PALEOMAGNETIC RECONNAISSANCE OF THE REGION DE LOS LAGOS, SOUTHERN CHILE, AND ITS TECTONIC IMPLICATIONS

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ABSTRACT

Several paleomagnetic sites from upper Paleozoic through upper Tertiary rocks in Southern Chile have given valuable tectonic information. Paleomagnetic data suggest clockwise rotation associated with the Liquiñe-Ofqui fault; however, some rocks present a small counterclockwise rotation. Nevertheless, the general pattern of rotation indicates dextral shear along the fault. These data further suggest that rocks west of the Liquiñe-Ofqui fault have been transported northward, probably 400 to 500 km, in at least the last 50 Ma. Rocks east of the fault have either had a southward transport or more likely have remained static with respect to cratonal South America. However, errors associated with the rotations and translations are large, and some of these results are suspect. Rotation and translation appear to affect rocks as young as 3 or 4 Ma, indicating that the Liquiñe-Ofqui fault has moved recently and probably is still active. Evidence of volcanism associated with the fault supports this result.

Key words: Paleomagnetism, Tectonics, Megafaults, Liquiñe-Ofqui Fault, Región de Los Lagos, Southern Chile.

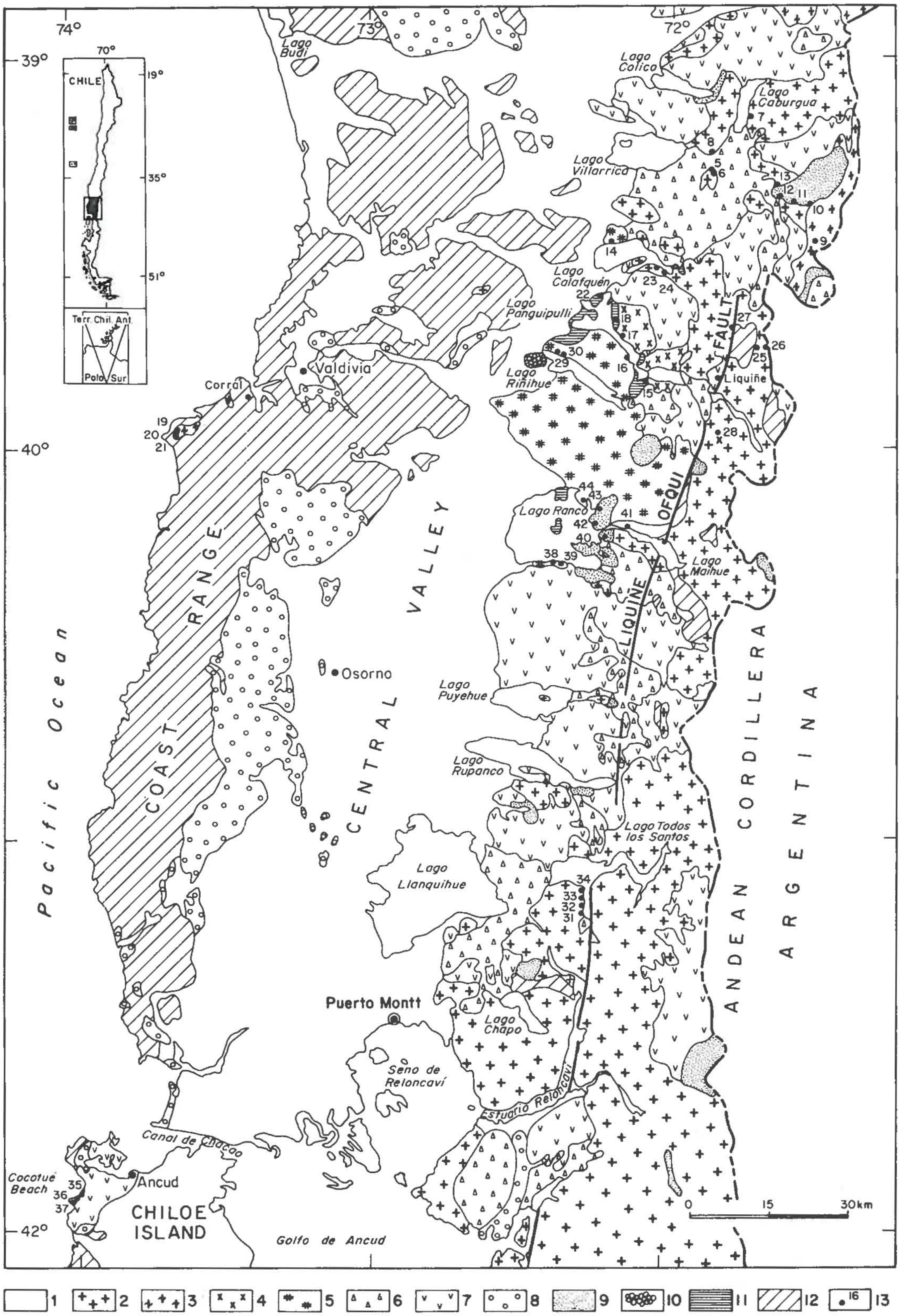
RESUMEN

El estudio paleomagnético efectuado en varias localidades de la Región de Los Lagos, en el sur de Chile, sugiere que rocas con edades comprendidas entre el Paleozoico superior y el Terciario superior presentan rotaciones horarias asociadas a la Falla Liquiñe-Ofqui aunque, en algunas de ellas, dicha rotación es levemente antihoraria. La tendencia general de rotación señala un movimiento dextral a lo largo de la falla e indicaría que las rocas al oeste de ella han sido transportadas hacia el norte por una distancia aproximada de, por lo menos, 400-500 km, en los últimos 50 Ma. Las rocas al este de la Falla Liquiñe-Ofqui han tenido un movimiento relativo hacia el sur o, tal vez, han permanecido estáticas con respecto a Sudamérica. Debido a que los errores asociados con la determinación de las rotaciones y translaciones son elevados, algunos de estos resultados deberían ser comprobados con estudios posteriores. Rotaciones y translaciones observadas a través de los datos paleomagnéticos en rocas de edades cercanas a los 3 y 4 Ma, indicarían que la Falla Liquiñe-Ofqui se ha movido recientemente, siendo probable que aún se encuentre activa.

Palabras claves: Paleomagnetismo, Tectónica, Megafallas, Falla Liquiñe-Ofqui, Región de Los Lagos, Chile.

INTRODUCTION

Large strike-slip faults around the world have been the subject of considerable interest, and many models have been advanced to explain them. Beck (1983, 1985, 1986, 1988) and Fitch (1972) suggested that oblique subduction may cause strike-slip faults. According to Beck (1986), the San Andreas fault system may be a transform boundary localized along pre-existing faults produced by oblique subduction. Similar North American faults may have caused transport of arc and forearc rocks thousands of kilometers northward. Paleomagnetic data have been fundamental in the calculations of amounts of displacement and rotation of blocks along strike-slip faults in western



Lago Budi
Lago Colico
Lago Caburgua
Lago Villarrica
Lago Calafquén
Lago Panguipulli
Lago Riñihue
Valdivia
Corral
Lago Ranco
Lago Maihue
Liquiñe
LIQUIÑE OFQUI FAULT
Osorno
Lago Puyehue
Lago Rupanco
Lago Todos los Santos
Lago Llanquihue
Puerto Montt
Lago Chapo
Seno de Reloncaví
Estuario Reloncaví
Canal de Chacao
Cocotue Beach
Ancud
CHILOE ISLAND
Golfo de Ancud
Pacific Ocean
COAST RANGE
CENTRAL VALLEY
ANDEAN CORDILLERA
ARGENTINA
CHILE
Terr. Chil. Ant.
Polo Sur
74°
73°
72°
70°
39°
40°
42°
19°
35°
51°
0 15 30km
1 2 3 4 5 6 7 8 9 10 11 12 13

North America. Strike-slip faulting is also important in collisional orogens such as the Himalayas. Molnar and Tapponnier (1978) indicated that strike-slip faults in Tibet are produced by an "indenter" mechanism, whereby India pushes material northward over the Eurasia continent, forming east-west fault systems north of the Himalayas. Other strike-slip faults have been produced by oblique accretion of allochtonous terranes; *e.g.*, the El Romeral fault in Colombia (Aspden and McCourt, 1986; McCourt *et al.*, 1984), and faults such as El Pilar in Venezuela (Speed, 1985).

These models of strike-slip faults perhaps can be applied to western South America where the Aluk, Farallón and Nazca plates have been subducted under the Chile Margin since Mesozoic times (Pilger, 1983; Cande and Leslie, 1986). Faults such as Atacama in Northern Chile (Allen, 1965; Arabasz, 1971) and the Liquiñe-Ofqui Fault (LOF) in the south (Hervé, 1976) could be related to oblique subduction.

The area of this investigation is located in Southern Chile, between 39° and 42°S (Fig. 1). The area lies mostly within the Andean Range, but some samples were collected in the Coast Range of Valdivia and on Chiloé Island. Ages of the sampled units range from late Paleozoic to late Tertiary.

The Liquiñe-Ofqui Fault is undoubtedly the most important structural element in the area but, despite intensive study, its tectonic history is not well known. If its movement involved large tilting or lateral displacements, it should be recognized paleomagnetically. Hervé (1976) indicated that the fault had dextral strike-slip motion during Late Cretaceous-early Tertiary times. Beck (1988) and Hervé (1976) indicated that this motion was related to oblique subduction. Forsythe and Nelson (1985) believe that the Liquiñe-Ofqui Fault is a result of the collision of the Chile Rise with the Perú-Chile trench. The Chile Rise (Fig. 2), according to their model, acts as a rigid indenter in a way analogous to the Molnar and Tapponnier (1978) model for active deformation in Tibet, with the Chile Rise playing the same role of India by "indenting" the South American continental margin and then pushing continental material aside to the north, along the Liquiñe-Ofqui Fault.

The purpose of this study was to learn more about the tectonic history of the area, using paleomagnetic data from both sides of the Liquiñe-Ofqui Fault. Focus was on the relative motion along the fault and its relationship to the subduction zone and the Southern Chile Triple Junction. Rotations, translations and motions of the rocks from both sides of the fault provide data to decipher the displacement history of the Liquiñe-Ofqui Fault. A

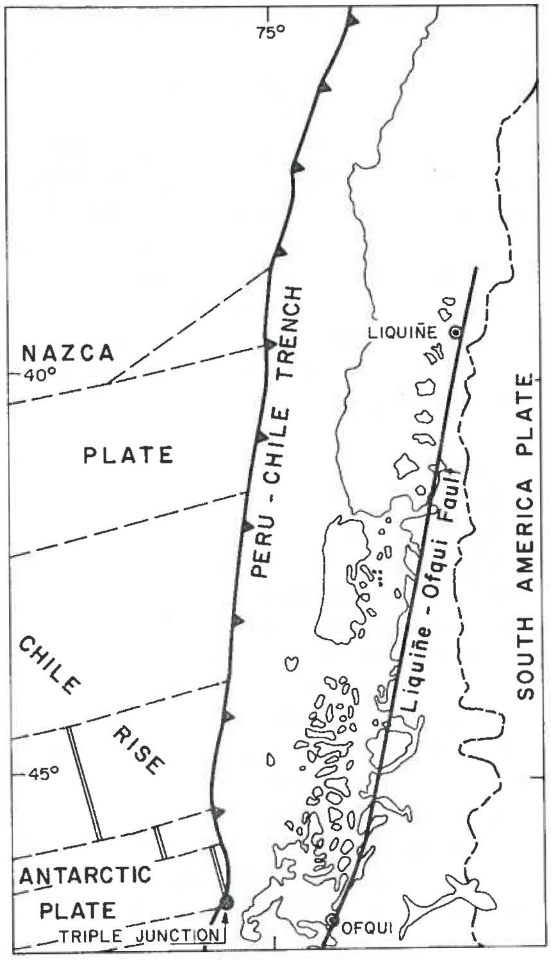


FIG. 2. Tectonic setting, showing plate location, and the main tectonic features of the area.

FIG. 1. Location map of the study area, showing geographic features and places, location of the sites and geology based on the Mapa Geológico de Chile (SERNAGEOMIN, 1982), modified by Munizaga *et al.* (1985). 1. Sedimentary Quaternary; 2. Miocene intrusives; 3. Cretaceous intrusives; 4. Jurassic intrusives; 5. Paleozoic intrusives; 6. Quaternary volcanism; 7. Pliocene-Pleistocene volcanism; 8. Undifferenciated Tertiary sediments; 9. Curarrehue Formation (Upper Cretaceous-lower Tertiary); 10. Tralcán Formation (Upper Triassic); 11. Panguipulli Formation (Upper Carboniferous-Permian); 12. Metamorphic Basement (upper Paleozoic); 13. Site.

search for allochtonous terranes was a subsidiary purpose of the study. The fact that this is the first paleomagnetic study made in this area gives it the character of a reconnaissance work.

REGIONAL GEOLOGICAL SETTING

In the Chilean territory between 39° and 42°S (Fig. 1) a group of metamorphic, igneous and sedimentary rocks crop out; their ages range from upper Paleozoic to Recent.

The Metamorphic Basement of the Coast Range is composed by strongly deformed schists and gneisses which have a sedimentary protholith, interlayered with oceanic volcanic and intrusive material including some ultramafic bodies. This assemblage represents the remnants of an accretionary prism built along the Pacific margin of Gondwanaland during the late Paleozoic (Forsythe, 1982; Hervé *et al.*, 1987). Metamorphic rocks of the same group are also found in the Andean Range.

The oldest stratified sequence in the Andes of the region is the Panguipulli Formation (Aguirre and Levi, 1964; Parada, 1975), a series of poor grade slates and metasandstones of marine origin that crop out sporadically from the northern shore of Lago Calafquén to the south shore of Lago Ranco. This formation discordantly overlies the Metamorphic Basement and is intruded by Jurassic granitoids (Panguipulli Batholith). An Upper Carboniferous to Permian age was assigned to it due to the presence of *Lepidodendron peruvianum* (Tavera *in* Hervé *et al.*, 1974), while Cingolani (oral commun.) suggests a Triassic age due to new fossil findings. Despite its age, intrusion and metamorphism by the Panguipulli Batholith suggest that the age of magnetization of the formation is Jurassic.

The Panguipulli Formation is unconformably overlain by the red continental sediments of the Upper Triassic Tralcán Formation (Aguirre and Levi, 1964; Hervé *et al.*: Nuevos antecedentes sobre la Geología de la Cordillera de los Andes de la Provincia de Valdivia. Instituto de Investigaciones Geológicas, Jornadas de Trabajo (Unpublished), Vol. 2 p. 87-98, 1972), which crops out only on the western shore of Lago Riñihue. The Curarrehue Formation (Aguirre and Levi, 1964) is a sequence of volcanic and continental sedimentary rocks whose main areas of outcrop are located along the east and south shore of Lago Ranco and east of Lago Villarrica. This formation consists of volcanic breccia, agglomerate, porphyritic andesite, tuff, sandstone, conglomerate and lutite. In the basal part, volcanic material of andesitic and dacitic composition predominates; while the upper levels are more sedimentary (Moreno and Parada, 1976). A Late Cretaceous to early Tertiary age was assigned from fossil plant evidence (Di Biase *in* Moreno and Parada, 1976). Nevertheless, several K-Ar ages near Lago Villarrica and east of Lago Ranco, have recently yielded Late Miocene-Pliocene ages and the rocks may, in fact, represent a late Cenozoic volcanic episode (Munizaga *et al.*, in prep.).

In the Coast Range and on Chiloé Island, Eocene and Miocene marine and continental sedimentary units overlie the Metamorphic Basement (García, 1968; Valenzuela, 1982) where they are intercalated with volcanic rocks (Vergara and Munizaga, 1974). On the northwest tip of Chiloé Island the volcanic rocks are dikes and necks in which a K-Ar age of 40.4 ± 1.8 Ma was obtained (Vergara and Munizaga, 1974). A new K-Ar age of 21.8 ± 1.7 Ma for these rocks is reported in this study.

Moreno and Parada (1976) gave the name of Plutonic Complex to the intrusive rocks of the Andean Cordillera that form the northern edge of the Patagonian Batholith (Munizaga *et al.*, 1984). This complex is composed by several distinct plutons ranging in composition from tonalite to granite and in age from Paleozoic to Cenozoic (Fig. 1). Paleozoic K-Ar ages between 295 and 282 Ma have been obtained from intrusive rocks of the northeast shore of Lago Ranco and northwest shore of Lago Riñihue (Munizaga *et al.*, 1985). A Rb-Sr isochron of these rocks yields an age of 253 ± 55 Ma. Munizaga *et al.* (1984) suggested that these Paleozoic outcrops are part of a northwest-trending magmatic belt extending from the Nahuelbuta Mountains to the Northern Patagonian Massif.

Parada (1975) named as Panguipulli Batholith a complex of diorite, tonalite and granodiorite cropping out around Lagos Calafquén, Panguipulli, Riñihue and Ranco. Rocks assigned to the Panguipulli Batholith intrude the Panguipulli Formation and underlie the Curarrehue Formation. Around Lago Panguipulli it yields Jurassic K-Ar ages of 171 to 164 Ma and a Rb-Sr age of 160 ± 20 Ma (Parada and Munizaga, 1978). Other Rb-Sr ages of 200 ± 18 Ma and 195 ± 24 Ma have also been obtained (Munizaga *et al.*, 1985).

Cretaceous plutons are found north of Lago Villarrica; K-Ar ages are around 90 Ma. They also are found nearby in Argentina and in Aisén to the south, where Hervé (1984) obtained Rb-Sr Cretaceous ages with reset Miocene K-Ar mineral ages. In the Coast Range, small stocks which intrude the Metamorphic Basement 130 km west of the contemporaneous Cretaceous granitoids of the Andean Cordillera also have yielded Cretaceous K-Ar ages. These include bodies south of Corral (103 ± 3 Ma, this study) and Estero Los Boldos (86 ± 3 Ma) near Valdivia (Munizaga *et al.*, 1985).

Miocene K-Ar ages in granitoids (granodiorite, diorite, tonalite) were obtained by Munizaga *et al.* (1984, 1985). These are distributed all along the area close to the LOF. As previously explained, some Miocene ages in plutons are a product of resetting (Hervé, 1984), but a large amount of granitic rocks in the area near LOF seems to have been effectively emplaced during the Miocene.

STRUCTURE

The most important structure in the area is the Liquiñe-Ofqui Fault System (Moreno and Parada, 1976; Hervé *et al.*, 1974; Hervé, 1976; Hervé, 1984; Thiele *et al.*, 1986), which extends at least 1,000 km from Liquiñe in the north to Ofqui in the south (Fig. 2). It has a general N10°E strike, but curves westward in the south (Golfo de Penas). The trace of the LOF runs through the active Andean volcanic chain. Hervé (1976) indicated that, in the Liquiñe area, this structure is a sealed, dextral strike-slip fault, associated with a 3 km wide cataclastic and mylonitic shear zone. According to Hervé (1976) field considerations indicate that strike-slip movement occurred sometime between Late Cretaceous and early Tertiary time. More recently, Hervé *et al.* (1979) indicated that both normal and right lateral components have been documented. Right lateral movements are suggested by mesoscopic faults developed within the mylonitic and cataclastic zone. Thiele *et al.* (1986) indicated that the Liquiñe-Ofqui fault in the Reloncaví Fiord affects rocks from 10 to 4 Ma. Hervé (1984) indicated that, near the LOF, in Aisén, K-Ar ages have been reset in the Miocene because the Rb-Sr whole rock crystallization age of a granitoid pluton (98 ± 4 Ma) was older than the K-Ar ages of 11-17 Ma of the same intrusive. Munizaga *et al.* (1985) also suggested that some of the K-Ar Miocene ages in plutonic rocks along the fault are reset. This could have been caused by shear heating during Miocene movement of the fault but it could be also due to heat from young nearby intrusions. Support for the latter is shown by the concordance between a Rb-Sr whole rock isochron age of 16 Ma and a Miocene K-Ar age of 10-12 Ma on an outcrop near Lago Llanquihue, near to the fault trace.

PALEOMAGNETISM

PROCEDURES AND ANALYTICAL METHODS

Fourty sites (311 samples) were collected from the rock units in the study area. The samples were drilled *in situ*, with a portable rock drill and oriented using sun and magnetic compasses. Seven or eight cores spaced over 50 to 200 m were collected at each site. Two laboratory specimens approximately 22 mm long were prepared from most samples. Table 1 shows age, unit and location of each site.

Remnant magnetizations were measured using spinner and cryogenic magnetometers, at Western Washington University and at the University of Arizona, respectively. Each specimen was measured several times during progressive demagnetization, by alternating field (AF) or thermal methods. AF demagnetization employed a tumbling-specimen demagnetizer, with 170 mT as the highest field obtainable. Thermal demagnetization, used a magnetically shielded oven; temperatures up to 580°C were obtained in increments of 100°, 50° and 25°C. After demagnetization, vector analyses were applied to obtain magnetic directions using principal component analysis (PCA) described by Kirschvink (1980). Orthogonal projections (Zijderveld, 1967) were used to evalutate the data. Site mean directions were calculated using the cumputations described by Fisher (1953).

TABLE 1. AGES AND FORMATIONS OF THE SITES

Site	Rock Unit	Age (Ma) K-Ar	Location(*) °S/°E	Site	Rock Unit	Age (Ma) K/Ar	Location(*) °S/°E
85CJ05	Tertiary intrusive	8.5±0.1	39.26/288.24	85CJ25	Tertiary intrusive	28.9±1.2	39.78/288.27
85CJ06	Tertiary intrusive	8.5±0.1	39.26/288.24	85CJ26	Tertiary intrusive	28.9±1.2	39.78/288.28
85CJ07	Tertiary intrusive	-------	39.15/288.25	85CJ27	Tertiary intrusive	15.0±0.9	39.76/288.17
85CJ08	Tertiary intrusive	-------	39.24/288.17	85CJ28	Jurassic intrusive	176±5	39.97/288.15
85CJ09	Cretaceous Intrusive(?)	-------	39.50/288.46	85CJ29	Paleozoic intrusive	294±6	39.78/287.61
85CJ10	Tertiary extrusive	3.0±0.5	39.38/288.44	85CJ30	Paleozoic intrusive	282±4	39.78/287.61
85CJ11	Tertiary extrusive	4.2±0.5	39.33/288.38	85CJ31	Tertiary intrusive	-------	41.21/287.72
85CJ12	Tertiary extrusive	4.1±0.4	39.35/288.38	85CJ32	Tertiary intrusive	-------	41.21/287.72
85CJ13	Tertiary intrusive	-------	39.35/288.38	85CJ33	Tertiary intrusive	-------	41.18/287.72
85CJ14	Tertiary intrusive	8.2±2.1	40.00/288.00	85CJ34	Tertiary intrusive	-------	41.17/278.72
85CJ15	Panguipulli Formation	Upper Pz	39.82/287.90	85CJ35	Cocotué basalts	40.4±1.8	41.85/285.98
85CJ16	Panguipulli Batholith	190 to 200	39.75/287.85	85CJ36	Cocotué basalts	and	41.85/285.98
85CJ17	Panguipulli Batholith	190 to 200	39.67/287.78	85CJ37	Cocotué basalts	21.8±1.7	41.85/285.98
85CJ18	Panguipulli Formation	= 85CJ15	39.67/287.79	85CJ38	Paleozoic intrusive	309±8	40.32/287.63
85CJ19	Cretaceous intrusive	103±3	39.93/286.42	85CJ39	Paleozoic intrusive	309±8	40.33/287.63
85CJ20	Cretaceous intrusive	103+3	39.93/286.42	85CJ40	Tertiary extrusive	-------	40.20/287.76
85CJ21	Cretaceous intrusive	103±3	39.93/286.42	85CJ41	Tertiary intrusive	13.1±0.6	40.23/287.87
85CJ22	Panguipulli Formation	= 85CJ15	39.59/287.78	85CJ42	Tertiary extrusive	13.7±2.0	40.21/287.73
85CJ23	Panguipulli Batholith	= 85CJ16	39.57/287.93	85CJ43	Tertiary extrusive	-------	40.15/287.75
85CJ24	Panguipulli Batholith	= 85CJ16	39.58/287.97	85CJ44	Paleozoic intrusive	295±7	40.12/287.67

* Locations of sites were obtained from the charts 1:50,000 from the Instituto Geográfico Militar of Chile.

RESULTS AND ANALYSES

The paleomagnetic results from this investigation are not of equal reliability; as in most of such studies, some degree of quality control was necessary. The results have been divided into three different categories based on quality of the measurements. **Category A** (Fig. 3a) includes the results with the highest reliability, characterized by a well determined single component of magnetization. In AF demagnetization, this single component is generally fit (using methods after Kirschvink,1980) from 20 to 100 mT. In thermal demagnetization, the fit is between 200° and 585°C. The Viscous Remnant Magnetization (VRM) component for specimens in this category usually represents less than 20% of the Natural Remnant Magnetization (NRM) and are eliminated by 20 mT. **Category B** (Fig. 3b) represents results with moderate reliability. This group is characterized by fairly well defined direc-

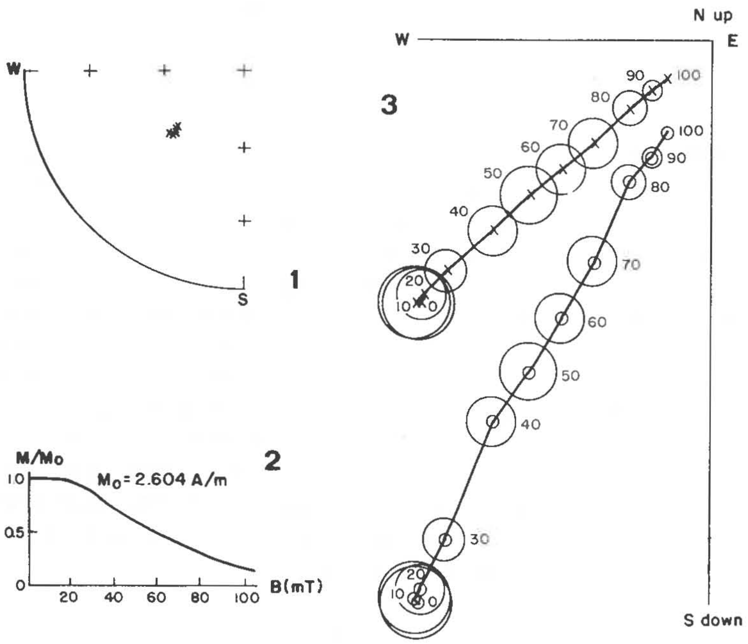


FIG. 3a. Magnetic behavior typical for specimens from Category A, with one dominant component of magnetization. 1. Stereographic projection presenting cluster of the directions; 2. Normalized intensity diagram with intermediate to fairly high coercivity; 3. Orthogonal projection showing direction of magnetization changes are insignificant between 0 and 100 mT. Circles are Gamma 95. They also show the consistency and reliability of this category.

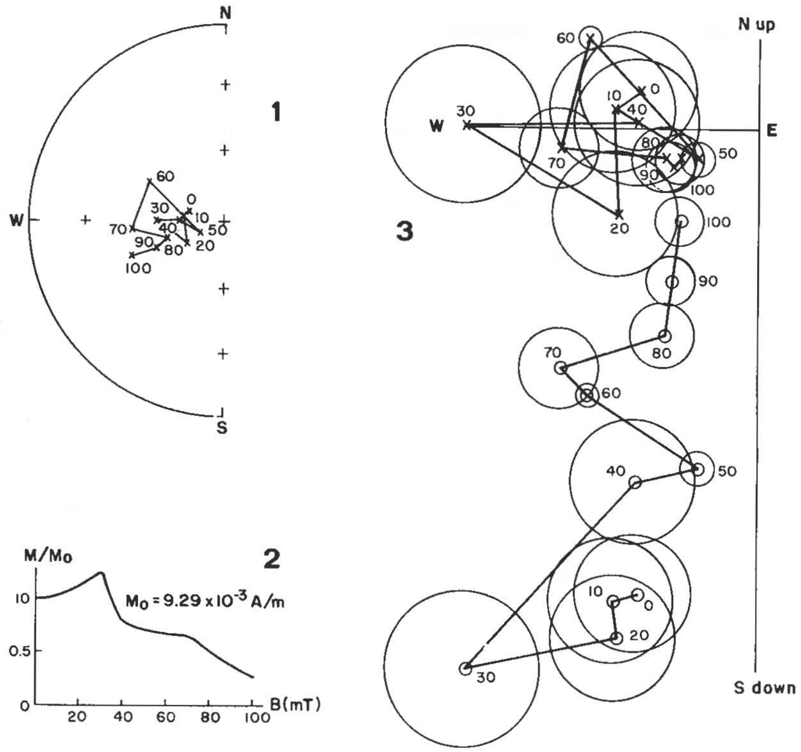


FIG. 3b. Magnetic behaviour typical of specimens from Category B. 1. Stereonet shows more scattered, but directions remain concentrated in a restricted area; 2. Normalized intensity displays a more jagged pattern of the decay; 3. Orthogonal projection presents a generally linear trend of the demagnetization path. Here, Gamma 95 is larger and less consistent than in Category A.

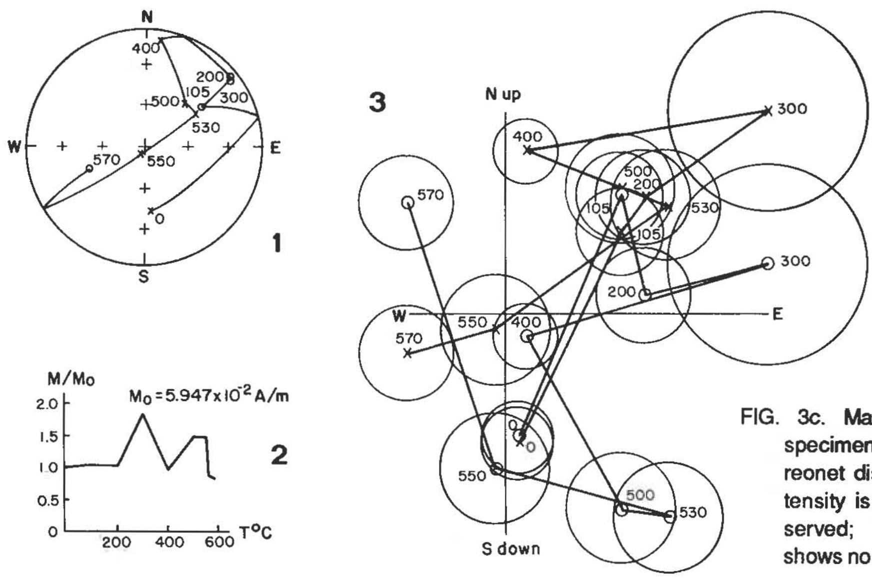


FIG. 3c. Magnetic behaviour typical of specimens from Category C. 1. Stereonet displays scatter; 2. Normal intensity is erratic and no decay is observed; 3. Orthogonal projection shows no linear pattern of the path.

tions of magnetization but peculiar or poorly defined magnetic behaviour. Some Category B samples have low coercivity and low intensities of magnetizations. Other rocks in this category have high coercivities and low magnetic moments (10^{-1} to10^{-4} A/m), but suffer erratic changes of magnetization during demagnetization. The third group, **Category C** (Fig. 3c), includes all those sites which did not give any realiable information and hence will not be further considered.

Table 2 shows the paleomagnetic results for sites of Categories A and B. Results from Category C are not discussed. All measurements are tabulated in García (1986). The paleomagnetic results are grouped according to unit or formation. Also, a separation within rock unit is made on the basis of location of group of sampling sites. This grouping according to rock unit and location is made to fa-

TABLE 2. SITE MEAN DIRECTION

Site	Category	Direction			Statistics			Demagnetization	
		D	I	N	R	K	α_{95}	Range	Type
					Paleozoic Intrusives				
85CJ38	A	110.4	70.7	7	6.976	250.0	3.8	10-100 mT	AF
		290.4	- 70.7						
85CJ39	A	343.4	- 72.9	8	7.923	90.9	5.8	5-50 mT &	AF & Th
								115-530°C	
85CJ44	A	136.5	69.8	8	7.988	583.4	2.3	10-100 mT	AF
		316.5	- 69.8						
					Jurassic Rocks				
85CJ15	B	344.2	- 63.6	8	7.927	95.9	5.7	0-170 mT	AF
85CJ24	A,B	17.2	- 57.1	8	7.929	98.6	5.6	15-100mT	AF
85CJ28	A	239.9	48.9	4	3.973	111.1	8.7	10-100mT	AF Host rock
		59.9	- 48.9						
85CJ28	A	40.0	- 69.5	4	3.896	28.9	17.4	10-100mT	AF Dyke
					Miocene Intrusives				
85CJ05	B	13.4	- 47.5	4	3.914	34.9	15.7	15-80 mT	AF
85CJ06	B	25.3	- 63.0	6	5.825	28.6	12.6	20-70 mT	AF
85CJ07	B	229.9	61.8	6	5.488	9.8	22.6	18-90 mT	AF
		49.9	- 61.8						
85CJ08	B	235.2	71.3	7	6.835	36.4	10.1	20-100 mT	AF
		55.2	-71.3						
85CJ13	A	356.7	- 55.9	4	3.944	53.6	12.7	10-70 mT	AF
85CJ13*	A	335.5	- 85.5	4	3.944	53.6	12.7	10-70 mT	AF
85CJ13	B	175.5	59.9	4	3.964	83.3	10.2	20-100 mT	AF
		355.5	- 59.9						
85CJ13*	B	90.6	87.7	4	3.964	83.3	10.2	20-100 mT	AF
		270.6	- 87.7						
85CJ14	B	265.5	61.2	5	4.946	74.1	8.9	20-100 mT	AF
		85.5	- 61.2						
85CJ41	A	343.6	- 60.0	5	4.979	190.5	5.6	5-90 mT	AF
85CJ41	A	192.3	69.5	3	2.999	2,000.0	3.1	20-60 mT	AF & Th
		12.3	-69.5						
85CJ25	B	30.7	- 52.7	5	4.885	34.8	13.2	0-100 mT	AF
					Miocene Extrusives				
85CJ10*	A	50.9	- 56.0	3	2.982	111.1	11.6	40-100 mT	AF
85CJ11*	A	227.3	55.1	7	6.974	230.8	4.0	10-100 mT	AF
		47.3	- 55.1						
85CJ12*	A	43.2	- 68.3	8	7.963	189.2	4.0	5-100 mT	AF
85CJ43	A, B	44.0	- 81.5	7	6.619	15.8	15.7	105-575°C	Th
					Cocotué Beach Volcanics				
85CJ35	A	168.2	70.7	6	5.985	333.3	3.7	20-100 mT	AF &Th
		348.6	- 70.7					110-450°C	
85CJ36	A	143.6	64.7	6	5.995	1,000.0	2.1	20-100 mT	AF
		323.6	- 64.7						
85CJ37	A	137.7	52.0	6	5.904	52.1	9.4	194-550°C	Th
		317.7	- 52.0						

Note: D is declination; I is inclination of Fisher site mean direction; N is number of samples; R is resultant of N unit vectors; K is estimate of precision parameter, α_{95} is semi-angle of cone of 95% confidence around mean direction. Sites with Upper hemisphere (reverse) directions have normal polarity equivalent listed beneath. AF is the alternating field demagnetization; and Th is thermal. Sites with * are those in which tilt correction was made.

TABLE 3. OBSERVED AND EXPECTED PALEOMAGNETIC DIRECTIONS

Rock Unit	Observed Directions			Expected Directions			
	Dec	Inc	α_{95}	Dec	Inc	ΔDx	ΔIx
Cocotué Volcanics (35-36-37)	326.8	-63.0	18.1	358.8	-63.8	5.7	3.2
Paleozoic Intrusives (38-39-44)	315.7	-72.3	12.8	323.2	-66.0	17.4	8.6
Jurassic Rocks W of LOF (24-15)	2.3	-61.2	15.0	7.3	-69.4	24.3	9.8
Jurassic Rock E of LOF (28)	59.9	-48.9	8.7	6.9	-67.1	22.0	10.2
Miocene Intrusives N and W of LOF (5-6-7-8-14)	42.4	-63.5	15.6	353.8	-60.0	4.0	2.6
Miocene Extrusives and Intrusives N and E of LOF (10-11-12-13a, b)	26.6	-61.5	14.6	353.8	-60.0	4.0	2.6
Miocene Extrusives and Intrusives N and E of LOF (10-11-12-13a, b, corrected for tilt)	43.7	-71-9	16.9	353.8	-60.0	4.0	2.6
Miocene Intrusives E Of LOF (25)	30.7	-52.7	13.2	353.8	-60.4	4.0	2.6
Miocene Intrusives W of LOF (41h, i)	355.4	-65.4	13.2	353.7	-60.7	4.0	2.6

Note: Expected directions are calculated from cratonal South America. ΔDx and ΔIx are the uncertainties at 95% confidence of declination and inclination. Thus, the confidence limit generated by the paleopole in direction space is an oval instead of a circle.

cilitate the understanding of the paleomagnetic results in time and space.

The main analysis done in this study is related to the difference between the expected and observed directions for the sampled units. The expected directions from cratonal South America were obtained from the reference paleomagnetic pole by Vilas and Valencio (1978), McElhinny (1979), Schultz and Guerreiro (1980), Irving and Irving (1982), Bellieni *et al.* (1983) and Valencio *et al.* (1983). The expected and observed directions are presented in Table 3. To quantify these comparisons, equations for Rotation (R) and Flattening (F) and their respective confidence limits (ΔR and ΔF) as given by Beck (1980) and modified by Demarest (1983) will be used. R represents the difference between the expected and observed declination of directions of remnant magnetization, and is often taken to reflect the amount of *in situ* rotation that a crustal block in a shear zone has experienced. F measures the difference in expected and observed inclination. Because inclination depends on latitude, F is a measure of relative change in latitude and thus may be used to detect large north-south displacements of crustal blocks. However, other factors besides rotations and translations can affect R and F. For a more complete discussion of the technique see Beck (1980) and Irving (1979).

Results of these analyses are presented in Table 4. Because of the reconnaissance character of this study, only in a few instances can we be confident that geomagnetic secular variation has been averaged to zero. Comparison of expected and observed directions is based on the assumption of a dipole geomagnetic field (Irving, 1964), which may not be necessarily true in all cases. Thus, the observed directions must be used carefully. Granitic rocks in many cases average part of the secular variations within site due to slow cooling, whereas in fast cooling rocks secular variations must be averaged between-site. Thus, the number of sites needed depends on the rock type.

Another result of operating with small data sets is to increase the radius of the circle of confidence about the mean (α_{95}), the radius of 95% of probability defined as:

$$\alpha_{95} = \frac{140}{\sqrt{k/N}}$$

k being the precise parameter and N, the number of measures

Thus, the confidence limits on rotation (ΔR) and flattening (ΔF) for this study tend to be large.

Another difficulty encountered was the missing of tilt corrections. It is normally necessary to correct primary directions of remnant mangetizations for any tilt that the rock mass may have acquired

TABLE 4. ROTATION AND FLATTENING

	R	± ΔR	F	± ΔF
Paleozoic Intrusives west of LOF (38, 39, 44)	-7.5	39.9	+6.3	12.3
Jurassic Rocks west of LOF (24, 15)	-5.0	32.5 ?	-8.2	14.3 ?
Jurassic Rocks east of LOF 28, Host rock)	+53.0	20.6 ?	-18.2	10.7 ?
Cocotué Volcanics (35, 36, 37)	-32.0	34.9	-0.8	14.7
Miocene Intrusives north and west of LOF (5, 6, 7, 8, 14)	+48.6	29.8	+3.5	12.7
Miocene Intrusive and Extrusive north and east of LOF (10, 11, 12, 13a, 13b)	+32.8	25.7	+1.5	11.8
Miocene Intrusive and Extrusive north and east of LOF (10, 11, 12; 13a and 13b corrected for tilt)	+49.9	55.6	+11.9	13.7
Miocene Intrusive center and east of LOF (25	+36.9	18.0 ?	-7.7	10.8 ?
Miocene Intrusive south and west of LOF (41h, 41i)	+1.7	26.8 ?	+4.7	10.8 ?

Note: Rotation (R) and Flattening (F) are calculated according to Beck (1980). Their uncertainties (ΔR and ΔF) at the 95% confidence level are calculated according to Beck (1980) , then according to Demarest (1983). ? indicates uncertainties should not be considered rigurous, because only one or two sites were used.

after it became magnetized. For plutonic rocks or remagnetized rocks of any sort, this may be impossible because, in many cases, evidence of the paleohorizontal is lacking. Thus, the F and R values listed in Table 4 may represent undetected tilt in some cases, rather than true rotation and translation, as described earlier.

PALEOZOIC INTRUSIVES

Five sites from well dated upper Paleozoic intrusives were sampled from the shores of Lagos Riñihue and Ranco, and only the three sites collected close to Lago Ranco yielded stable single magnetizations (Category A). Two of these have reverse polarity and no control of the paleohorizontal was obtained from these intrusives. Pilot demagnetization using AF and thermal methods on comparable samples revealed no systematic differences, so AF was used. However, thermal demagnetization gave information about blocking temperature spectra. For this group, some rocks present a single component of magnetization and others present two or more, but in all a single primary component can be isolated. In general, between 0 and 20 mT a small component, probably VRM, is removed. Between 20 and 100 mT, single components are isolated, showing high coercity with a median destructive field (MDF) between 40 and 60 mT. (MDF is the

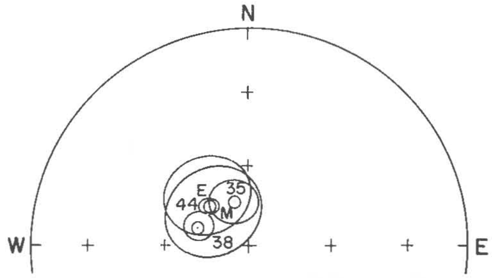


FIG. 4. Stereographic projection for the Paleozoic Intrusives. Mean direction for each site is labeled with site number, group mean direction (M), and expected direction (E). Included are respective circles of confidence (α_{95}).

AF peak in which 50% of the NRM is removed, and it is a rough measure of the stability.)

If directions yielded by these rocks are primary, the problem of paleohorizontal still exists (*e.g.*, Beck *et al.*, 1981). As shown in Table 4, the unit mean direction presents small values of counterclockwise rotation and northward translation, neither significant at the 95% probability level. Figure 4 shows the mean direction for the sites, the unit and the expected direction with their confidence limits. This means that no difference between observed and expected directions exists. This is an important result in that it seems to "tie" a large portion of the sampling area to the South American craton since late Paleozoic time.

JURASSIC ROCKS AND ROCKS WITH JURASSIC REMAGNETIZATION

Eight sites were collected in this group, four from the Panguipulli Batholith, three from the Panguipulli Formation, and one from an isolated Jurassic intrusive east of the LOF. Only sites CJ15 (Category B), CJ24 (Categories A and B) and CJ28 (Category A) have acceptable results. CJ15 is a metasandstone from the Panguipulli Formation, and it was demagnetized using both thermal and AF processes. AF demagnetization between 0 and 170 mT removed less than 40% of the NRM and produced erratic changes in magnetization, probably due to noise caused by low magnetic moment (10^{-3} A/m). Thermal demagnetization shows that more than 95% of the NRM was erased at temperatures between 300 and 350°C. The directions derived from AF and thermal were very similar. The magnetic bahaviour suggests that pyrrhotite is the main magnetic mineral. CJ24 is a grandiorite from the Panguipulli Batholith. AF demagnetization shows that a small low coercivity component is completely demagnetized by 20 mT; thereafter to 100 mT, where less than 10% of the NRM remains, a single component of magnetization is removed. Site CJ28 includes samples from a granodioritic host rock and a dacitic dike which intrudes it. The host rock has reverse polarity whereas the dike is normal. This indicates that the host rock has not been remagnetized by the dike; unfortunately, however, there is no information about the age of the dike. The host rock has a MDF between 20 and 100 mT.

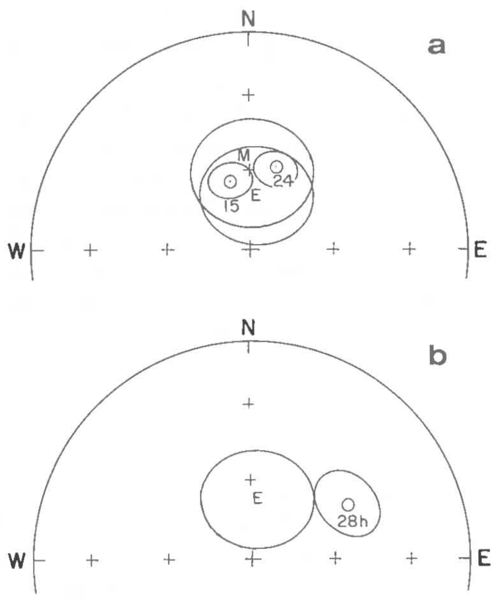


FIG. 5. Stereographic projection for Jurassic rocks and rocks with Jurassic remagnetization. a. Subgroup **i**, west of LOF; b. Subgroup **ii**, composed by only one site, east of LOF. M is the mean direction; E is the expected direction and the circles are α_{95}.

These three sites were divided into two subgroups: **i.** CJ15 and CJ24, located west of the LOF; and **ii.** CJ28, east of the LOF. In the first, these two sites have significantly different directions (using method of McFadden, 1982), so the mean direction was averaged giving unit weight to each site. The average suggests small amounts of counterclockwise rotation and negative flattening, indicating southward translation. However, the significance of R and F cannot be determined because α_{95} cannot be estimated accurately from only two sites. Figure 5a shows the site-mean direction, their mean and the expected direction. As with the Paleozoic intrusives, no difference between observed and expected is apparent. Subgroup **ii.** yields clockwise rotation and negative flattening values, again indicating southward translation. Figure 5b indicates that the discrepancy between observed and expected directions may be significant, although the validity of this result may be questioned because one site is involved.

MIOCENE INTRUSIVES

Seven from fourteen sites in upper Tertiary plutons gave reliable information. CJ05, CJ06, CJ07, CJ08 and CJ14 belong to Category B. All but CJ14 are located east of Villarrica and are coarse grained intrusives. CJ05 and CJ06 have normal polarity; CJ07, CJ08 and CJ14 are reverse. CJ05, CJ06, CJ07 and CJ08 have a low coercivity component, probably a VRM. Approximately 80% of the NRM belongs to this low coercivity component which is removed by AF demagnetization between 0 and 30 mT. Single components were obtained between 20 and 100 mT. In general, orthogonal plots are fairly jagged due to noise in the measurements and spurious remagnetizations. CJ14 shows a higher MDF than the other Miocene pluton sites, but it too has erratic magnetizations due to noise, probably caused by weak magnetization.

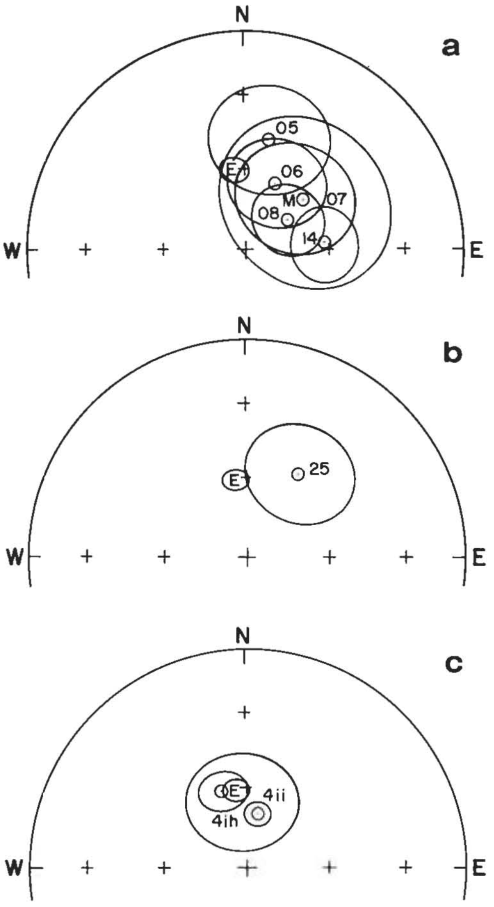


FIG. 6. Stereographic projection for Miocene Intrusives. a. Group of sites north of the study area and west of the LOF; b. Group of site CJ25, east of the LOF; c. Group of site CJ41, west of LOF. M is the mean direction, and E, the expected direction and the circles are α_{95}.

CJ41 and CJ13 are two sites of this rock group belonging to Category A. CJ41 was obtained from the northwest shore of Lago Maihue and shows two polarities, both with high intensities and high coercivities. CJ13 is a coarse tonalite east of LOF and east of Lago Villarrica. It also shows two polarities, the older one shows up clearly after AF demagnetization over 40 mT, which removes more than the 90% of the NRM. The older magnetization is reversed and the younger is normal. Possibly this site could represent a self-reverse (Irving, 1964). CJ25 is a diorite which has behaviour similar to CJ15; high coercivity after AF demagnetization, and complete demagnetization at temperature between 300° and 400°C, indicating that pyrrhotite is the main magnetite mineral. However, a component trending towards the origin was isolated betwen 30 and 60 mT.

The group formed by CJ05, CJ06, CJ07, CJ08 and CJ14 is located west of LOF in the north of the study area. It indicates clockwise rotation of about 44°, with a small and unsignificant northward translation (Fig. 6a). Due to the number of sites and the slow cooling of the granite rock, secular variation is probably averaged adequately.

The second group is CJ25 (Fig. 6b) alone, which is located in the north-central zone, east of LOF. It shows clockwise rotation and negative flattening. This site probably does not average secular variation, but the trend here is clearly toward clockwise rotation. The last group consists of site CJ41 (Fig. 6c), west of LOF in the central zone of study area, which spanned two intrusives and recorded two polarities. The mean of the section yielded a small clockwise rotation and positive flattening, indicating northward translation. However, the statistical significance of R and F is impossible to determine from only two sites.

MIOCENE EXTRUSIVES

Six sites assigned to the Curarrehue Formation yielded Miocene K-Ar ages. These sites are gathered into two groups: the first group, from east of Lago Villarrica CJ10-11-12 (Category A) are dacite and rhyolite. They were demagnetized by both, thermal and AF. CJ10 and CJ12 have normal polarity and CJ11 has reverse. These three sites were corrected for tilting, but a fold test (for pre-folding magnetization; Graham, 1949) was inconclusive. These three sites are characterized by high coercivities, high magnetic moment and high blocking temperatures. MDF is about 60 mT and single components of magnetization are isolated between 20 and 100 mT.

Of the second group, east of Lago Ranco, only CJ43 gave reliable results. Thermal demagnetization shows a smooth decay between 0 and 580°C, indicating a broad spectrum of blocking temperatures. However, the distribution of sample directions from this site was streaked and this site had to be eliminated because it would not be showing a single paleomagnetic field direction.

The first group close to Lago Villarrica, plus the site from Miocene intrusive CJ13 (a and b) were gathered in the same group. The three lava flows

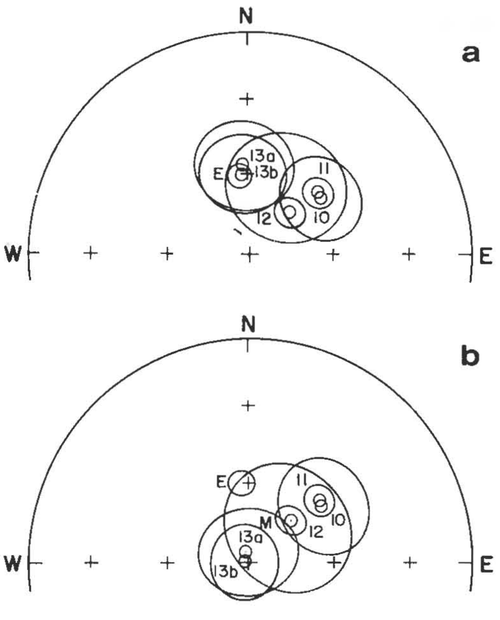


FIG. 7. Stereographic projection for Miocene Extrusives plus CJ13, an intrusive associated to them. a. Group with CJ13 uncorrected for regional tilt; b. The same group with CJ13 corrected for tilt. M is the mean direction; E is the expected direction and included are circles of confidence (α_{95}).

from the Miocene extrusives have been corrected for tilt, and CJ13 was added, first without tilt correction (Fig. 7a) and second with the same regional tilt as CJ11 and CJ12 (Fig. 7b). In both cases, clockwise rotations and positive flattening are predominant.

COCOTUE BEACH BASALTS

These sites (18 cores) were sampled from this basaltic unit on the northwest tip of Chiloé. Thermal and AF demagnetization was carried out on these specimens. The three sites belong to Category A. Sites CJ35 and CJ36 behave similarly, showing a single component of magnetization between 20 and 100 mT, and 110-530°C. A VRM component is erased between 0 and 20 mT, and 0-110°C. These two sites have high coercivities and very strong magnetization (10^{-1} to 1 A/m). Site CJ37 presents two components, one with high coercivity and low unblocking temperature, and another with low coercivity and high unblocking temperature. The latter component seems to be the primary since it is concordant with the directions given by CJ35 and CJ36.

Using the method of McFadden (1982) it appears that these three sites were magnetized independently. Thus, the mean of site-means must average at least some of secular variation (Fig. 8). The computations of R and F (Table 4) give a counterclockwise rotation and almost no flattening. However, R and F in this unit may not reflect true block displacement, because a slight tilting recognized in these rocks has not been eliminated. Also, the paleopole for 40 Ma was obtained from the North American APWP by rotating into the South American reference frame using Euler poles given by Engebretson *et al.* (1985); this may also lead to some error. A new K-Ar age of 21.7 ± 1.7 Ma is given in this study. The pole for 20 Ma is close to the 40 Ma one used above, so the computations of R and F for 40 Ma and 20 Ma are not very different.

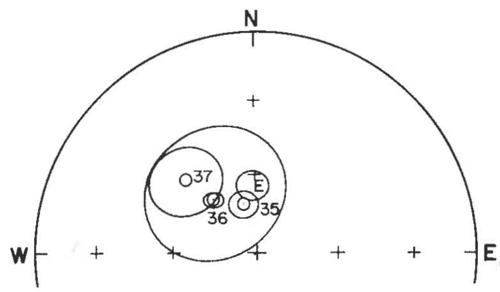


FIG. 8. Stereographic projection for Cocotué Beach Basalts. M is the mean direction; E is the expected direction and included one respective circles of confidence (α_{95}).

INTERPRETATION

The rotations, flattening and their confidence limits given in Table 4 and the analysis of the paleomagnetic data indicate that both counterclockwise and clockwise rotations are present in the area. Figure 9 shows the geographic relationship between rotations and translations of the units. Figure 10 shows R as a function of outcrop proximity to the LOF. From these figures and data, it appears that east of the LOF, rocks show uniform clockwise rotation. Large southward transport is suggested by two groups, and a small northward translation in a more reliable group farthest north. The two groups which show southward translation contain only one site each, so their flattening has very large error and may be spurious; very probably inadequately averaged secular variation is to blame. The northern group is more reliable than the other two. Also this group has a fairly good paleohorizontal control. It shows positive F and positive R, both corrected and uncorrected for tilting.

West of the LOF, the situation is different. Three groups show counterclockwise rotation, two of them with small angles, less than 8°, in a location close to the LOF and a third group in Chiloé Island presents counterclockwise rotation of around 30°. However, as mentioned earlier, this counteclockwise rotation could be affected by undetected tilting and inaccuracy in the reference paleopole. Two other groups present clockwise rotations, one small and the other large. Four of these groups of rocks indicate northward translation in different amounts ranging up to 7°. Only one group has negative flattening (southward translation). In general, this side of the fault shows consistent northward translation with negligible rotations. Figure 10 shows that proximity to the fault correlates with larger clockwise rotations. The Cocotué Beach volcanics show a counterclockwise rotation unique to rocks west of the LOF. However, this may not be real.

The groups range in age from 25 to 4 Ma. If rotations are due to faulting, then the movement of the fault is as late as 4 Ma. This is another important result.

If the dominance of positive F west of the fault is real, there has been northward motion of the western block relative to the South American craton. This indicates that the fault has a dextral strike-slip motion, which is consistent with clockwise rotations near the fault and with geological observations.

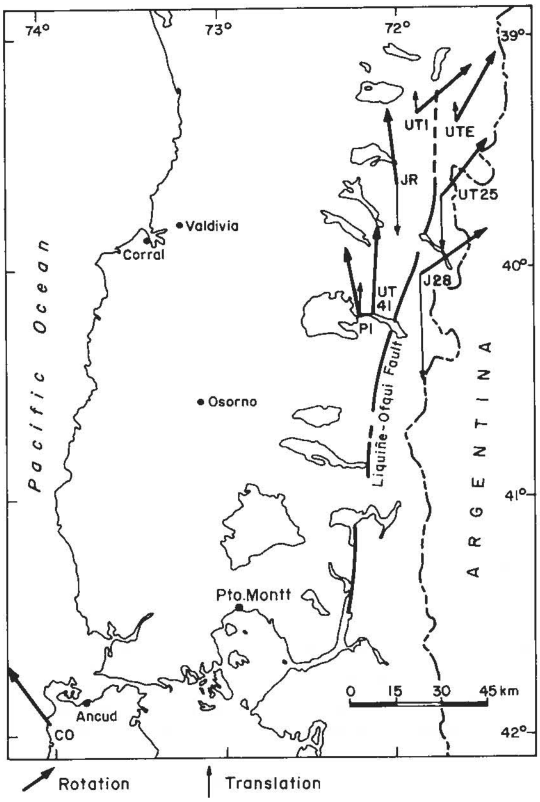


FIG. 9. Rotations and translations for each group. Thick arrow is rotation measured from the vertical (N). Thin arrow is translation, northward (up) and southward (down). The amount of F is given by the length of the thin arrow (degree *ca.* 0.8 mm). The groups are: PI. Paleozoic Intrusives; JR. Jurassic rocks west of the LOF; J28. Jurassic intrusive east of the LOF, CJ28; UTI. Upper Tertiary Intrusive west of the LOF; UT41. Upper Tertiary Intrusive, CJ41); UT25. Upper Tertiary Intrusive east of the LOF, CJ25; UTE. Upper Tertiary Extrusives plus CJ13; CO. Cocotué Beach Basalts.

TECTONIC SUMMARY

The aim of the study was to make a paleomagnetic reconnaissance and relate it to the geology and tectonics of the area. From the results described above, several major conclusions can be deduced. However, these conclusions have to be regarded as tentative because of the reconnaissance character of the study. Many possible errors may be associated with the results, most of them arising from the small number of sites per group, the likelihood that secular variation has not been averaged to zero, and the lack of control of paleohorizontal in most of the sites. Also, not all sites have yielded reliable magnetic directions. Taking into account these sources of errors, several tectonic conclusions may be suggested.

The LOF may be a major intracontinental shear zone, possibly related to oblique subduction of the Nazca plate and under South America. This hypo-

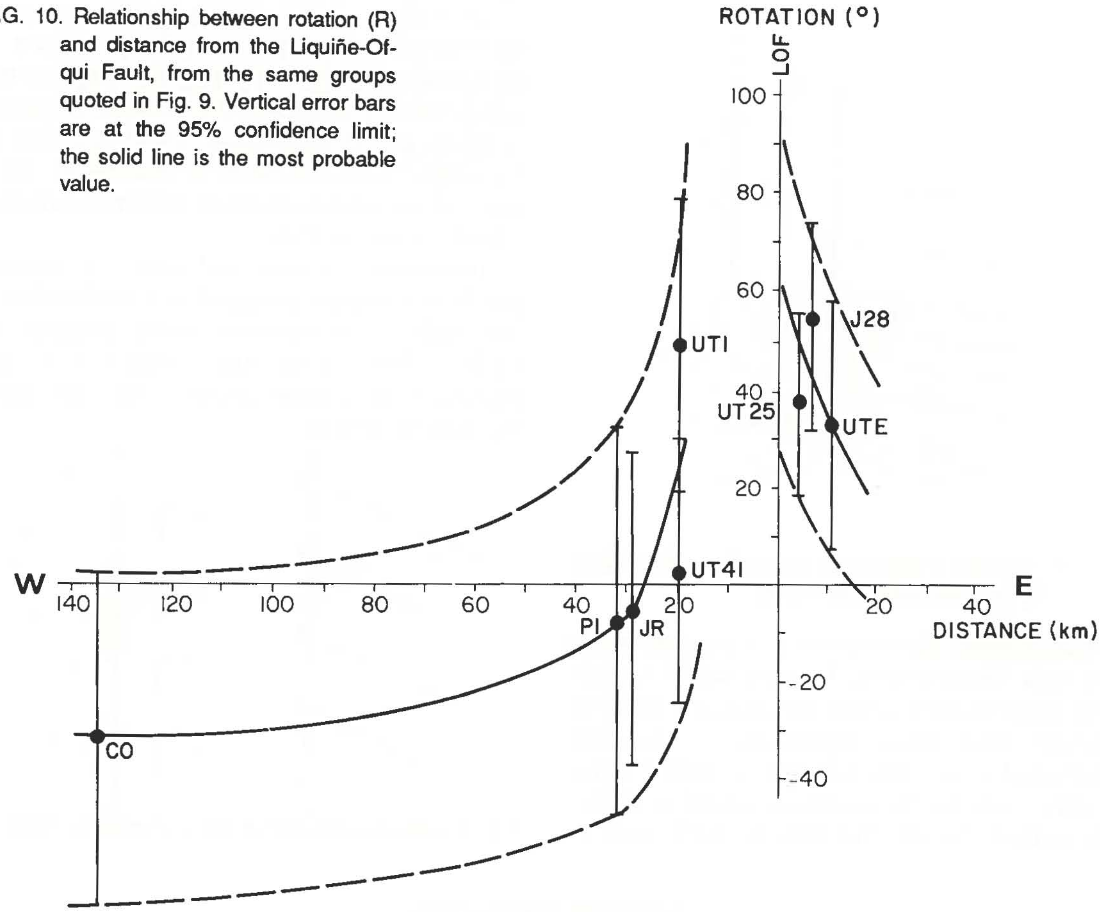


FIG. 10. Relationship between rotation (R) and distance from the Liquiñe-Ofqui Fault, from the same groups quoted in Fig. 9. Vertical error bars are at the 95% confidence limit; the solid line is the most probable value.

thesis has been presented by Hervé (1976) and Beck (1988). It is consistent with the plate reconstructions presented by Pilger (1983) who showed that an oblique convergence vector existed along the Chilean margin during the last 50 Ma. The present study suggests clockwise rotations of the group of rocks near the LOF. These clockwise rotations indicate dextral shear. The presence of a component of northward translation in rocks west of the LOF larger than those to the east suggests that the western block has had northward relative motion, supporting dextral strike-slip displacement. The indenter model of Forsythe and Nelson (1985) also calls for northward motion of this western area, their Chiloé Block. According to the data presented here the northward motion of the western block is about 4° or 5°, *i.e.* approximately between 440 and 550 km. The eastern block has no well defined movement. Two of the groups are probably tilted. This supposition is based on the assumption of a static position of the eastern block relative to South America. If the block has not moved, the apparent translations suggested by large F values may indicate tilt.

The age of movement of the LOF found in this study does not match the one given by Hervé (1976). He indicated that geological evidence shows that the last movement took place during Late Cretaceous-early Tertiary. The paleomagnetic evidence suggests that the fault was still active during the Late Miocene or Early Pliocene. Figure 10 shows that clockwise rotation increases near the fault. The different amount of rotation for each group suggests that small crustal blocks moved independently in a distributed shear zone.

The Miocene was a period of intensive magmatic activity. Munizaga *et al.* (1984) indicated that large plutons were intruded around the fault during the

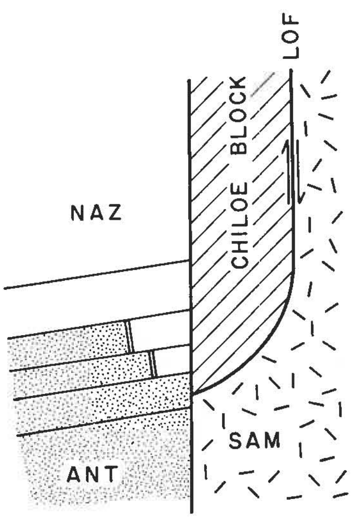


FIG. 11. Indenter model for the Liquiñe-Ofqui Fault, given by Forsythe and Nelson (1985).

Miocene. Now, the evidence of movement during the Late Miocene-Early Pliocene would suggest that these plutonic pulses accompanied fault movement since shear concentrates in thermally weakened crust. The evidence of dextral shear matches with the two models suggested to explain the origin of the LOF. The indenter model given by Forsythe and Nelson (1985) and the oblique subduction model presented by Beck (1988) are shown in Figs. 11 and 12, respectively. However, the indenter model does not explain why there is not a symmetric equivalent of the LOF south of the triple junction. Another argument against the indenter theory is that the collision of the Chile Rise to the coast of Golfo de Penas is very recent and it could not alone produce 400 or 500 km of displacement in the last 2 or 3 Ma.

Nevertheless, it must be taken into account that the LOF may be generated by a combination of both models. The combined stress produced by the Chile Rise and the Nazca plate, only in Late Pliocene in its present position, may have been the cause of the fault.

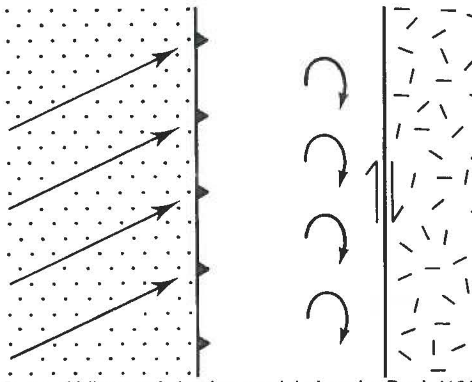


FIG. 12. Oblique subduction model given by Beck (1988).

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