Paleomagnetism of probably remagnetized late Mesozoic volcanic rocks near Lago Verde, Aisén, Southern Chile

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ABSTRACT

Paleomagnetic data were obtained for 12 sites in gently dipping, fresh to slightly altered volcanic and volcaniclastic rocks near Lago Verde, Aisén Province, Southern Chile. Similar directions found in high and low stability magnetite and pyrrhotite, plus increase in dispersion upon correcting for tilt, suggest that the remanence is a post-tilting secondary magnetization. It is uncertain whether the rocks sampled are correlative with nearby exposures of the Ibáñez Group (Jurassic), or the Divisadero Group (early to middle Cretaceous). However, intrusion of rocks of the Patagonian batholith, a likely cause of remagnetization, is well dated at about 90 Ma. Compared to a new 90 Ma reference pole, the Lago Verde result indicates that the area has been rotated about 17° clockwise, with no significant latitudinal displacement. This result is similar to results of other nearby paleomagnetic investigations east of the Liquiñe-Ofqui Fault.

Key words: Paleomagnetism, Tectonics, Lago Verde, Chile.

RESUMEN

Paleomagnetismo de rocas volcánicas del Mesozoico superior probablemente remagnetizadas, cerca de Lago Verde,Región de Aisén, sur de Chile. Se obtuvo información de paleomagnetismo en 12 sitios de las rocas volcánicas y volcanoclásticas de los alrededores de Lago Verde. Estas rocas tienen manteos suaves y están frescas a levemente alteradas. Tanto el hecho de observarse direcciones similares en magnetita como pirrotina, de alta y baja estabilidad magnética respectivamente, como el aumento de la dispersión con la corrección por manteo, sugieren que la remanencia es una remagnetización secundaria posterior a la inclinación de las capas. No es seguro si las rocas estudiadas corresponden al Grupo Ibáñez (Jurásico) o al Grupo Divisadero (Cretácico inferior a medio). Sin embargo, la intrusión del batolito patagónico, una probable causante de la remagnetización, están bien datada en *ca.* 90 Ma. Comparado a un nuevo polo de referencia de 90 Ma, los resultados de Lago Verde indican una rotación horaria de alrededor de 17°, sin desplazamiento latitudinal significativo. Este resultado es comparable con aquél de otros estudios paleomagnéticos en áreas vecinas al este de la Zona de Falla Liquiñe-Ofqui.

Palabras claves: Paleomagnetismo, Tectonics, Lago Verde, Chile.

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INTRODUCTION

Paleomagnetic investigations have added a new dimension to the study of the tectonics of the Andes. Most such work has been concentrated in the Central Andes of Peru, Northern Chile and neighboring sections of Argentina and Bolivia (reviews in Beck, 1998; Somoza *et al.*, 1996; Beck *et al.*, 1994; Roperch and Carlier, 1992; Beck, 1988). These central Andean paleomagnetic studies show a pattern of crustal block rotations clearly related to the abrupt change in geographic and tectonic trends that occur near Arica, Northern Chile (the Arica Deflection). Rotations are nearly all counterclockwise north of Arica and clockwise farther south. Much debate has centered on the origin of these central Andean rotations. which have been attributed to oroclinal bending (Heki *et al.*, 1984; Isacks, 1988), local rotations driven by oblique subduction (Beck, 1987), extension driven by oblique-rollback during subduction (Hartley *et al.*, 1992) and a combination of oroclinal bending and shear-driven local block rotations (Beck *et al.*, 1994). Despite much effort, the question of the cause of rotations in the central Andes is still open.

Rotations have also been reported in the south of Chile (García *et al.*, 1988; Cembrano *et al.*, 1992; Beck *et al.*, 1993; Rojas *et al.*, 1994). For the most part these rotations are small (less than a few tens of degrees) and seem to be related to the Liquiñe-Ofqui Fault (Cembrano *et al.*, 1996). Rotations are clockwise east of the Liquiñe-Ofqui Fault Zone (LOFZ), but counterclockwise on its west side.

In this paper the authors report on paleomagnetic data acquired from an area immediately east of the LOFZ. Paleomagnetic sampling accompanied mapping described by Steele (1995). Although the Lago Verde rocks probably have been remagnetized, the time of remagnetization can be estimated. The rocks yield a well-defined mean direction and paleomagnetic pole position. Postmagnetization structural complications appear to be minimal. Although there are problems with the time of magnetization, the data seem to indicate that the region has experienced a small (15-20°) clockwise rotation.

EXPERIMENTAL PROCEDURES AND RESULTS

Oriented samples were obtained at 14 sites east and north of Lago Verde (Fig. 1). From four to eight samples/site were collected by *in situ* drilling; samples were oriented by means of a combination solar/ magnetic compass. In the laboratory pairs of specimens from one or two sample/ site were chosen for pilot magnetic cleaning (eight to ten steps), by alternating field (a.f.) demagnetization to 100 mT and by thermal demagnetization to 675°C. After pilot demagnetization the more effective of the two methods was used to magnetically clean the remaining samples in the site. In most cases, the two methods yielded closely similar results, in which case the quicker method (a.f.) was used. Sample directions were determined by fitting anchored lines to the demagnetization data (Kirschvink, 1980). Mean directions and corresponding virtual geomagnetic poles (VGPs) were calculated following Fisher (1953).

For the most part the magnetizations decayed in a straight line toward the origin, after a small amount of soft secondary magnetization was removed (Fig. 2). Figure 3 shows the range of unblocking temperature and coercivity spectra observed. The square shoulder curve at the top from thermal demagnetization of site 12 combined with high coercivity suggests the predominance of stably magnetized magnetite. The sharp drop in remanence between 320° and 380°C and even higher coercivity suggest that pyrrhotite may carry about half the remanence in site 17. The distributed unblocking temperatures and low coercivity for site 10 indicates potentially poorer stability of remanence. However, all three sites have very similar mean directions, consistent with simultaneous (re)magnetization. Most site-mean directions were well-defined, although two sites (15 and I9) were discarded because of high within-site scatter (α_{95}> 20°). Additional details of laboratory methods are given in Steele (1995). Results are summarized in table 1.

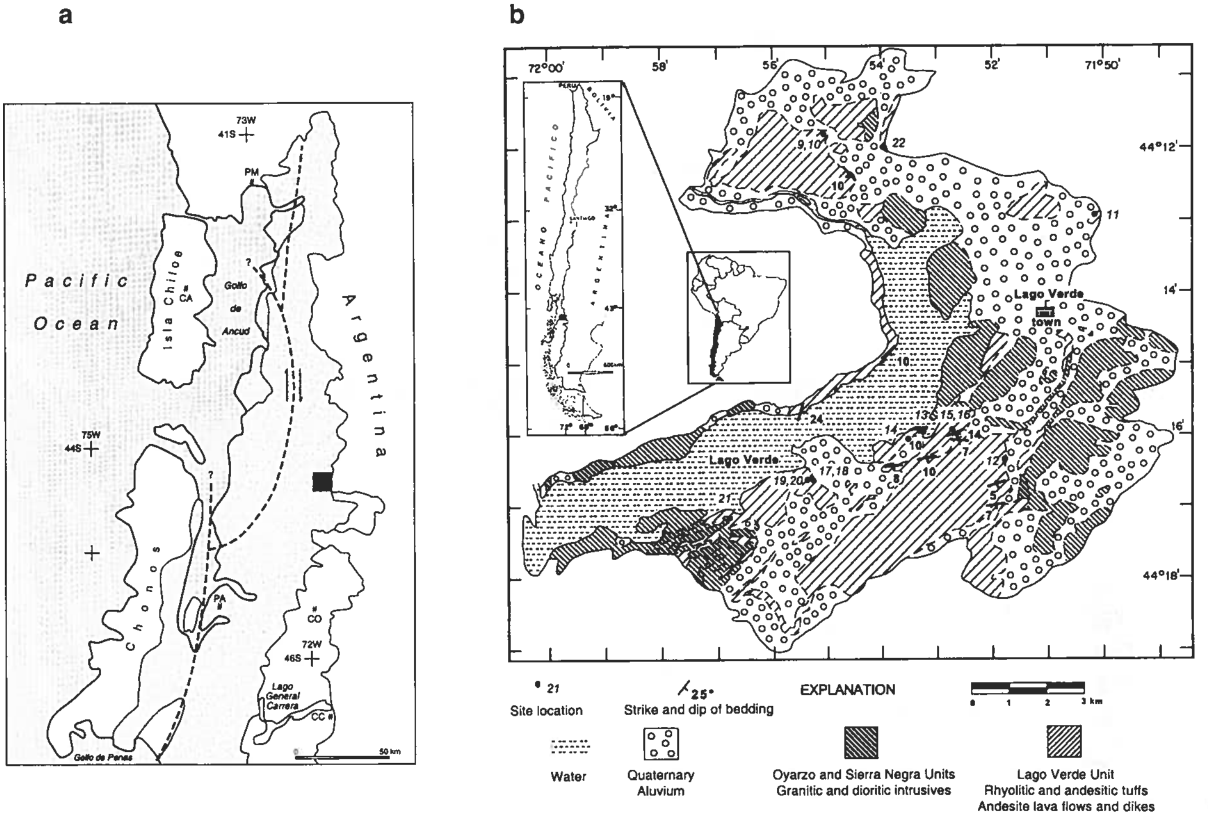

FIG. 1. a- location map. Lago Verde area is shown by large square. Dashed line is trace of Liquiñe-Ofqui Fault Zone, modified after Cembrano *et al.* (1996). Stippled pattern is the northern Patagonian Batholith; **CA-** Castro; **CC-** Chile Chico; **CO-** Coihaique; **PA-** Puerto Aisén; **PM-** Puerto Montt; **b-** geology of the Lago Verde area, modified after Steele (1995).

TABLE 1. DIRECTIONS OF REMANENT MAGNETIZATION IN LATE MESOZOIC VOLCANIC ROCKS FROM THE LAGO VERDE AREA, SOUTHERN CHILE.

Site	Dec-u	Inc-u	Dec-c	Inc-c	N	k	α_{95}	Demag
93bs09	20.6	-75.3	30.2	-65.8	5	34.5	13.2	25-95 af
10	6.5	-65.0	16.4	-56.6	8	13.3	15.8	20-95 af
11	13.6	-73.6	25.0	-64.5	7	20.5	13.7	20-100 af
12	9.7	-63.8	3.1	-55.7	7	260.0	3.8	25-100 af
13	359.0	-58.8	355.5	-50.2	6	203.2	4.7	25-100 af
14	358.7	-47.3	356.3	-38.7	6	49.9	9.6	25-100 af
16	6.8	-51.4	2.9	-43.2	6	94.2	6.9	260-575 T
17	11.7	-60.4	5.4	-52.4	6	151.3	5.5	260-360 T
18	17.2	-53.8	11.3	-46.3	6	30.9	12.2	30-100 af
20	353.5	-56.1	351.2	-47.3	6	281.7	4.0	30-100 af
21	47.4	-64.1	32.9	-59.4	4	300.2	5.3	30-100 af
22	11.2	-75.9	359.8	-67.7	5	171.0	5.9	180-380 T

Dec, Inc are mean declination and inclination for site. u,c represents the direction uncorrected for tilt and corrected for tilt, respectively. **N-** number of samples/site. k, α_{95} are the precision parameter of Fisher (1953) and the radius of the circle of 95% confidence, respectively. Last column gives the range of alternating field (af) or thermal (T) demagnetization used to determine the site-mean direction; af in mT, T in degrees Celsius.

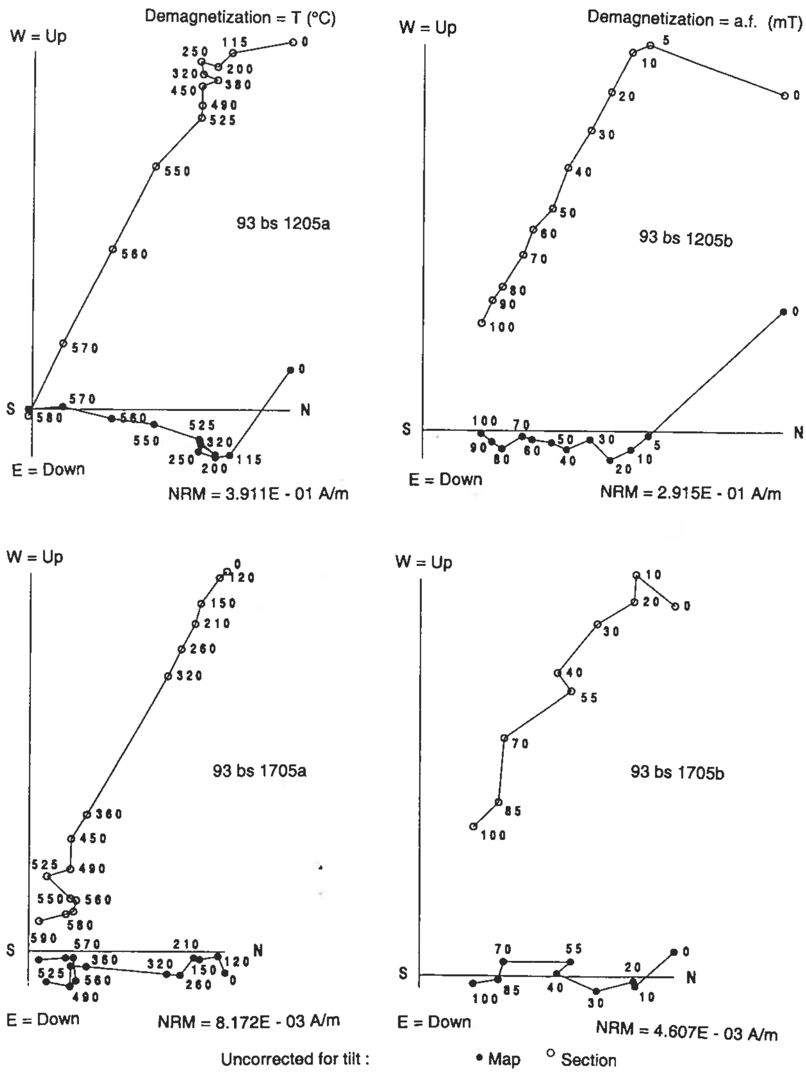

FIG. 2. Orthogonal diagrams showing linear thermal (left column) and alternating field (right column) demagnetization paths for magnetite- (top) and magnetite plus pyrrhotite- (bottom) bearing pilot samples. The lower intensity of magnetization for the pyrrhotite-bearing sample may be due to destruction and replacement of most of the magnetite during metamorphism.

ANALYSIS OF PALEOMAGNETIC DIRECTIONS

Site-mean directions before (a) and after (b) correction for observed tilt are shown in figure 4. Dips in the field area are quite gentle, so it was not possible to obtain a definitive fold test. However, as shown in table 2, directional scatter increases marginally when the tilt-correction is applied.

As discussed in Steele (1995), the correct correlation of the igneous rocks near Lago Verde is difficult to determine. However, they are lithologically similar to rocks of the Ibáñez and Divisadero Groups that crop out nearby.

The Ibáñez and Divisadero Groups are described in detail by Niemeyer *et al.* (1984), based on exposures in the general Coihaique-Lago General Carrera area. Both units are dominantly volcanic, being composed mainly of intermediate lavas, pyroclastic rocks, and volcanogenic sedimentary rocks. The Lago Verde exposures are included by

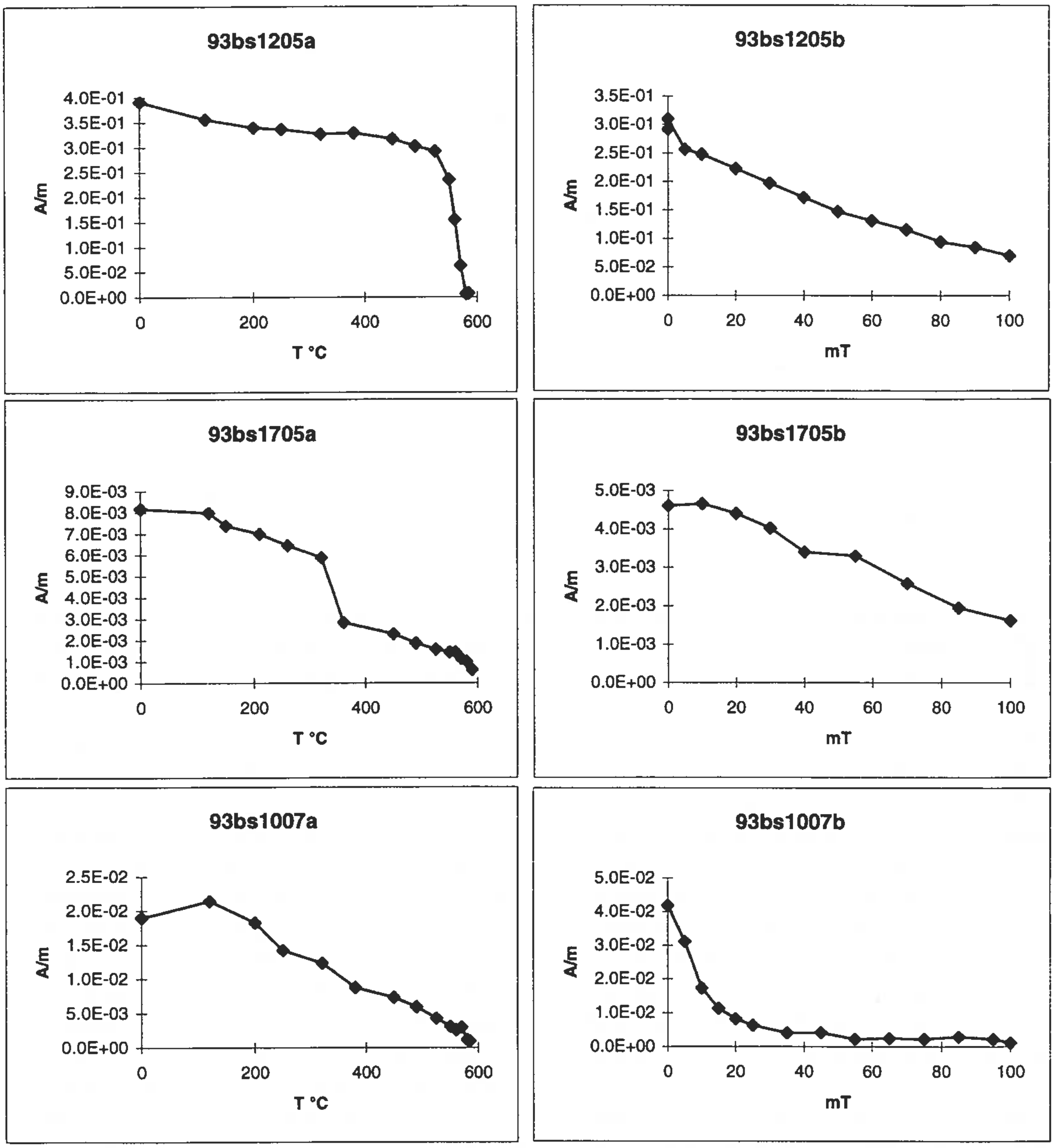

FIG. 3. Intensity *versus* demagnetization diagrams showing the range of behavior in the Lago Verde sites. Site 12 exhibits unblocking of the remanence near the Curie temperature of magnetite, and fairly high resistance to alternating field demagnetization. Site 17 shows a sharp drop in intensity around 340°C plus higher stability to alternating field demagnetization, both consistent with pyrrhotite carrying about half of the remanence. Site 10 shows distributed thermal unblocking and a pronounced concave upward alternating field demagnetization curve suggestive of poorly stable coarse-grained magnetite. Abbreviations as in figure 2.

TABLE 2. MEAN DIRECTIONS AND PALEOMAGNETIC POLES, LAGO VERDE ROCKS.

	Dec	Inc	k	α_{95}	Lat-S	Long-E
Uncorrected	9.7	-62.8	51.3	6.1	82.6	211.1
Corrected	7.4	-54.7	45.0	6.5	79.8	148.8

For Dec, Inc, k, α_{95} see table 1. Lat-S, Long-E are latitude and longitude of paleomagnetic pole in degrees.

Pankhurst *et al.* (1998) in a western belt of their Chon Aike province, which extends throughout Patagonia and West Antarctica. They regarded the Chon Aike rocks as a silicic 'large igneous province', probably created by partial melting of the continental crust by heat derived from basaltic magma introduced into the lower crust during continental extension.

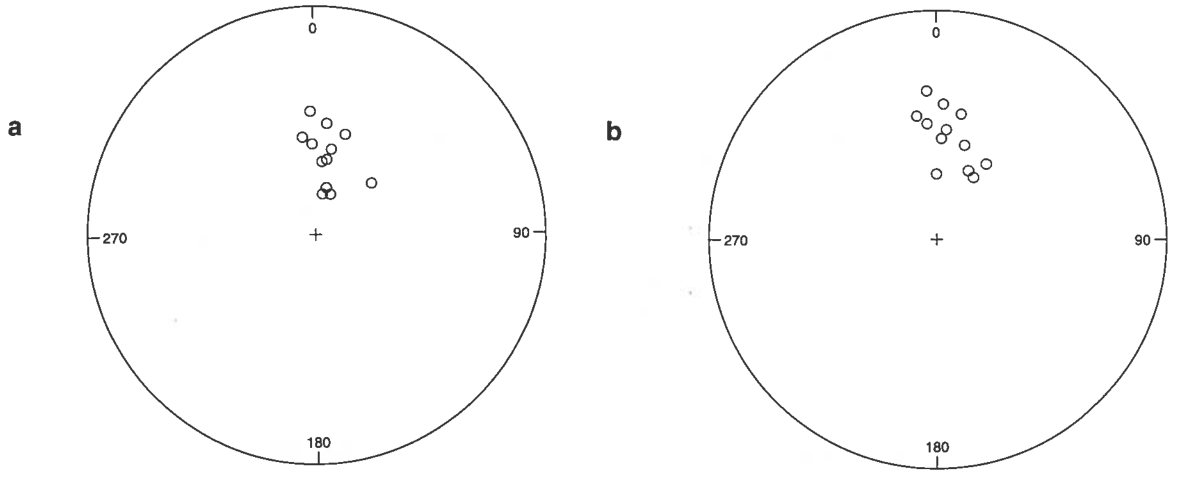

FIG. 4. Equal-area projection of site-mean directions of remanent magnetization for Lago Verde rocks before **(a)** and after **(b)** correction for tilt. All sites have normal polarity.

According to Niemeyer *et al.* (1984) and other authors, the Ibañez Group is Middle and Late Jurassic in age, whereas the Divisadero Group is Lower Cretaceous. In places, a Late Jurassic-Early Cretaceous sedimentary unit, the Coihaique Group, is present between Ibáñez and Divisadero volcanic rocks. The latter two units are quite similar lithologically and for this reason the Coihaique Group, where present, serves as an important stratigraphic marker. However, sedimentary rocks are not present in the Lago Verde area, so it is uncertain with which of the two volcanic units the local rocks should be correlated. The fact that Lago Verde rocks are intruded by rocks of the (mid-Cretaceous and younger) Patagonian batholith provides a younger age limit.

The observation that all sites sampled near Lago Verde have normal polarity is important. If the magnetization found in these rocks is primary (that is, was acquired at the time the rocks first formed), then it should date to sometime during the interval Middle Jurassic-middle Cretaceous (160-100 Ma). However, during most of that interval the earth's magnetic field underwent frequent reversals of polarity. Although there were periods of constant normal polarity during the Jurassic and early Cretaceous that approached 4 m.y. in length (Gradstein *et al.*, 1994), the probability that a thick suite of volcanic rocks would obtain a single magnetic polarity prior to about 120 Ma seems small (although of course not negligible). Thus, the explanation that the Lago Verde rocks acquired their magnetization after 120 Ma, during the mid-Cretaceous Normal Superchron is preferred.

If the Lago Verde volcanic rocks obtained their magnetization after 120 Ma, then one of two things must be true. Either the magnetization is primary, and the Lago Verde volcanic sequence belongs to the upper part of the Divisadero Group, or they were remagnetized during emplacement of phases of the Patagonian batholith. As described by Steele (1995), the Lago Verde volcanic rocks were intruded by rocks of the Patagonian batholith that have been dated at 88±2 Ma by R. Pankhurst and F. Hervé (personal communication, 1995). Thus, it is reasonable to suppose that the Lago Verde volcanic rocks acquired their remanent magnetization at about 88 Ma, because of reheating, chemical alteration, or both. The remagnetization scenario is supported by local evidence of moderately intense alteration and incipient greenschist metamorphism (Steele, 1995; Aguirre *et al.*, 1997). Remagnetization after tilting is suggested by the fact (Table 2) that scatter increases slightly when the tilt correction is applied. Thus, the remanent magnetization of the Lago Verde volcanic rocks is tentatively regarded as a post-tilting remagnetization, acquired at about 90 Ma.

INTERPRETATION

One important use that can be made of the Lago Verde paleomagnetic result is to determine whether the sampling area has been displaced (moved latitudinally and/or rotated) with respect to stable South America since the rocks acquired their remanent magnetization. To do this requires a reliable 90 Ma reference pole for the South American continent. As discussed by several authors (*e.g.*, Beck, 1988; Roperch and Carlier, 1992), this poses a problem.

Although there is no highly reliable 90 Ma reference pole, other late Mesozoic reference poles for South America that the authors consider particularly reliable are available; these are listed in table 3 and plotted in figure 5. For a description and justification of the criteria used in the selection of these reference poles, see Beck (1998).

From figure 5 several things are obvious: **1-** there was little apparent polar wander (APW) with respect to South America during the interval 165 to 70 Ma; the 165 and 70 Ma poles are only about 13° apart. This means that an incorrect choice of reference pole will not completely invalidate the accompanying tectonic interpretation; **2-** the Lago Verde area is not conspicuously allochthonous with respect to South America. As shown in figure 6, both corrected and uncorrected Lago Verde poles lie within a few tens of degrees of the cluster of late Mesozoic reference poles. Nevertheless, some displacement seems to be indicated.

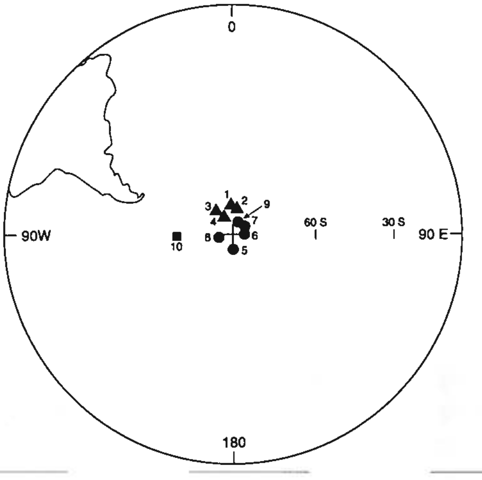

FIG. 5. Southern-hemisphere equal-area projection showing late Mesozoic South American reference poles, keyed to table 3; **triangles-** Late Cretaceous poles; **circles-** Late Jurassic and Early Cretaceous poles. **Black square** is the 200 Ma pole of Macdonald and Opdyke (1974).

TABLE 3. LATE MESOZOIC PALEOMAGNETIC REFERENCE POLES FOR SOUTH AMERICA.

Unit	Age	λ°S	ϕ°E	N	K	α_{95}	Reference
1	70 Ma	78.7	358.4	18	31.6	6.3	Butler *et al.*, 1991
2	75	80.5	6.1	7	64.0	7.6	Montes-Lauar *et al.*, 1995
3	80	79.2	327.6	8	45.0	8.3	Montes-Lauar *et al.*, 1995
4	80	83.1	330.8	-19	77.4	3.8	Montes-Lauar *et al.*, 1995
5	115	84.9	180.8	11	66	5.6	Somoza, 1994
6	125	86.0	75.9	55	35	3.3	Geuna and Vizan, 1998
7	130	84.6	65.9	421	32.2	1.2	See PR, below
8	158	85.3	262.5	15	31.8	6.9	Schult and Guerreiro, 1979
9	165	85.4	19.9	21	31.6	5.7	Vilas, 1974

Units: 1- Patagonian basalts; **2-** Passa Quatro + Itatiaia intrusions; **3-** Sao Sebastiao intrusions; **4-** Poços de Caldas complex; **5-** Cerro Barcino lacustrine and fluvial sedimentary rocks; **6-** Sierra Chica de Córdoba basalts and redbeds; **7-** Parana basin igneous rocks; **8-** Porto Franco volcanic rocks; **9-** Chon Aike Formation (intermediate lavas) - Puerto Deseado and Estancia La Reconquista. **PR-** is a combination of work by Ernesto *et al.* (1990); Raposo and Ernesto (1995), and Ernesto *et al.* (1996); λ, ϕ are latitude and longitude, respectively. **N-** number of independent sites involved in the study; **K-** precision parameter (Fisher, 1953). α_{95}, circle of 95% confidence about the mean pole.

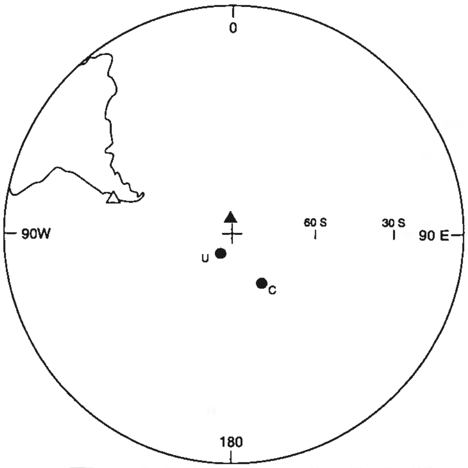

FIG. 6. Solid triangle shows reference pole discussed in the text; circles are Lago Verde poles corrected (C) and uncorrected (U) for tilt. Lago Verde field area shown by open triangle.

The preferred scenario is that the magnetization of the Lago Verde volcanic rocks is secondary, acquired post-tilt at about 90 Ma. Thus, it is necessary to compare the uncorrected pole (Table 2) with a 90 Ma reference for South America.

Beck (1998) recently analyzed South American apparent polar wander for the Late Mesozoic. From about 165 Ma to about 115 Ma a distinct APW stillstand was found, defined by five very tightly grouped, highly reliable paleomagnetic poles. The mean stillstand pole is located at 88.8°S, 72.4°E, with K=244.7 and α_{95}=4.9°. (K and α_{95} are the precision parameter and circle of 95% confidence about the mean pole, calculated by the method of Fisher, 1953). A second tight grouping of four poles defines the Late Cretaceous (80-70 Ma) reference pole; 80.8°S, 346.7° E, K= 457.7, α_{95}= 4.3°. An episode of 9.2° of APW occurred during the interval 115 Ma to 80 Ma.

Thus, to obtain a 90 Ma reference pole for South America, perhaps, the best that can be done is to interpolate between these two well-defined polar clusters; this gives a pole at 84.4°S, 351.6°E. An alternative 90 Ma pole can be calculated by interpolating between the African 80 Ma and 100 Ma poles of Besse and Courtillot (1991), as rotated into South American coordinates by Roperch and Carlier (1992). The two 90 Ma poles are <3° apart. The South American pole is preferred for obvious reasons. Because this 90 Ma reference pole is interpolated, there is no way of estimating its confidence limits; in calculations that follow an arbitrary 10° for α_{95} is used.

Compared to the appropriate 90 Ma reference direction, the mean direction of the Lago Verde rocks (uncorrected for tilt) is rotated 17.0±15.0° clockwise. Error limits on this and subsequent similar calculations are at the 95% probability level (see Beck, (1980) and Demarest (1983)). Expected and observed inclinations are nearly identical, indicating that the Lago Verde area has not moved appreciably north or south with respect to the interior of the South American continent.

Despite several arguments to the contrary, it is possible that the Lago Verde rocks are Ibáñez Group equivalents, hence Middle or Late Jurassic in age, and carry a primary remanence. In that case, the tilt-corrected direction should be compared with an older reference pole. If the magnetization of the Lago Verde rocks is Bathonian, or younger, the stillstand pole given above provides an appropriate reference. Compared to this reference pole the Lago Verde area has experienced a clockwise rotation of 8.4±10.5°. The expected inclination for this calculation is -62.0°, which is significantly different from the observed (tilt-corrected) inclination of -54.7°. As shallower inclinations are encountered at lower latitudes, this result suggests that the Lago Verde area has been displaced southward with respect to the interior of South America.

In this (primary magnetization) scenario, rotation is still clockwise, but only about half the magnitude of the first calculation. However, the inclination anomaly is large and statistically significant. Taken at face value, this result implies a southward displacement of a part of the southern Andes, measured with respect to stable South America, of *ca.* 785 km. In light of results from other continents, particularly western North America, this is not impossible. However, most South American paleomagnetic studies do not find such large latitudinal displacements. Specifically, several studies of rocks of similar age located near the continental margin in northern and central Chile (*e.g.,* Irwin *et al.,* 1987; Forsythe *et al.,* 1987) found no latitudinal displacement. Also, younger rocks studied by Rojas *et al.* (1994) that are located outboard of the Lago Verde area do not appear to have been displaced latitudinally. Thus, if margin-parallel displacement of the Lago Verde area has occurred, it must have been the result of a tectonic process that affected only Chile south of about 34°S at times earlier than mid-Tertiary. While this is not impossible, its likelihood tends to be discounted.

COMPARISON WITH NEARBY AREAS

Cembrano *et al.* (1992) reported paleomagnetic results for nine sites from the Alto Palena Formation, located about 75 km north of Lago Verde. The Alto Palena Formation consists of sedimentary and pyroclastic rocks that are Neocomian in age. Like the Lago Verde volcanic rocks of the present study, the Alto Palena Formation is intruded by rocks of the Patagonian Batholith and probably remagnetized. Unlike the Lago Verde rocks, remagnetization appears to have taken place before tilting. All Alto Palena rocks have normal polarity. The mean VGP after tilt-correction for the Alto Palena rocks is 84.2°S, 159.9°E, with an angle of 95% confidence of 5.5°. Cembrano *et al.* (1992) speculated that the remagnetization occurred at about 100 Ma, although, as there are no dated intrusions nearby, any time during the Cretaceous long normal interval 120 to 80 Ma) probably is possible. On the assumption that the Alto Palena rocks were remagnetized at the same time as the Lago Verde rocks (90 Ma), a clockwise rotation of 13.2° can be calculated. This result is very similar to the one obtained at Lago Verde. However, the mean inclination at Palena is conspicuously shallow, resulting in poleward-transport statistics that are moderately large although not significant (at 95% confidence)-P = 665 ± 1010 km. As in the case of the Lago Verde data, this result tends to be discounted. Perhaps the age of remagnetization is earlier than 90 Ma. For instance, using the 165-115 Ma stillstand pole (which includes the earlier part of the mid-Cretaceous long normal interval) the Alto Palena result is more nearly concordant, with 6.9±7.8° of clockwise rotation and nearly negligible (300±650 km) southward transport. More geochronological data for the area would eliminate this ambiguity.

Earlier, Garcia *et al.* (1988) made a paleomagnetic reconnaissance of the Lake District and found large clockwise rotations immediately east of the Liquiñe-Ofqui Fault, and, for the most part, smaller counterclockwise rotations to the west. One group of Miocene intrusions west of the fault gave a clockwise rotation. Most inclinations measured in these Lake District rocks were concordant. The Lake District study involved many plutons, for which the paleohorizontal is not known. Rojas *et al.* (1994) found counterclockwise rotations west of the Liquiñe Ofqui Fault near Chaitén, Chiloé Province. Rojas *et al.* (1994) and Beck *et al.* (1993) discussed the significance of the pattern of block rotations in Southern Chile.

CONCLUSIONS

Volcanic rocks exposed near Lago Verde, Southern Chile, appear to have been remagnetized by intrusion of plutons of the Patagonian batholith, probably at about 90 Ma. If so, they have been rotated clockwise roughly 15-20°, essentially *in situ*. Because of the proximity of the dextral Liquiñe-Ofqui Fault, it is tempting to attribute the rotation to that feature. However, the Lago Verde field area lies *ca.* 50 to 60 km east of the Liquiñe-Ofqui Fault, and no strike-slip faults are known in the vicinity. Thus, it is suspected that rotation is related to a general state of sub-crustal ductile shear, probably caused by north-oblique subduction of the Nazca plate; if so, the Liquiñe-Ofqui Fault could be merely another manifestation of this state of shear. The small clockwise rotation found by Cembrano *et al.* (1992) at Palena may be caused by the same mechanism; the fact that the Alto Palena rotation is smaller than the Lago Verde rotation could be due to the fact that the former is farther inboard. The suggestion of significant relative southward displacement of the Alto Palena rocks is interesting, but unexplained.

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