave a sanidine (TAP 97-MC) Ar-Ar plateau age of 0.038±0.0026 Ma (Singer, unpublished data). A distal block-and-ash flow near Alcerreca was dated by Ar-Ar on feldspar and gave a total fusion age at 1.27±0.04 Ma. Taapacá volcano, therefore, has an extended lifetime and has been active up to the latest Quaternary. It thus represents a significant volcanic hazard to the town of Putre located at the base of the volcano and built on Taapacá volcanic avalanche deposits.

NEVADOS DE PAYACHATA (VOLCAN POMERAPE AND VOLCAN PARINACOTA)

This complex of twin stratovolcaones ('payachata' in Aymara refers to 'twin peaks') and surrounding smaller centers has been studied in some detail by Wörner *et al.* (1988) and Davidson *et al.* (1990). Table 1 lists the K-Ar whole rock ages of Wörner *et al.* (1988) and provides locations as coordinates. For a detailed account of the volcanic history, refer to Wörner *et al.* (1988).

Pomerape is the older, glaciated center. Only one sample from Pomerape (POM-116) has been dated by K-Ar, giving an age of 0.106±0.007 Ma for two replicate analyses. Two concordant ages on a small mafic satellite center (POM-149, POM-152, 0.219 ±0.024 Ma and 0.192 ±0.012 Ma) on the lower northern flank are around 0.2 Ma. Pomerape is, therefore, a stratovolcano of Upper Pleistocene age but clearly lacks Holocene activity.

There are several phases of evolution for the younger Parinacota volcano:

- The base is formed by the andesites forming the shore of Lago Chungará and its overlying rhyodacite dome sequence (264 ka to 110 ka Table 1). These ages correlate with those of separate scattered centers in the area to the northwest and southwest, the Caquena domes and Chucuyo flow (CAQ-007= 275±45 ka and CHU-171 = 285 ± 63 ka, respectively).
- The Old Parinacota cone, comprised mostly of andesites and dacites, was built on these older lavas. The younger rocks proved difficult to date precisely by K-Ar (*ca.* 50 ±11 ka to 12 ±15 ka, Table 1).
- A giant Mount Saint Helens-type sector collapse destroyed this old cone at around 18.000 years. This age is obtained by He-exposure age dating of fresh surfaces on blocks left exposed after the collapse (Table 2: PAR-082=18150±650 a).
- The present Parinacota cone was built since that time by the 'Healing Flows', the youngest of which has a He-exposure age of only 1660±350 years.
- More young lava flows erupted on the southern flank from a north-south directed fissure. Three lava flows have been distinguished, the 'Upper' and 'Lower' Ajata flow from the lower center and the 'High' Ajata flow from a center higher up on the same fissure. Their He-exposure ages are consistent with the stratigraphic relations. The Lower Ajata (slightly more weathered) gave an older age of around 6,000 years (5985±640 a and 6560±1220 a on clinopyroxene and hornblende, Table 2). The more pristine and overlying flows (Upper Ajata and High Ajata) gave younger ages, between 1.400 and 3,000 years (Table 2).

Parinacota volcano has been rebuilt after its catastrophic collapse in only 18,000 years to its present height in a surprisingly short period of time, which contrasts strongly with the long evolution (*ca.* 200.000 a) of the old Parinacota cone. This proves two points: **a-** the rate and style of eruption as well as the composition of the lavas changed significantly after the cataclysmic event (see also Wörner *et al.*, 1988): **b-** the higher rates of eruptions since 18.000 years and explosive activity up until a few thousands years ago suggest that Parinacota should be considered a 'dormant' volcano that is likely to erupt again in the near geological future.

VOLCAN TACORA

Tacora volcano is the northernmost volcano in Chile and our north-south transect. We dated only one sample (TAC-004) which is a boulder from a small river draining the southwest side of the volcano. Its age of 0.489±0.015 Ma is, therefore, difficult to interpret. Some workers argue (deSilva and Francis, 1991) that Tacora has had Holocene activity.

DISCUSSION

GEOCHRONOLOGICAL IMPLICATIONS ON THE STRATIGRAPHY AND UPLIFT OF THE WESTERN ANDEAN ESCARPMENT (WARP) AT 18°S

The region around the Arica bend at 18°S superbly documents the inter-relation of uplift, erosional and climatic response through the last 30 Ma. Because there has been some confusion about stratigraphy in that area (see García *et al.*, 1996 *versus* Salas *et al.*, 1966 and Seyfried *et al.*, 1999), the evaluation of the new Ar-Ar ages presented here warrants a more detailed discussion of the stratigraphy. The locations of the dated samples are given in figures 3, 5; stratigraphic relations are compiled in figure 6.

OXAYA-AZAPA-LUPICA-FORMATION AND YOUNGER SEDIMENTARY STRATA

The lower Western Andean Escarpment (WARP) has been the depocentre of predominantly coarse-grained alluvial deposits (Azapa Formation, Salas *et al.*, 1966. This clastic wedge has a volume of about 10 km^3 per km north-south distance and quickly accumulated before 22 Ma, the oldest of the Oxaya ignimbrites overlying it. Such deposits mark a significant episode of uplift and erosion, which ended with the deposition of the Oxaya ignimbrite sheets (23 to 19 Ma). These form today the gently sloping ramp from the upper WARP to the Coastal

Cordillera and are dissected by a fossil Miocene drainage system, several deep active valleys and the giant tilted Oxaya Block. Within a narrow zone of minor reverse faulting (the 'Western Andean Thrust Belt' of Muñoz and Charrier, 1996) they are strongly folded and faulted. Further to the east they are again flat-lying and form some of the highest peaks of the Western Cordillera at altitudes between 4,300 and 5,200 m.

We argue (with Salas *et al.*, 1966; Kohler, 1999) that Oxaya ignimbrites and Azapa conglomerates are distinct from, and younger than, the volcaniclastic and sedimentary rocks of the Lupica Formation, based on the following arguments:

- Oxaya ignimbrites have been correlated here by dating, field mapping and geochemical comparison. There is an erosional unconformity between Oxaya ignimbrites and the rocks of the Lupica Formation, which can be found exposed at high altitudes on the Western Cordillera.
- Composition and volcanological aspect of Oxaya ignimbrites and volcaniclastic rocks of the Lupica Formation are different: Lupica rocks are always strongly altered, folded and mainly of intermediate andesitic composition. Plagioclase - phyric andesite flows and breccias are abundant as are intercalated fine-grained lacustrine and fluvial deposits. By contrast, the Oxaya ignimbrites are very monotonous rhyodacitic in composition, andesites are found only overlying the ignimbrites and do so only locally, they are always dense, mostly aphyric and fresh.
- Lupica-type rocks have been identified as abundant detrital clasts in rocks of the Azapa conglomerates below the Oxaya ignimbrites. Therefore, the Lupica andesites and rhyolites could not be of the same age as the Azapa conglomerates.
- Clasts from the Belén metamorphic basement are also found in the Azapa conglomerate. On the other hand, rocks of the Lupica Formation overlie and cover these basement rocks, which have been exposed only later by tectonic movements and erosion. If Lupica rocks cover the basement, then these rocks cannot have the same age as the Azapa conglomerate which carries metamorphic clasts: The cover rocks should be older than the rocks that show the basement clasts after later uplift and erosion of both, Lupica and Belén basement rocks,
- Oxaya ignimbrites give consistent Ar-Ar sanidine plateau ages, which are always older than 19 Ma. Oxaya ignimbrites are found as strongly folded erosional remnants in the Belén-Tignamar area overlying unconformably older Lupica rocks in a tectonically complicated fashion. K-Ar dates on these occurrences of around 18 Ma (García *et al.*, 1996) are entirely consistent with our Oxaya ages.

In our interpretation, Oxaya ignimbrites and the underlying sediments (Azapa formation of Salas *et al.*, 1966) therefore are younger than the Lupica Formation (Fig. 6).

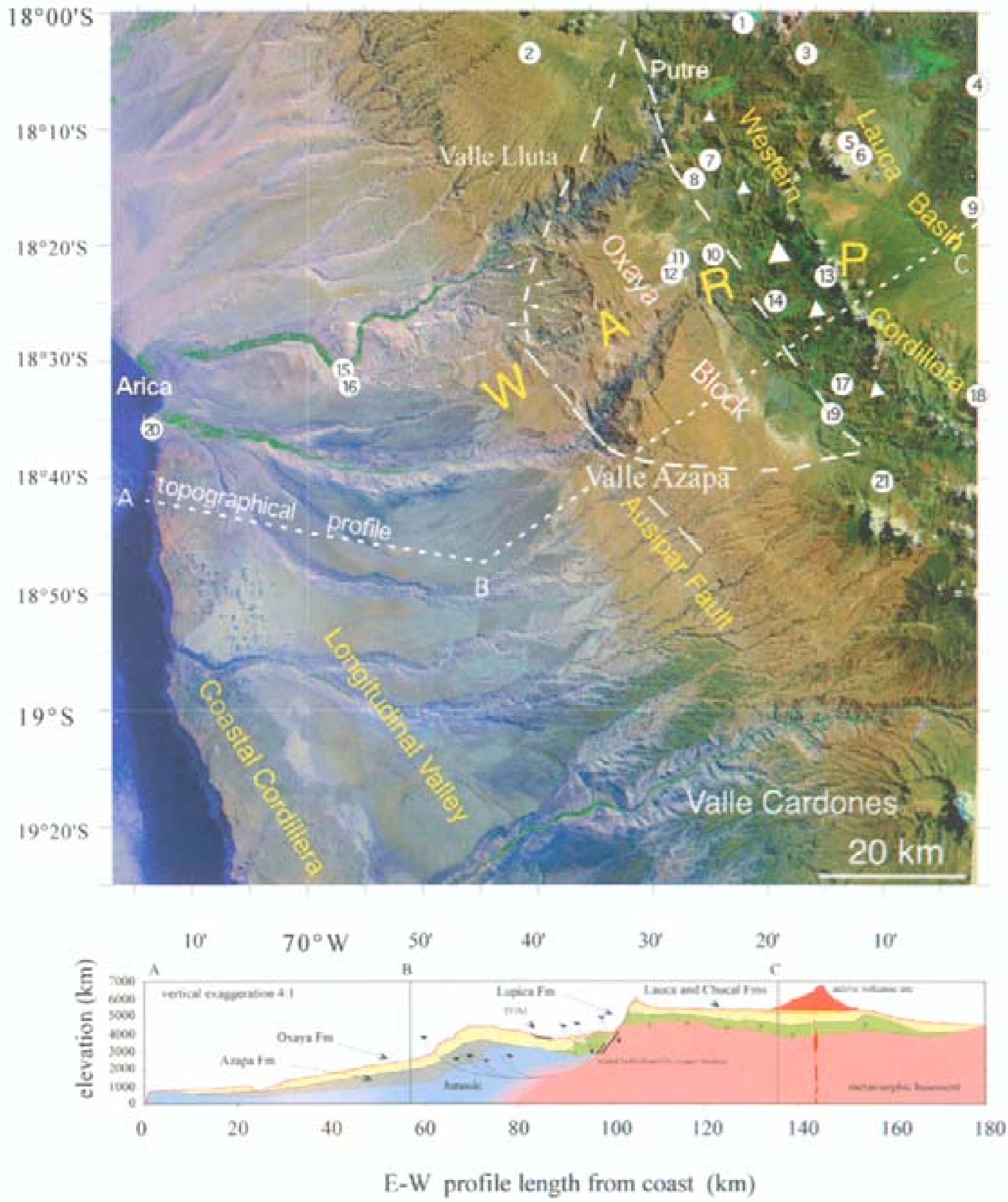
The Huaylas and Jorcane Formations (García *et al.*, 1996; Muñoz and Charrier, 1996) together are bracketed between 11.5 and 2.7 Ma, the age of andesites at Cerro Copaquilla underlying and the Lauca-Pérez Ignimbrite overlying these Formations. The ages derived from the intercalated ignimbrite at Tignamar (10.6 Ma) and the paleontological evidence (8-9 Ma, Salinas *et al.*, 1991) is consistent with this age range. The age of the Diablo Formation has not been determined directly by dating their rocks. However, it must be older than the rotation of the Oxaya Block (12 Ma) and of similar age as the andesite volcanoes (Zapahuira Formation, 11-19 Ma), from which the clasts were derived (García *et al.*, 1999; Kohler, 1999).

Sedimentary units of ages and characteristics similar to the Huaylas, Jorcane and Diablo Formations are also known from southern Perú (*e.g.*, Chuntacala Formation, Tosdal *et al.*, 1985). It would be a worthwhile exercise to directly correlate these Formations across the political border.

MIOCENE MAGMATISM AND UPLIFT AT 18°S

Oxaya ignimbrite volcanism (19.4 to 22.72 Ma) was succeeded by large andesitic volcanoes giving Ar-Ar ages of 20.33±0.38, 20.02± 0.3, 18.70±0.80, 15.07±0.12, and 9.18±0.33. These andesite shield volcanoes occur along a north-south oriented chain from 17 to 20°, approximately covering the north-south extension of the Oxaya Ignimbrites.

Continued uplift resulted in regional westward tilting and significant steepening of the Oxaya ramp producing the monoclinal structure known over several hundred km on the Western Andean margin (Allmendinger *et al.*, 1997; Lamb *et al.*, 1997). At 18°S, part of the steepened slope collapsed forming the Oxaya Block. The age of this block rotation must be older than the oldest sedimentary rocks overlying it (*i.e.*, older than the 10.6 Ma Tignamar ignimbrite, Table 1). Its upper age limit is given by a lava flow,



1	TAP-97-MC	8	ZAP-03	15	POC-94-135
2	HUY-94-165	9	CHO-098	16	LLU-102
3	TAP-001	10	COP-94-216	17	LUP-94-105
4	AJA-177	11	ZAP-182	18	Lau 91-023
5	LAU-105	12	ZAP-	19	TIG-94-106
6	LAU-102	13	BEL-94-159	20	APT-011
7	ZAP-01	14	BEL-94 -198	21	CMA-10

FIG. 5. Satellite image of the region Arica-Chungará at 18°S in northern Chile with location of dated samples (satellite image base courtesy of Uhlig, 1999).

TABLE 2. EXPOSURE AGES OF LAVAS FROM THE PARINACOTA VOLCANO.

^4He [nccSTP/g]	^3He [pccSTP/g] crushing	R/Ra	^4He [ncc STP/g]	^3He [pccSTP/g] melting	R/Ra	$^3He_{cos}$ [10^6atoms/g]	$^3He_{cos}/^3He_{tot}$	Production rate atoms/g/a	Exposure age [a]
Parinacota									
PAR-082, 18°11'06"S; 69°15'00"W, depth: 0.0 - 4.7 cm, : 2.55 ± 0.01 g/cm³, altitude: 4485 ± 5 m columnar jointed block from debris avalanche (stage III of Wörner *et al.*, 1988), hornblende, 300-500 µm									
n.d.	n.d.	-	0.18 ± 0.16	0.843 ± 0.031	3350	22.6 ± 0.8	0.998	1245	18150 ± 650
PAR-034, 18°10'15"S-69°11'22"W, depth: 0.0 - 5.6 cm, : 2.45 ± 0.02 g/cm³, altitude: 4555 ± 5 m Healing flow of Parinacota new cone (stage IV of Wörner *et al.*, 1988), clinopyroxene, 125 - 250 µm									
0.60 ± 0.34	0.0021 ± 0.0017	2.5 ± 2.0	1.15 ± 0.77	0.083 ± 0.016	52 ± 36	2.12 ± 0.45	0.951	1279	1660 ± 350
PAR-083, 18°11'43"S;-69°11'2"W, depth: 0.0 - 4.9 cm, : 2.591 ± 0.005 g/cm³, altitude: 4535 ± 5 m High Ajata flow (stage V of Wörner *et al.*, 1988), orthopyroxene, 125 - 250 µm									
5.19 ± 0.18	0.0083 ± 0.0066	1.14 ± 0.91	7.95 ± 0.82	0.078 ± 0.013	7.03 ± 1.41	1.76 ± 0.45	0.838	1271	1385 ± 350
High Ajata flow (stage V of Wörner *et al.*, 1988), clinopyroxene, 125 - 250 µm									
0.77 ± 0.15	0.0015 ± 0.0010	1.39 ± 1.30	0.06 ± 0.06	0.102 ± 0.013	1200	2.75± 0.35	0.999		2160 ± 280
High Ajata flow (stage V of Wörner *et al.* 1988), magnetite concentrate									
1.21 ± 0.14	0.0057 ± 0.0050	3.35 ± 3.00	0.94 ± 0.48	0.0743 ± 0.0079	56.7 ± 30.0	1.88±0.24	0.941	927.7	2030 ± 190
PAR-220, 18°13'10"S-69°09'31"W, depth: 0.0 - 4.7 cm,: 2.62 ± 0.02 g/cm³, altitude: 4690 ± 5 m Low Ajata flow (stage V of Wörner *et al.*, 1988), clinopyroxene									
4.98 ± 0.13	0.021 ± 0.034	3.18 ± 0.50	14.38 ± 0.43	0.368±0.031	18.3 ± 1.6	8.16 ± 0.86	0.826	1364	5985 ± 640
Low Ajata flow (stage V of Wörner *et al.*, 1988), hornblende									
n.d.	n.d.	-	n.d.	0.333 ± 0.062	-	8.9 ± 1.6	0.999	1364	6560 ± 1220
PAR-011, 18°12'34"S;-69°0'23"W; depth: 0.0 - 4.7 cm, : 1.81 ± 0.04 g/cm³, altitude: 4640 ± 5 m Upper Ajata flow (stage V of Wörner *et al.*, 1988), olivine, 250 - 500 µm									
10.84 ± 0.12	0.0979 ± 0.0044	6.45 ± 0.30	2.19 ± 0.45	0.0251± 0.0067	8.20 ± 0.14	>0.143	>0.213	1350	>106
Upper Ajata flow (stage V of Wörner *et al.*, 1988), clinopyroxene, 250 - 500 µm									
0.59 ± 0.16	0.0050 ± 0.0034	6.0 ± 4.4	0.33 ± 0.30	0.156 ± 0.023	325	4.12 ± 0.61	0.982	1350	3050 ± 450

(table 2 continued)

^4He [nccSTP/g]	^3He [pccSTP/g] crushing	R/Ra	^4He [ncc STP/g]	^3He [pccSTP/g] melting	R/Ra	$^3He_{cos}$ [10^6atoms/g]	$^3He_{cos}/^3He_{tot}$	Production rate atoms/g/a	Exposure age [a]
La Poruña									
POR-02, 21°53'5''S; 69°3'00''W, satellite cone of San Pedro San Pablo volcanoes N of Calama, hand specimen, depth: 0.0 - 7.2 cm,: 2.46 ± 0.04 g/cm³, altitude: 3485 ± 5 m, olivine, 300 - 500 µm									
1.18 ± 0.11	0.0136 ± 0.0034	8.3 ± 2.2	0.92 ± 0.34	3.112 ± 0.033	2430 ± 800	83.32 ± 0.89	0.997	807.4	103000 ± 1100
Lascar									
La-03, 23°17'21''S; 67°45'00''W depth: 0.0 - 3.12 cm,: 2.49 ± 0.06 g/cm³, altitude: 4020 ± 5 m, flow at Tumbre orthopyroxene, 300 - 500 µm									
0.66 ± 0.13	0.0072 ± 0.0035	7.87 ± 4.16	3.14 ± 0.93	0.312 ± 0.054	71 ± 24	8.2 ± 1.4	0.974	1139	7170 ± 1250

$^3He_{COS}$ = [(R/Ra)m – (R/Ra)cr) Ra [^4He]m
Cos =cosmogenic
n = 10^{-9}
p = 10^{-12}

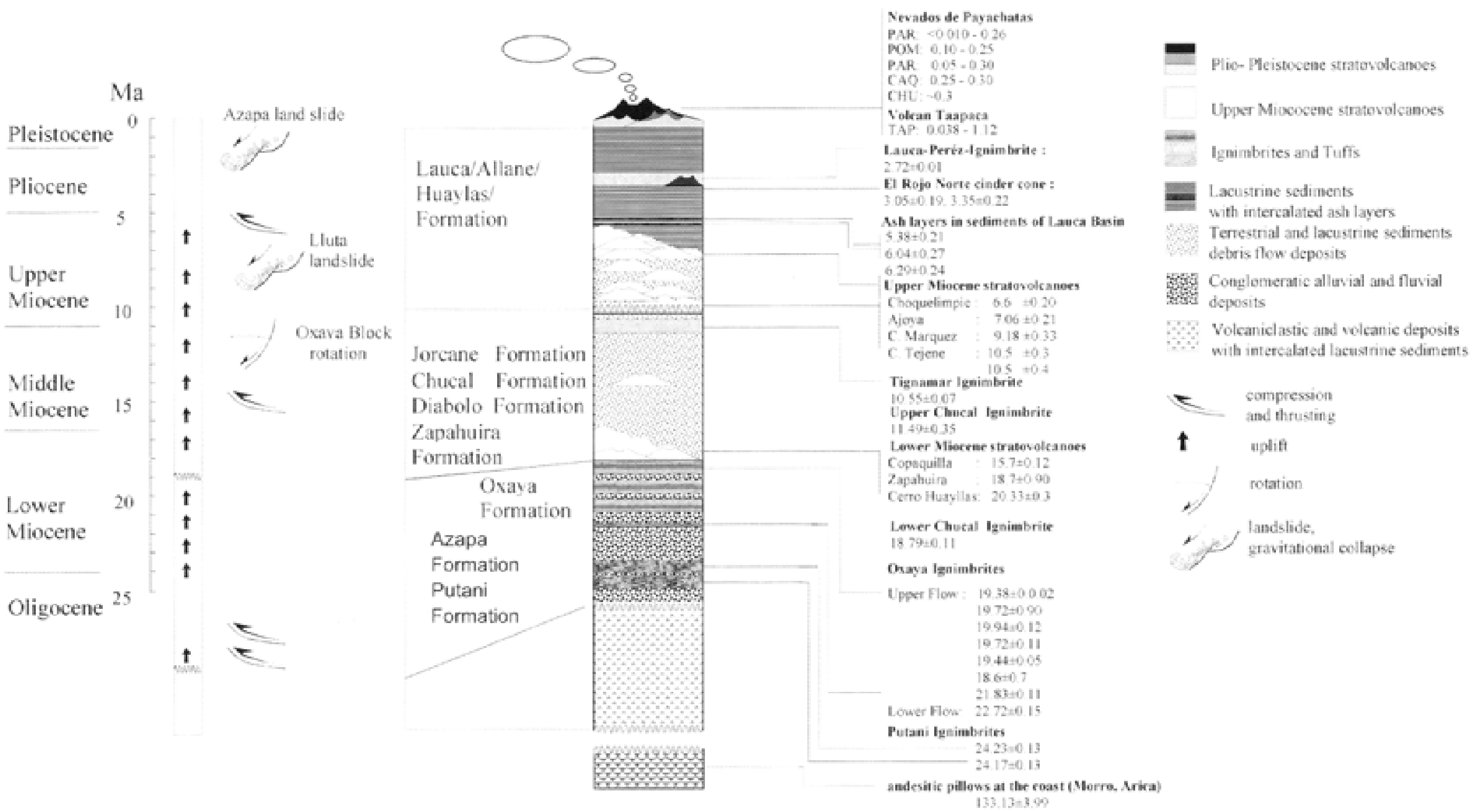


FIG. 6. Stratigraphic relations for Cenozoic rocks of northern Chile (18°S) based on new Ar-Ar dating, field and geochemical correlations.Ages are given in Ma; the uncertainty is 2σ, see table 1.

which is 'flowing up slope' and thus was clearly rotated together with the Oxaya Block. The lava flow was dated by García *et al.* (1996) and Muñoz and Charrier (1996) at 11.4±0.3 Ma (K-Ar whole rock age). Our own Ar-Ar total fusion whole rock age on a lava from the nearby Copaquilla volcano (COP 94-216) gave 15.07±0.12 Ma (Table 1), older than the age (12.1±0.7) for that center by García *et al.* (1996). Again, the Ar-Ar age tends to be older than the K-Ar age. However, a slightly disturbed age spectrum in our Ar-Ar analysis calls for a cautious interpretation of the data. From this reasoning, we conclude that Oxaya block rotation occurred after >12 to and before 10.5 Ma. Based on their data, García *et al.*, 1999 and reference therein) argued for a younger age for the displacement of the Oxaya Block.

In any case, the maximum age for the initial drainage system and valley incision on the Oxaya Block is clearly older than its rotation. For example, the Negro Valley (Fig. 1) is tilted to the east although its morphology still indicates an E to W course. Valley incision ceased in its upper course subsequent to the rotation of the Oxaya Block. Oxaya surface and its drainage pattern must then predate the block rotation and thus must be older than about 12 Ma.

An important consequence of the rotation and frontal uplift of the Oxaya Block was the over-steepening of its western front. This resulted in a giant landslide (Uhlig, 2000) exposed on both sides of the Quebrada Lluta for 20 km to the east of Poconchile. The age of the Lluta collapse must be younger than the Oxaya Block rotation (12 Ma) and older than the Lluta Valley, which dissects it. This lower bound is difficult to estimate: a proto-Lluta Valley already existed at 2.72 Ma when it was entered by the Lauca-Pérez Ignimbrite. As a conservative estimate we place the timing of the Lluta collapse at an age of 5 to 10 Ma.

Alluvial and fluvial braided stream sediments up > 200 m accumulated at elevations around 3,000 m in the depression between the Western Cordillera and the tilted Oxaya block (Huaylas and Jorcane Formations). The age of this formation is constrained to range from about 10.6 to 2.7 by an intercalated Tignamar ignimbrite (10.55 ± 0.05, Ma, Table 1), by mammalian fossils (8 to 9 Ma, Salinas *et al.*, 1991) and by the Lauca-Pérez Ignimbrite (2.71±0.01 Ma) overlying the Huaylas sediments.

Oxaya Ignimbrites and Miocene andesites of the Zapahuira formation are thrust onto Huaylas sediments (García *et al.*, 1996). Age equivalents of the Huaylas formation are flat-lying lake and salar sediments of the Lauca Basin (Kött *et al.*, 1995) and the Allane basin on the Chilean Altiplano (Fig. 1). Kött *et al.* (1995) have shown the 6.6 to 2.7 Ma old Lauca Basin sediments to be not affected by tectonism, apart from minor subsidence. The westernmost Altiplano and the Western Altiplano Escarpment has therefore remained tectonically relatively inactive in the past 6 Ma.

The implication of the reverse faults, which must be younger than about 10 Ma, for the uplift of the Altiplano and Western Cordillera has been discussed controversially. Muñoz *et al.* (1994), Charrier *et al.* (1994), and more recently Charrier *et al.* (1999) argued that the so-called Western Andean Thrust Belt (Muñoz and Charrier, 1996) is responsible for the uplift of the Western Cordillera and Altiplano. We cannot comment on the paleoecological arguments (Muñoz *et al.*, 1994), Charrier *et al.*, 1994, Charrier *et al.*, 1999), but maintain several arguments against such an interpretation:

- The west-vergent faults have shallow angles of less than 25° and displacements of only a few hundred meters maximum. It is difficult to explain uplift of several 1,000 m by such small structures.
- The age of these faults is fairly well constrained to be younger than about 10 Ma and older than 2.7 Ma, because the thrusting occurs onto sediments of that age (Salinas *et al.*, 1991) and the Lauca-Pérez-ignimbrite (2.7 Ma) is unaffected. However, a major portion of uplift must have occurred before 10 Ma as is documented by the Azapa conglomerates, the Oxaya ignimbrite event and correlations between tectonism and magmatism throughout the Central Andes (Kay *et al.*, 1999). This earlier phase of uplift is related to older and steeper reverse faults (García *et al.*, 1999)
- North of the Azapa Valley, the surface of the Oxaya ignimbrites forms a large undisturbed smooth ramp with a constant angle of about 2°. There is no evidence for large thrusts, but the elevation of the Western Cordillera and Altiplano is just the same.

The Huaylas sediments (see below) accumulated in the eastern depression and are younger than the Oxaya block rotation, yet, they are overthrusted by the reverse faults of the 'Western Andean Thrust Belt', which thus cannot be responsible for the formation of the basin in which they accumulated. On the other hand, there are several arguments in favor of a gravitational collapse origin within an overall compressive regime:

- The rotation occurred where the Western Andean flank is by far the steepest.
- Lithospheric loading to explain the easterly tilt by overthrust is not a viable explanation, because; **a**- the relatively short wavelength (18 km west-east maximum width of the eastward tilted surface); **b**- the observed loading on the thrusts is only a few hundred meter, and **c**- its limited extension compared to the extent of the uplifted Western Cordillera in northern Chile.
- A last and most important constraint is the short duration of movement (less than 2 my) which does not allow to link the short event of Oxaya Block rotation in the Arica area to the bulk of the uplift of the Andes. With reference to the initial slope of the Oxaya surface, the uplifted frontal part of the structure is geometrically balanced by the downward movement of the block. Thus, there is no net uplift related to the structure. Therefore, we conclude that some limited amount of crustal shortening, probably not more than a few 100 m at each of the three identified thrust faults occurred after about 10 Ma. However, the main process of uplift is not due to shortening, but rather to tilting of the Western Andean Escarpment on a regional scale as already pointed out by Lamb and Hoke (1997) and Isacks (1988).

A WIDER ANDEAN PERSPECTIVE

ARC MIGRATION AND THE OXAYA IGNIMBRITE EVENT

The Oxaya ignimbrites represent a large volume of rhyodacitic magma (3,000 km^3), which was erupted in a very short period of time. Andesitic volcanism on the western slope and westernmost Chilean Altiplano immediately succeed the Oxaya ignimbrites at 19 Ma and lasted until about 9 Ma at this westerly position (*ca.* 100 km from the coast). The data also show (Fig. 7) that andesite volcanism after 10 Ma shows an extremely wide east-west distribution over some 200 km.

These data taken together imply, that andesite volcanism that followed the ignimbrites occurred in the west of the present volcanic arc only until about 9 Ma. After that, we observe a shift of volcanism towards the east. It is interesting to note, that Miocene volcanism of such age and position is not observed anywhere south of Cerro Chusmiza (19°30') until in the Maricunga Belt at 25°S (Kay *et al.*, 1999). Therefore, the western front of Miocene volcanism (18 to 10 Ma) was shifted far to the east in this area. The implications of this distribution of Miocene volcanism with respect to slab configuration at that time remains to be explored but could indicate that a flat slab regime persisted in that region until prior to 10 Ma. This is consistent with the onset of extensive ignimbrite volcanism in the San Pedro de Atacama area around that time.

A more general comparison towards the north and south is conveniently done by placing the results of this study into the context of the reviews by Kay *et al.* (1999) and James and Sacks (1999). The wide distribution of magmatism in the Miocene has been linked to the steepening of the subduction zone and influx of hot asthenosphere into the mantle wedge after a phase of flat slab subduction, uplift, and no magmatism (Isacks, 1988; Wörner *et al.*, 1999; Kay *et al.*, 1999; James and Sacks, 1999). The timing of the volcanic gap and the wide magmatic zone after steepening has been different, however, in different parts of the Central Andes: these events appear to be older towards to the north of our study area in southern Perú where the end of the volcanic gap is at *ca.* >35 Ma (James and Sacks, 1999; Tosdal *et al.*, 1981, 1985). The gap and associated magmatism after slab steepening is significantly younger towards the south near 30°S (*ca.* 20 to 17 Ma, Kay *et al.*, 1999).

While the timing is different, the main processes seem to have been similar allowing a comparison with these respective regions:

The influx of hot asthenosphere at from east to west 18°S after 25 Ma must have been very rapid, because our dating shows that uplift, erosion, ignimbrite magmatism and onset of andesite volcanism far to the west occurred very close in time (22-19 Ma). The data by Kay *et al.* (1999) suggest that in the south, these processes may have been even closer in time and more dramatic, as there they can be linked also to the delamination of the lower lithosphere below the Andes.

Flat slab conditions may have persisted in the region between 20 and 25°S where Miocene magmatism is absent to the west of the present arc

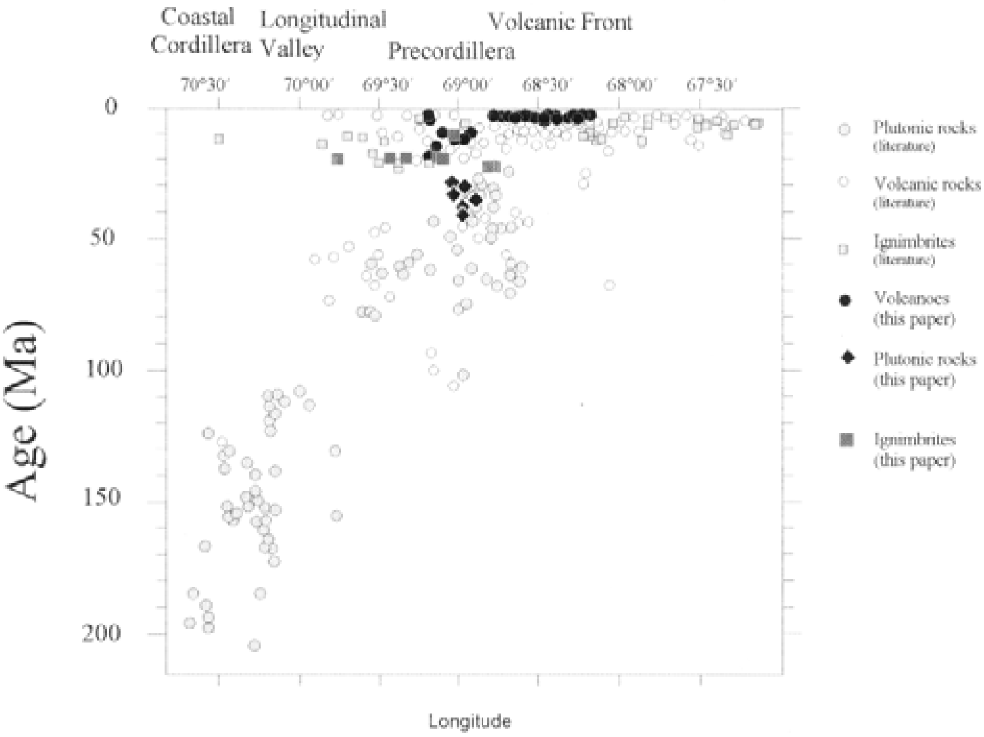


FIG. 7. Compilation of K-Ar and Ar-Ar ages projected into in a west-east section. Note the scarcity of magmatic rocks between 35 and 25 Ma, and the migration of the western front of the magmatic arc towards the east between *ca.* 10 and 3 Ma.

and particularly rare even in the region E of the Salar de Atacama. It is here also, where extensive ignimbrite magmatism and crustal melting started much later around 10 Ma (deSilva, 1989), suggesting steepening of the slab only at that time

It would be interesting to expand on the notion by Kay *et al.* (1999), that the origin of rare metal deposits in the Andes may ultimately be linked to the dip of the slab, the time of crustal thickening and cessation of magmatism. They argued that upon crustal thickening (linked to a shallowing slab), the residual mineralogy with which the magmas interacted in the crust, changes from amphibol-dominated to water free garnet-bearing assemblages. In our study area, crustal thickening around 25 to 20 Ma is **not** linked to a change in residual mineralogy. Near 18°S, this is not observed until after the eastward migration of the arc front at about 7 Ma (McMillan *et al.*, 1993; Wörner *et al.*, 1999; and unpublished data). Here, also magmatism with a high pressure residual crustal assimilation residue is also associated with the (smaller) ore deposit in the core of the *ca.* 7 Ma old Choquelimpie volcano, suggesting a similar link.

- We disagree with James and Sacks (1999) in the notion that crustal shortening is a consequence of this steepening of the slab, caused be the heating and weakening of the crust. This may be true for the Eastern Cordillera, but it is not substantiated in the west. Here, an extensive erosional event (Azapa conglomerates) and thus rapid crustal thickening and uplift is preceding the thermal event.
- We concur with James and Sacks (1994) and their interpretation of the literature data that crustal shortening in the Western Cordillera is very limited, not sufficient to explain the observed crustal thickening and uplift and even is absent in the thickened forearc. Our discussion above and (Wörner *et al.*, 1999) suggested that uplift in the Western Cordillera is caused mainly by regional tilting rather by crustal shortening.

• We argued (Wörner *et al.*, 1999) that magmatic addition is also not enough to explain crustal thickening, in contrast to the suggestion by James and Sacks (1999). A review of arc magma production rates, an estimate of magmatic addition to the Andean crust through time and an analysis of when and where the volume deficit occurred in the evolution of the Andean crust (Wörner *et al.*, 1999) reveals the following conclusion: thickening in the forearc, Eastern Altiplano, Eastern Cordillera and Subandean belt is easily explained by shortening, tectonic erosion, and underplating in the forearc. Magmatic addition is calculated to be rather constant through time and amounts to about 30 km^3/Ma and km north-south extend extent of the Andean orogen. Still, a volume of about 3,000 km^3 of crustal volume is missing per km north-south extent. This volume is missing in the lower crust between the forearc and the central Altiplano and it has been 'missing' since about 25 Ma (Wörner *et al.*, 1999). The deficit must have evolved over a short time of a few Ma, *i.e.*, the duration of the major phase of crustal uplift between 25 and 19 Ma. Clearly, if magmatic addition would account for the deficit (3,000 km^3 per 6 Ma and km north-south distance), it would be an extreme igneous event comparable only to a flood basalt event. There is no evidence in the geological record for such an event.

Several possible scenarios have been developed to explain the problem of the missing crustal volume: **1-** hydration at low temperatures of the uppermost mantle below the Andean crust (James and Sacks, 1999; Giese *et al.*, 1999) which would result in 'crustal' seismic velocities in the upper mantle. In this case, the crust is not as thick as previously though; **2-** it has been considered that the crust was initially significantly thicker than previously assumed, due to previous magmatic underplating events (Haschke *et al.*, 1999); **3-** crustal shortening estimates over all of the Andean orogen may be too small by at least 20%. If more shortening had occurred during the thermally induced lateral north 'collapse' of the Andes in the early Miocene (Isacks, 1988), then ductile flow of the lower crustal wedge from below the Eastern Cordillera towards the west could account for the volume deficit there and at that time. We prefer in fact the latter model, which would also be compatible with most arguments put forward by James and Sacks (1999).

CONCLUSIONS

Comparison and discussion of own and published geochronological data shows that Ar-Ar dating on separated minerals from magmatic rocks are the best available and reliable tool to date magmatic events, tectonic movements or uplift with associated changes in paleoclimatic conditions at a high temporal resolution of ±0.3 Ma. K-Ar data on biotite from intrusive rocks and ignimbrites could be in error (too young) by up to several Ma due to Ar loss from the biotite structure.

The present data base adds to the geochronological information compiled by Allmendinger *et al.* (1997) and presents significantly more data for the northern part of the region considered. Figure 8 shows the compilation of Allmendinger *et al.* (1997) with the new age dates from this work added. Clearly, data compilations suffer from biased sampling by preference for a certain working area or time slice, and accessibility. A clear example is the focus of dating work in the Atacama Basin area and for the time slice of 12-3 Ma (Fig. 8, Allmendinger *et al.*, 1997). The impression of a strong magmatic focus in that area and time, which is created by their figures, is partly the result of such sampling bias. However, with more data accumulating, this bias should diminish and this is one aspect of the present contribution (Fig. 8). Indeed, the massive concentration of ages between 3 and 12 Ma between 22° and 24°S is relatively diminished by our additional data from further north.

MIOCENE IGNIMBRITE MAGMATISM

Ignimbrite magmatism is widespread but clearly non-contemporaneous. The oldest ignimbrites postdating the first major phase of uplift in northernmost Chile are dated at around 24 Ma, a most voluminous phase of outpouring of rhyodacitic

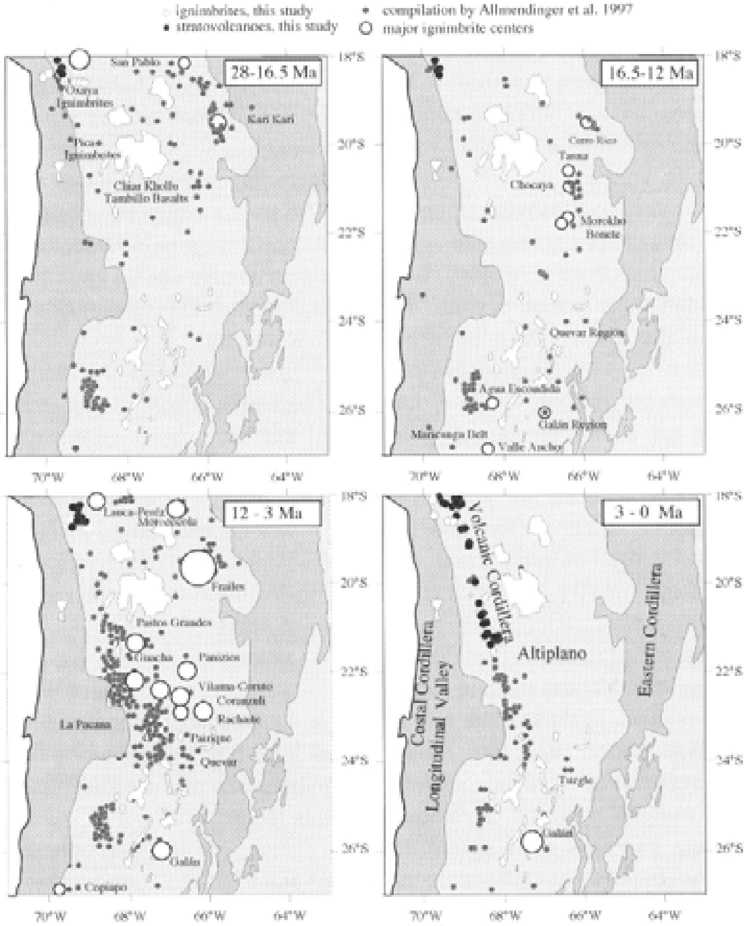


FIG. 8. Age distribution and newly dated samples in northern Chile and western Bolivia (based on the compilation of Allmendinger *et al.*, 1997 and references therein).

ignimbrites occurred between 19 and 20 Ma with a smaller precursor ignimbrite at 22 Ma. These Oxaya ignimbrites represent a volume of > 3000 km³. Ignimbrite magmatism further south has ages around 14 to 18 Ma (Alto de Pica area, Baker, 1977; Vergara and Thomas 1988; Vergara *et al.*, 1986; Naranjo and Paskoff, 1985; Lahsen, 1982) and becomes still younger in the Atacama Basin area (3-12 Ma, compilation by Allmendinger *et al.*, 1997). For these younger ignimbrites, deSilva (1989) argued that an 'ignimbrite flare-up' in the so-called 'Altiplano-Puna Volcanic Complex' to the E of the Atacama basin was caused by crustal thickening and increased magmatic input into the base of the crust, causing crustal melting and the development of large caldera complexes. Such a relation between slab geometry, crustal thickening, crustal melting and ignimbrite magmatism thus may exist throughout the Central Andes, however at different times.

TYPES AND TEMPORAL EVOLUTION OF STRATOVOLCANOES

Dating on Plio-Pleistocene to Recent stratovolcanoes has shown that some of these large structures can exist and remain intermittently active for up to 1 to 1.5 my (*e.g.*, Volcán Aucanquilcha, Volcán Isluga). This type of stratovolcano typically forms from varied lithologies and eruptions of silicic andesite to rhyodacite magmas. Eruption rates are low as indicated by frequent erosional unconformities. Basal input into the magma systems at depth is therefore also presumed to be rather low. As a result, their morphologies are rugged and steep.

Such volcanoes are fed from a low-temperature LO-T ('low-input/low-output') magmatic system and establish stable long-lived magma chambers in the crust. Magmatic processes are mainly extended differentiation, magma mixing, and shallow assimilation.

These long-lived centers contrast with smoothly cone-shaped stratocones of rather monotone mafic andesite. Best examples are the north-south chain of cerros Chela, Palpana, Miño (but other examples also exist throughout the study area). All these centers gave ages close to 3-4 Ma and nearby small mafic monogenetic centers (cerros Carcote, Las Cuevas, El Rojo Sur) are also of similar age. The monotonous mafic composition, narrow age range and linear arrangement of centers argue for a faster fracture-controlled ascent. Such centers are fed from HOT ('high-input / high-output') magmatic systems and develop mostly by recharge-fractionation and tapping.

The overall location of magmatism in the Central Andes is obviously controlled by the melting region in the mantle wedge and magma ascent is mostly governed by buoyancy. When favorable ascent paths through the upper crust do not exist, one may speculate that LO-T magma systems develop. If however, crustal scale fractures exist above the melting region in the mantle, ascent could be focussed and much faster, resulting in HOT-systems, which then are much less long-lived.

Morphology, ages, duration and composition of individual volcanic complexes reflect the characteristics of the deep magmatic plumbing system, magma production rate and state of stress in the crust. Conspicuous is a series of mafic andesite stratovolcanoes between 18 and *ca.* 10 Ma and around 3 to 4 Ma. A high magma production and probably extensive (or less compressive) stress in the crust characterize both these magmatic phases at that time.

WARP EVOLUTION AT 18°S

Our new ages better constrain models of Andean evolution from a 'western' perspective and date stratigraphy, the timing of uplift and (gravitational?) tectonic processes in northernmost Chile.

The major magmatic phases in the WARP-sector Arica-Chungará in Miocene to Recent times are:

- extensive Oxaya ignimbrite volcanism (< 3,000 km^3) occurred between 22 and 19 Ma, immediately followed by:
- mafic andesite shield volcanoes (18.5-7 Ma). The western front of the wide zone of magmatism at this time migrates towards the west onto the present Altiplano and narrows from a very wide east-west distribution at the same time.
- the Lauca-Pérez Ignimbrite erupted at 2.7 Ma and can be correlated from western Bolivia down the Western Altiplano Escarpment to the coast near Arica.
- volcanism at the active magmatic front concentrated into a narrow east-west zone by about 3 Ma and shows a conspicuous activity gap at the latitude of Pica (Pica Gap) which could be related to the subduction of the small Iquique aseismic ridge in this region.

The Oxaya Ignimbrite is related to a major phase of crustal melting after a period of magmatic quiescence. This ignimbrite event is triggered by the influx of hot asthenosphere after a period of flat slab subduction.

Uplift and tilting of the WARP continued and resulted in a large gravitational collapse and the formation of the antithetically rotated Oxaya Block around 12 Ma.

The age of tilting constrains the age of the surface of the Oxaya Block which has not changed its surface morphology significantly in the last 12 Ma, making it one of the oldest morphologies on Earth.

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