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Tectonic controls and Cenozoic magmatism at the Torres del Paine, southern Andes (Chile, 51°10'S)

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ABSTRACT

Five Miocene intrusive complexes are located along the N-trending, nearly trench-parallel San Lorenzo-Balmaceda Lineament in southern Patagonia. These complexes are characterized by mildly alkaline to calc-alkaline magmatism. The deformation and kinematics in the foreland of the granitoid-dominated Torres del Paine laccolith (12±2 Ma) were studied in order to evaluate the influence of the pre- to syn-intrusive crustal stress field on magma emplacement. Compression and transpression led to large-scale folding, with fold wavelength of up to 10 km, and faulting of the Cretaceous flysch sedimentary rocks as well as alkaline gabbro sills. Geochronological data from folded gabbros point to an Oligocene minimum age for regional folding at 29.4±0.8 Ma. Reverse faults and convergent sinistral strike-slip faults occur as well as conjugate reverse faults. The shortening axes trend ENE- to E. These directions correlate with the oblique convergence between the Nazca- and the South America-plate. The magma ascent was parallel to the NNW-SSE striking Lago Grey-fault zone and probably coincides with the fossil intersection of the oceanic Madre de Dios transform fault. The intrusion correlates with a change from transpressional to transtensional dynamics as documented by a kinematic change from left-lateral convergent strike-slip faulting to left-lateral divergent strike-slip faulting. The changes in dynamics and kinematics correlate in time and space with a reorganisation of the plate tectonic situation during the Miocene. After the collision of the Chile ridge, separating the Nazca-plate from Antarctica, the situation in the south-western part of South America changed from rapid ENE-WSW-directed oblique convergence between the Nazca- and South America-plate, to an east-west-directed slow frontal convergence between the Antarctica and South America plates. The observed geometric divergence of the San Lorenzo-Balmaceda lineament and the apparent control of magma ascent through upper crustal faults may be explained by the interpretation of the SLB as a possible large-scale lower crustal strike slip zone and by shear partitioning from lower crust to upper crust.

Key words: Cordillera de los Andes, Torres del Paine, Magmatism, Deformation.

Revista Geológica de Chile, Vol. 30, No. 1, p. 65-81, 5 Figs. 2 tables, July 2003.

RESUMEN

Controles estructurales del magmatismo cenozoico en Torres del Paine, Andes del sur (51°10'S). Cinco complejos intrusivos se sitúan a lo largo del Lineamiento San Lorenzo-Balmaceda, que es paralelo a la fosa oceánica de la Patagonia meridional. Estos complejos se caracterizan por tener un magmatismo levemente alcalino a calcoalcalino. Se estudiaron la deformación y la cinemática en el antepaís del lacolito Torres del Paine dominado por granitoides (12±2Ma) para evaluar la influencia del campo de esfuerzos corticales pre- y synintrusivo en el emplazamiento del magma. La compresión y la transpresión produjeron un plegamiento en gran escala, con pliegue de longitud de onda de hasta 10 km, y un fallamiento del flysch cretácico y de filones de gabro alcalino. La edad (29,4±0,8 Ma) de los gabros apuntan a una edad máxima oligocena para el plegamiento regional. Ocurren fallas inversas y fallas de rumbo convergentes y sinistrales asi como también se conjugan las fallas inversas. El ascenso del magma fue paralelo a la zona de falla Lago Grey de rumbo NNW-SSE,y probablemente coincide con la intersección fósil de la falla transformante oceánica Madre de Dios. La intrusión se correlaciona en el tiempo con un cambio de dinámica transpresional a transtensional documentada por un cambio cinemático de falla de rumbo sinistral convergente a divergente y, en el espacio, con una reorganización de la situación tectónica de placas durante el Mioceno. Después de la colisión de la dorsal de Chile que separa las placa de Nazca y Antártica, la parte suroccidental de Sur América cambió desde una convergencia rápida oblicua de dirección ENE-WSW entre la placa de Nazca y la placa Sudamerica a una convergencia frontal lenta de dirección este-oeste entre las placas Antártica y Sudamerica. La divergencia observada entre el lineamiento San Lorenzo-Balmaceda y el aparente control del ascenso de magmas a través de fallas de la corteza superior puede ser explicada intepretando al SLB como un posible sistema de rumbo de la corteza inferior a gran escala, y por la partición del cizalle entre la corteza inferior y la superior.

Palabras claves: Cordillera de los Andes, Torres del Paine, Magmatismo, Deformación.

INTRODUCTION

Five Miocene intrusive complexes are located along a more than 650 km long N-trending lineament in southern Patagonia (Fig. 1). These intrusives are characterized by mildly alkaline to calc-alkaline magmatism pointing to mantle sources (Michael, 1983, 1984, 1991; Stern, 1990; Welkner-Rowe, 1999). This line of Miocene plutons strikes sub-parallel, with a divergence of about 15°, to the present and the Miocene trench and parallel to the western flank of the Magellan basin. It is located about 25 km east of the NNE-trending axis of recent calc-alkaline Andean volcanoes and about 70 km east of the eastern margin of the calc-alkaline Patagonian Batholith. The latter includes Upper Mesozoic to Lower Tertiary calc-alkaline plutons ranging in age from 160 to probably 34 Ma (Halpern 1973). The line is west of the Cenozoic alkaline volcanic activity of the Patagonian plateau. The five plutons are spatially related to the western part of the Magellan basin which was affected by compressional tectonics since the late Cretaceous (*e.g.*, Russo *et al.*, 1980; Winslow, 1979; Wilson, 1983).

Although the Miocene plutons of the sub-Andean region are chemically diverse, they represent a magmatic activity, which was quite restricted in time and space. The emplacement in this distinct trench-sub-parallel position during the Miocene may be related to the subduction of the oceanic plate below South America (Michael, 1983). The plutons formed along this line are the Torres del Paine granite pluton (12 ± 2 Ma, Rb/Sr model, Halpern, 1973; 13 ± 1 Ma, K-Ar biotite, Michael, 1983), the granodioritic Cordillera Fitz Roy pluton (18± 3 Ma, Nullo et al. 1978), Cerro Balmaceda (alkaline, 28 Ma, K/Ar, ENAP in Skármeta and Castelli 1997) and the granitic Cerro San Lorenzo Pluton (6.4±0.4 -6.6±0.5 Ma, K/Ar biotite, Welkner-Rowe, 1999). The pluton of Cerro Donoso (calc-alkaline) is located south of the Torres del Paine and is not dated (Fig. 1). The authors call this line San-Lorenzo-Balmaceda Lineament (SBL) after the northern and southern most of these plutons.

The deformation and kinematics in the foreland of the Torres del Paine pluton was studied intensively in order to evaluate the influence of the pre- to syn-intrusive crustal stress fields on the time and place of magma movement. A combination of field work, interpretation of satellite images and air photographs,

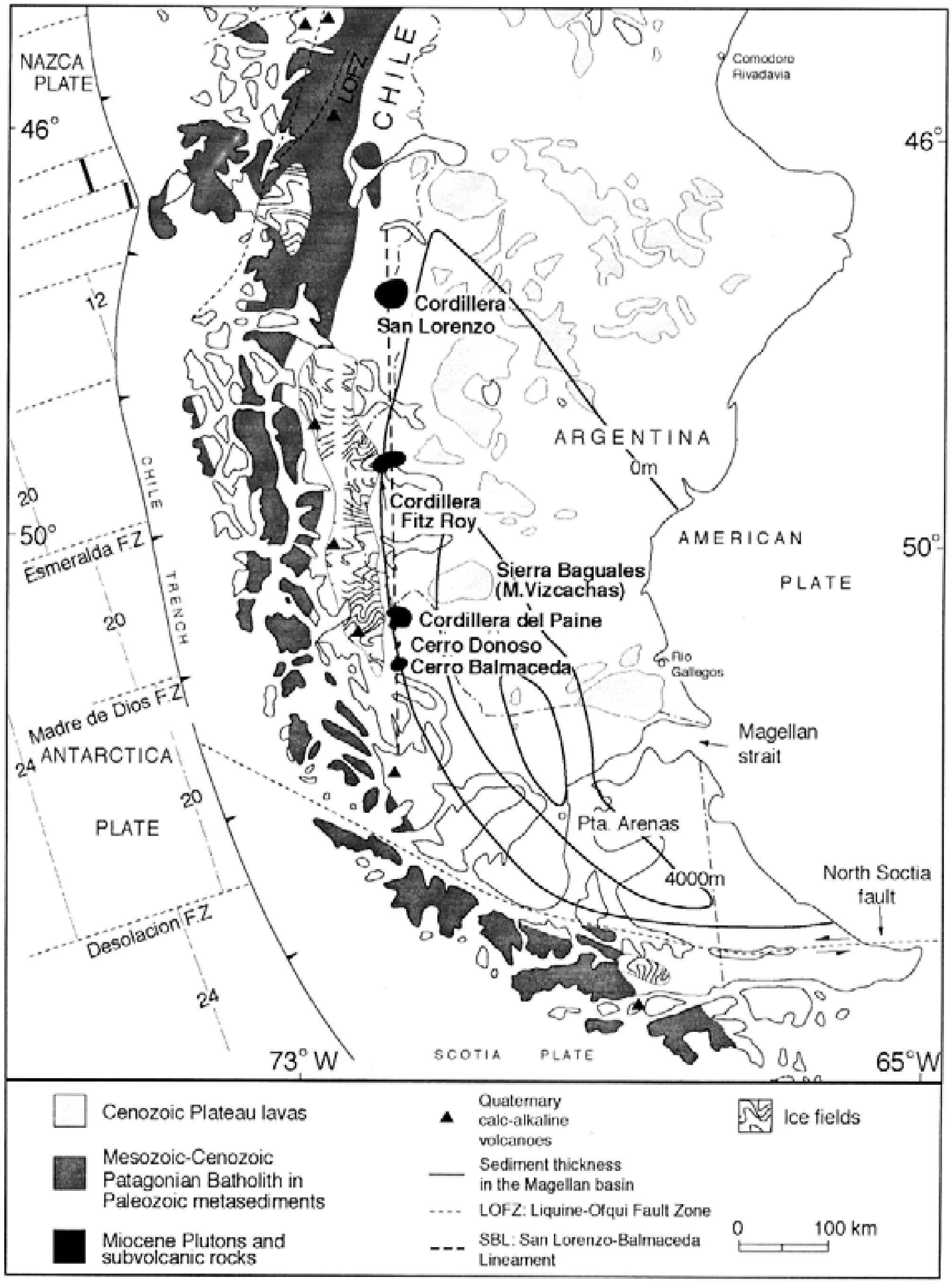


FIG. 1. Geological map of southern South America. Map modified after Stern (1990), Michael (1991) and Coutand et al. (1999). Numbers, west of the Chile trench, are approximate ages of Pacific crust.

geochronology, geochemistry and petrography will used to provide data on the definition of the kinematic framework before, during and after pluton emplacement.

GEOLOGY OF LAS TORRES DEL PAINE AREA

THE PLATE TECTONIC SITUATION

The Torres del Paine region is situated at 51°10'S, south of the present triple junction of the Antarctica, the Nazca- and the South America-plates at 47°S. This part of the South-western Pacific experienced a major plate tectonic re-organization during the Tertiary. The Chile ridge, separating the Nazca-plate from Antarctica (Fig. 1) collided obliquely with western Tierra del Fuego about 14-15 Ma (Gorring *et al.*, 1997). The triple point migrated northwards to its present position at 47°S (*e.g.*, Gorring *et al.*, 1997; Coutand *et al.*, 1999). The trench west of Torres del Paine was affected by the collision of the Chile ridge at 13-14 Ma, assuming constant plate velocities. This is just before or during the emplacement of the Torres del Paine Pluton.

THE AREA UNDER INVESTIGATION

The investigated area is located in the Ultima Esperanza region in Southern Chile (Figs. 1, 2). It is part of a fold-and-thrust belt, which forms the western part of the Magellan basin (*e.g.*, Winslow 1979, 1982; Wilson, 1983, 1991; Biddle *et al.*, 1986). The area is located east of the Patagonian Cordillera. The Patagonian Cordillera can be subdivided geologically from west to east into three main geological units (Kraemer, 1993):

- Palaeozoic metasedimentary rocks, which are intruded by the Jurassic to Tertiary calc-alkaline Patagonian batholith.
- The main cordillera with Jurassic volcanic rocks and tectonic slices of ophiolithes.
- The Magellan foreland basin.

The stratigraphic sequence exposed in the investigated foreland is related to the western flank of the Magellan basin. The Magellan basin may be divided roughly into two structural units, an eastern province formed by normal-fault related structures and a western province formed by the southern Andes fold and thrust belt (*e.g.*, Biddle *et al.*, 1986). Strike-slip deformation is known from the southern edge of the basin along the South America-Scotia Plate boundary and from tear folds in the fold and thrust belt. Strike-slip faulting is found to be insignificant, elsewhere in the basin (Biddle *et al.*, 1986).

Triassic to Late Jurassic extension affected the area predominantly by normal faults, grabens and half grabens (Soffia and Harambour, 1988; Biddle *et al.*, 1986). The development of the Magellan basin correlated with the uplift of the Patagonian Cordillera during Late Cretaceous compression (*e.g.*, Russo *et al.*, 1980; Winslow, 1979; Wilson, 1983). Uplift and shortening occurred along the western and southern part of the basin during the late Cretaceous and Tertiary (Biddle *et al.*, 1986). Shortening was accompanied by the formation of folds and thrust faults. Thrust faults often reactivated existing normal faults (Soffia and Harambour, 1988). Low angle thrust faults led to great horizontal displacements (Soffia and Harambour, 1988). Cenomanian folding and thrusting propagated to the northeast towards the craton until Late Tertiary (Diraison *et al.*, 1998). According to Winslow (1982) folding of the thrust and fold belt started earlier in the southeast than it did in the northwest. The youngest deformed strata of the Tierra del Fuego are of middle Eocene age; to the northwest post-middle Miocene beds are involved; farther north Pliocene rocks are warped and tilted.

The authors' investigations are mainly concentrated along a 30 km long, southwest-northeast-trending strip reaching from Lago Grey in the west to Río Ascencio in the east, including the Torres del Paine laccolith, which is located at about 51°20'S and 73°W (Fig. 2). The area around the Torres del Paine intrusion complex was mapped in detail. Additional information was obtained from exposures at the northern flank of the intrusion.

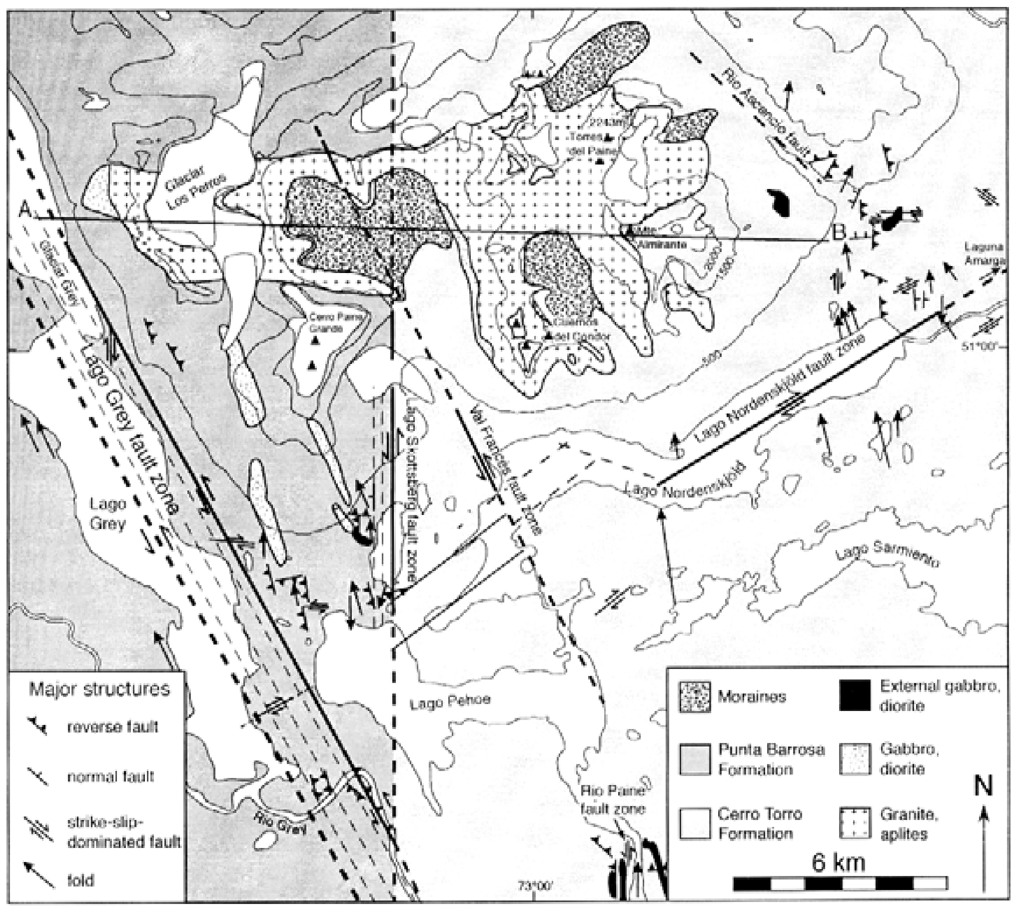


FIG. 2. Geological map of the Torres del Paine foothills, with the major tectonic elements based on the results of the present study and unpublished data of L. Baumgartner. The lithological boundary between Punta Barrosa and Cerro Toro Formation, north of the Paine Intrusion is adopted after Wilson (1983).

CRETACEOUS SEDIMENTARY ROCKS

The stratigraphic record includes rocks of the Punta Barrosa Formation and the Cerro Toro Formations (Fig. 2). The ages of the Punta Barrosa Formation is Albian to Cenomanian while the Cerro Toro Formation is assigned Turonian to Santonian ages (Zeil, 1958; Katz, 1962; Wilson, 1983; Riccardi, 1988). However, the lack of fossils in the Punta Barrosa Formation precluded an exact age assignment (Wilson, 1983). New findings of fossil plant relics will hopefully provide better data (Oberhänsli *et al.*, in prep).

The sandy Punta Barrosa Formation has a gradational upper contact with the Cerro Toro Formation to the south of the study area (Wilson, 1983). The Punta Barrosa Formation has a wedge-shaped geometry pinching out eastward within about 50 km (Wilson, 1983). The Formation is interpreted to be a turbidite sequence, indicating the first arrival of 'flysch'-sediments in this part of the Magellan basin (Wilson, 1983) and uplift of the Main Cordillera Complex (*e.g.*, Dalziel, 1981). The contact to the Cerro Toro Formation is tectonically disturbed around the Torres del Paine mountains. The Punta Barrosa Formation is primarily composed of thick-bedded

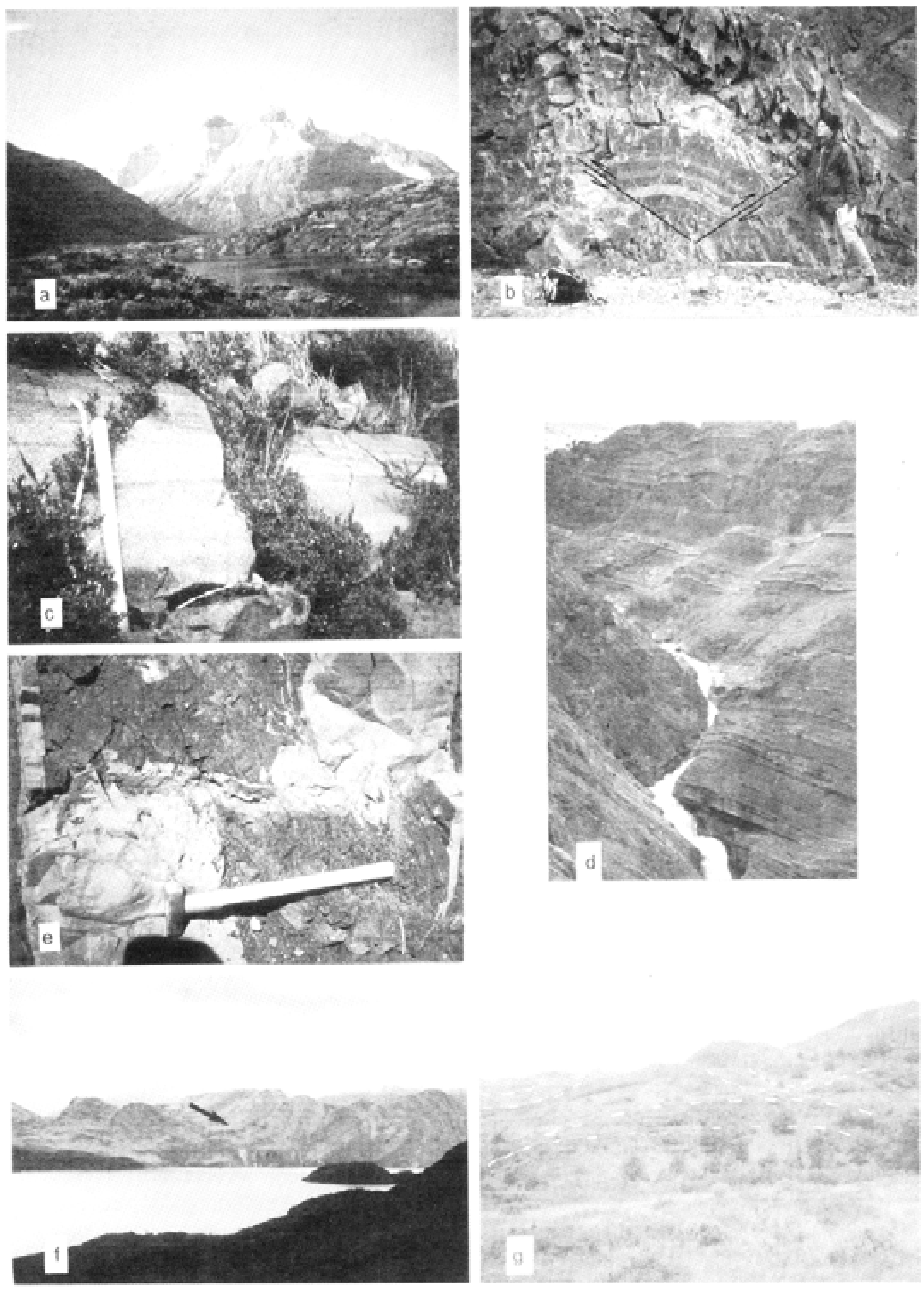


FIG. 3. **a-** View on the Torres del Paine Mountains with sedimentary rocks at the base and top (dark grey) of the granitic intrusion (white); **b-** Sandstone succession of the Punta Barrosa Formation with intercalated shales, displaced by conjugate faults. On the left, neptunic dike. Road cut south of Lago Grey; **c-** Magmatic layering in the 'external gabbros'. Outcrop at the eastern bank of the Rio Paine; **d-** Shales, intercalated with calcareous shales and marls of the Cerro Toro Formation. Valle Ascencio; **e-** Mafic dike of the Torres del Paine foothills with en-echelon-structures. Valle Ascencio; **f-** Large-scale open fold in the Cerro Toro Formation. SE-side of the Lago Nordenskjøld (arrow: fold-axis); **g-** Anticline-syncline pairs above flat-lying fault. Southwest of Rio Paine.

sandstone sequences with intercalated shale (Fig. 3b). West of Lago Pehoe thin conglomerate layers are exposed. In addition, caliche-like structures occur, indicating a probable (short-lived) subaerial position (Altenberger *et al.*, in prep.). Furthermore numerous neptunian (clastic) dikes occur (Fig. 3b).

The Cerro Toro Formation is dominated by shales, intercalated with marls, with lenses of sandstones and conglomerates (Fig. 3d). Generally, this sedimentary succession is described as a flysch composed of turbidite sediments, formed due to tectonic subsidence of the Magellan basin and uplift of the Main Cordillera (*e.g.*, Zeil, 1958; Wilson, 1983; Riccardi 1988).

THE INTRUSIVE ROCKS OF THE TORRES DEL PAINE REGION

The sedimentary rocks of the Torres del Paine region were intruded by the Torres del Paine intrusive complex (gabbros and granitoids), gabbro sills (external gabbros) and mafic as well as microgranitic dikes.

THE TORRES DEL PAINE INTRUSIVE COMPLEX

The Torres del Paine intrusive complex forms a 20 by 10 km laccolith, which reaches a thickness of up to 2000 m (Fig. 3a). Rb/Sr whole rock data of the granite and K/Ar data of biotite indicate an age of about 12-13 Ma (12 ± 2 Ma, Rb/Sr model, Halpern, 1973; 13±1 Ma, K-Ar biotite, Michael, 1983). The pluton is composed of basal gabbros, monzodiorites, quartz-monzodiorites and granitoids (Fig. 2, see also Michael, 1991). The mafic intrusions reach a maximum vertical thickness of about 300 m. The mafic rocks are medium- to coarse-grained, whereas the acidic rocks are fine- to medium-grained biotite granites. The magmas intruded the Cerro Toro Formation and Punta Barrosa Formation after regional folding. A conceptual model for the emplacement of the Torres del Paine laccolith is outlined by Skarmeta and Castelli (1997). They suggest dike-like ascent of the magma at a regional fault zone (Rio Nutria-fault zone). The lateral extension of the magmatic body is thought to be controlled by a large-scale (basal) fault zone, which should now form the basis of the pluton (Fig. 4). The model of Skármeta and Castelli (1997) describes some of the principal geometric features of the Paine laccolith well. Nevertheless it does not fit the authors' data and field observations. With respect to the location of the feeder or dike zone, and the lack of any evidence for the existence of a large-scale basal thrust fault.

EXTERNAL GABBROS

The Cerro Toro and Punta Barrosa Formation were intruded by gabbros and diorites before the emplacement of the Torres del Paine laccolith. In contrast to the larger Torres del Paine gabbro these intrusions form sills and dikes with thickness of up to 50 m. Quensel (1910) described these gabbros as 'External gabbros', which are highly altered. Major and trace element analyses reveal an alkaline composition (Altenberger *et al.*, 2000). However, the amount of CO_2 and H_2O is high and probably caused by magmatic processes (Altenberger *et al.*, 2000). The gabbros are composed of plagioclase, hornblende (brown or green), ± clinopyroxene, biotite, apatite and opaques. The diorites do not contain pyroxene. A typical feature of the gabbros are amygdules composed of calcite, euhedral quartz and minor amounts of euhedral perthite and highly carbonatized pipe-like structures (Altenberger *et al.*, 2000). They are all characterized by a well developed and often steeply dipping magmatic layering, indicating a probable predominance of lateral growth (Fig. 3c). In cases where the sills and dikes maintain their original contacts, the clastic and marly sediments show a contact-metamorphic overprint up to a distance of about 20-50 m. Geological mapping of the area east of Lago Pehoe (Fig. 2) reveals that the 'external gabbros' are folded together with the country rocks by regional, large scale folding. Therefore, the 'external gabbros' intruded before the Torres del Paine laccolith.

In order to establish the relationship between deformation and magma emplacement, the authors dated biotites of one of these gabbros. The calculated K-Ar age is 29.4±0.8 Ma (Table 1). There is no regional metamorphism probable reaching temperatures above 300°C, *i.e.*, above the closing temperature of biotite for the K-Ar system. Therefore, the obtained Oligocene biotite age indicates that large-scale folding took place after 29.4±0.8.

TABLE 1. RESULTS OF BIOTITE DATING BY K-Ar.

K_2O (wt.%)	40 Ar* (nl/g) STP	40 Ar* (%)	Age (Ma)	Error 2σ (Ma)	Error 2σ (%)
7.34	7.01	82.50	29.4	0.8	2.7

MAFIC AND MICRO-GRANITIC DIKES

The Torres del Paine laccolith and the Cretaceous sediments are truncated by numerous dikes of mainly basaltic composition. A few dikes of granitoid composition can be found (Fig. 3e). Whereas micro-granitic dikes are directly identified as apophyses and dike swarms of the Paine granite, a direct relationship of the mafic dikes to those in the foreland is not possible. In addition to the large number of mafic dikes in the foreland, only few mafic dikes occur in the granitoid intrusions (Michael, 1983). Petrographical analyses subdivided the mafic dikes of the foreland into pyroxene-, amphibole- and plagioclase-dominated types (Altenberger *et al.*, in prep.). Absolute ages of these groups are still missing. However, our structural studies (see below) indicate that most of the mafic dikes intruded after the emplacement of the Torres del Paine granitoid body. Post-granitic normal fault zones cut them (see below). The dikes strike predominantly east or ESE and subordinately NW and NE, and dipping steeply. Only ESE-striking dikes dip moderate to the southeast.

Most mafic dikes run parallel to existing fault systems and are therefore structurally controlled (see also below). The orientation of the dikes differs regionally. Whereas east of the Val Francés fault zone (Fig. 2) most of the dikes strike east or south-east, west of the fault zone north- and north-east-striking dikes predominate and east- as well as south-east-striking dikes are lacking. There is no obvious correlation of the mineralogical composition with the strike direction of the dikes.

The granitoid dikes are related to the intrusion of the Paine laccolith. In some regions (*e.g.*, Val Ascencio, Fig. 2) graintoid dikes can be traced back to the Torres del Paine granitoid intrusion.

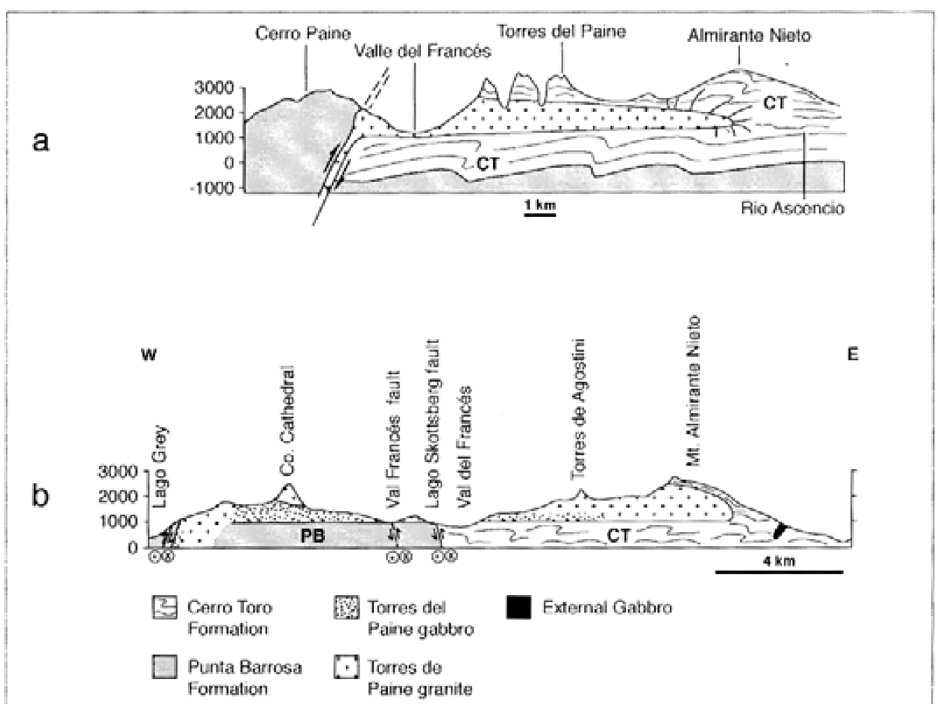


FIG. 4. **a-** Geological east-west cross sections through the Torres del Paine mountains; **a-** cross section of Skármeta and Castelli (1997). **b-** Cross section based on the results of the present study and unpublished data of L. Baumgartner.

STRUCTURES

FOLDS

Open folds with wavelength of 5 m to 10 km (Fig. 3f) bend the Upper Cretaceous sediments of the Cerro Toro Formation. The folds present a series of anticlines and synclines. Similar deformation was observed farther east by Katz (1962) and Wilson (1983). An axial plane cleavage was formed. The axial planes (s_1), are vertical or dip steeply to the west. The fold axis plunge mostly with 5-15° to NNW. In the Punta Barrosa Formation folds of similar orientation occur. The folds in the sand-dominated Punta Barrosa Formation have smaller folding wavelength (up to 1 km). They are close to tight chevron folds. In addition, along major fault planes nearly isoclinal folds were formed. Locally, the fold axis of synclines and their adjacent anticlines are not parallel and converge with an angle of about 30-45°. Anticline-syncline pairs above flat-lying faults occur in the Cerro Toro Formation, southeast and northwest of the Lago Nordenskøld. They are interpreted to be the result of a ramp-flat transitions-system (Fig. 3g). Locally, the orientation of the fold-axis above these ramp-flat surfaces differ up to 60° from the regional orientation. The wavelength of the ramp-flat-folds are restricted to a 10-150 m range.

FAULTS: OCCURRENCE AND KINEMATICS

All investigated faults are brittle or brittle-ductile and steeply dipping. Subhorizontal faults are rare. Complex fault systems include strike slip, reverse and normal faults. The following description of the faults is in chronological order and refers to the time of the intrusion of the Paine granite. In order to interpret the kinematics of the faults by domains of compression and tension (fault plain solutions, Table 2) and principal stress axis the authors use the program FaultKin written by Allmendinger *et al.* (1993), taking the fault plane and lineations for calculation.

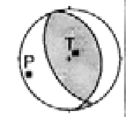
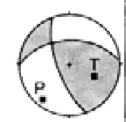
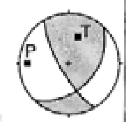
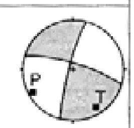
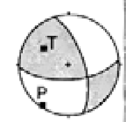
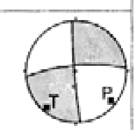
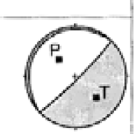
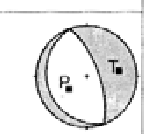
PRE-INTRUSIVE FAULTS

NNW- to NNE- striking reverse faults. North-northwest striking faults, dipping to the southwest or northeast occur frequently. Either southwest-dipping faults with an orientation subparallel to the axial planes of the large-scale folds or conjugate sets of the southwest- and northeast-dipping faults are exposed (Fig. 3b). Bending or separation of the layers between these faults indicate upward movement of the enclosed rocks. They formed during compression with a nearly horizontal σ_1 (Table 2). The intersection line of the conjugate faults are parallel to subparallel to the regional fold axes, plunging gently to the NNW. In some cases it can be observed that these faults disect the small- and large scale regional folds (Fig. 5a). Therefore, the faults are the continuation of the crustal shortening by folding. Hence the stress orientation during faulting does not change significantly after folding.

Lago Skottsberg-fault zone. At the eastern shore of Lago Skottsberg (Fig. 2), a fault zone defines the contact between the Punta Barrosa and the Cerro Toro formations. It cuts pre-existing folds and conjugate fault systems as described above. An Oligocene 'external gabbro' body (29 Ma) that intruded at this place into the Punta Barrosa Formation, is disected.

The fault zone is characterized by the formation of a new foliation (s_2), which overprinted the regional axial plane cleavages (s_1) of both Cretaceous formations (Fig. 5b) The zone of intensively foliated rocks has a width of about 300 m and is well preserved at the western lake shore of Lago Skottsberg. The foliation strikes to the north or NNW, dips nearly vertical or steeply to the west and is parallel to the bedding planes (s_0) of the Punta Barrosa and Cerro Toro formations. The bending of the axial plane cleavage s_1, which is oblique to the bedding planes s_0, points to a left-lateral sense of shear with a strong component of high-angle normal faulting (Fig. 5b), dropping the western block down. Therefore, the present situation reveals a divergent strike-slip fault. However, there is field evidence, that shear localization in the above described bedding-parallel zones does not represent the responsible stress system, directly. In shale-dominated series near the Lago Skottsberg fault zone small-scale faults with the same trend but opposite dip occur. These faults are not bedding-parallel and dip with 60-75° to the east. The sense of movement

TABLE 2. STRUCTURAL AND MAGMATIC EVENTS IN THE TORRES DEL PAINE REGION.

Age	Structures	Magmatic events	Orientation	Kinematics	Dynamics
29.4±0.8 (Ma)		Intrusion of the 'external gabbros'			
	Folds, tight to open foliation s_1		b = 330-360/0-10		Compression-dominated
	Reverse faults, conjugate		20NW-25NE/50-65SW /50- 60SE	Reverse faults, top to the east. Conjugate faults, top to the east and to the west	
	Lago Skottsberg-fault zone with foliation s_2		0-10NW/70SW, parallel bedding plane	Probably rotated convergent strike-slip (sinistral-reverse), exposed as divergent strike-slip fault (sinistral-normal)	
	Lago Grey fault zone with foliation S_3	Mafic dikes // to LGFZ (age uncertain)	LGFZ;30-40NE/65-75SW	LGFZ: convergent fault strike-slip (sinistral-reverse)	
	Lago Nordenskjøld fault zone	Mafic dikes, // to LNFZ: (age uncertain)	LNFZ;40-50NE/80-90SE	LNFZ: strike-slip (dextral) with a component of high-angle normal faulting	
12±2 Ma		Intrusion of the Paine granite	Laccolith nearly horizontal base		
	Strike slip faults	Mafic dikes // to the faults. Some dikes show en-echelon behaviour	105-115SE/88SW-70NE dikes: 115-135SE mostly steeply dipping	Sinistral with a slight component of normal faulting	
	Strike-slip faults	Mafic dikes // to the faults. Some dikes show en-echelon behaviour	85-90E/65-70S	Sinistral, with a slight component of normal faulting	Transtension-tension 
	Rio Paine fault zone		0-5NW/85W	Divergent strike-slip fault (sinistral normal)	
		Mafic dikes	40-60NE mostly steeply dipping		
	Normal faults		40-50NE/70-90SE	Normal faults	
	Normal faults		20-30NW/60-80NE	Normal faults	

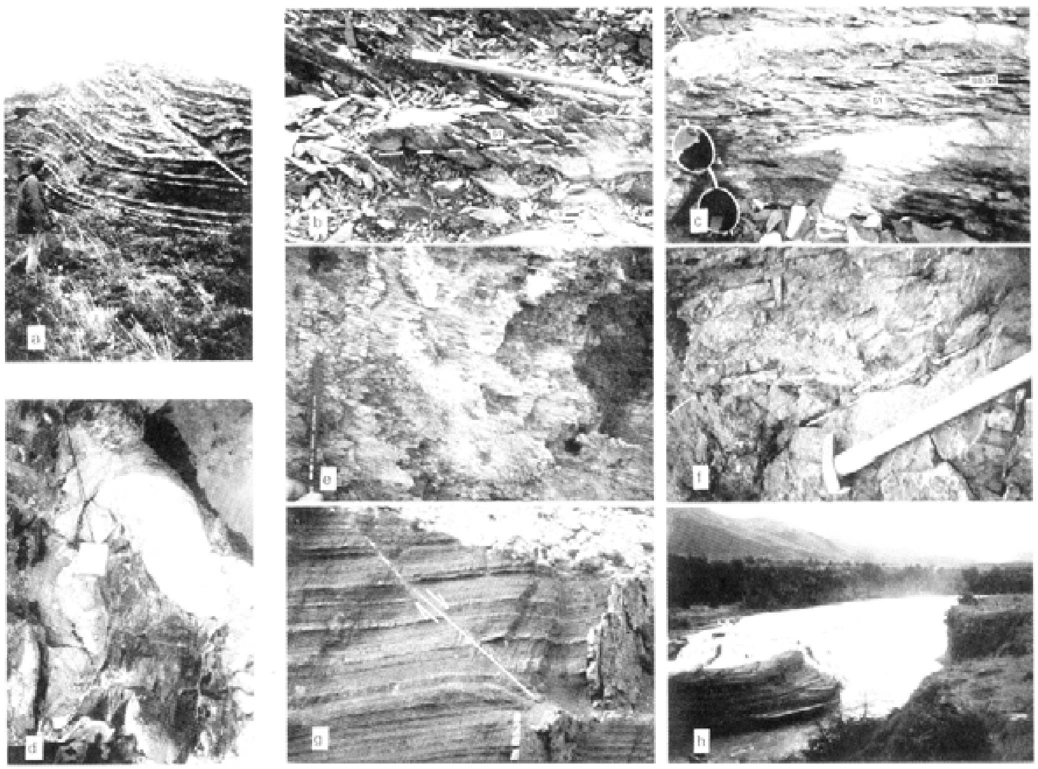


FIG. 5. **a-** NNW-striking reverse fault overprinting small- scale regional folds. West of Río Paine; **b-** Lago Skottsberg-fault zone: the bending of the regional foliation s_1, which is oblique to the bedding planes s_0, points to a left lateral sense of shear. s_2 is parallel to s_0. W of Lago Skottsberg; **c-** Lago Grey-Fault zone. The bending of the regional foliation s_1, which is oblique to the bedding planes s_0, points to a left-lateral sense of shear. s_3 is parallel to s_0. East of Lago Grey; **d-** Isoclinally folded neptunic dike. Southern bank of Lago Grey; **e-** Striae at east-striking sinistral strike-slip fault. Northwest of Lago Pehoe; **f-** southeast-trending left-lateral strike-slip fault. Northwest of Lago Pehoe; **g-** Northeast-trending moderately dipping normal faults, Val Ascencio; **h-** Cliff, pointing to a Northeast-trending steeply dipping normal fault (in the foreground). River follows older NNW-trending fault. Cascada Paine.

is characterized by left lateral strike slip kinematics with strong component of high-angle reverse faulting, in which the eastern part moved above the western part. Therefore, the authors suspect that the LSFZ is a left lateral strike-slip fault zone with a strong component of high-angle reverse faulting. In places in which s_0 is nearly vertical, the s_2 planes rotated in the s_0 planes and feigns normal fault kinematics. An interpretation as a large scale 'flower structure' is not probable. A flower structure would also show reverse kinematics in the case of fault planes, which dip, to the west. Those structures are not developed in the mapped area.

To the south of the LFSZ the foliation rotates northwest. This is probably due to a bending at the younger Lago Nordenskjøld-fault zone. To the north, the Lago Skottsberg-fault zone is truncated by the Torres del Paine granite. There are no field or air photograph evidences, that the fault was active after the emplacement of the laccolith.

Wilson (1983) and Skármeta and Castelli (1997) described this fault as the prolongation of the 'Río Nutria fault'. The Río Nutria fault was first mapped by ENAP geologists (A. Canon[1]; Cortéz, 1964), and was described by them to place the Punta Barrosa Formation (formerly described as Erezcano Formation, later named as Zapata Formation and redefined in that area as Punta Barrosa Formation by

[1] 1963. Reconocimiento geológico al oeste de la Sierra Toro y la Península Ultima Esperanza (Unpublished), *Empresa Nacional del Petróleo*, 41 p. Puntas Arenas, Chile.

Wilson (1983) over the Cerro Toro Formation. The Río Nutria fault indicates reverse fault kinematics, in which the western part was thrust onto the eastern part. Their interpretation was based on observations of localities *ca.* 35 km farther south, west of Lago Toro. A reinterpretation of the present left-lateral Lago Skottsberg fault, with a strong component of high-angle normal faulting, as part of a left lateral fault with a strong component of high-angle reverse faulting is probable (see above). This kinematics differs significantly from that observed at the Río Nutria type locality.

Lago Grey-fault zone and the antithetic Lago Nordenskjøld-fault zone. Lago Grey is situated at a large fault system in the Punta Barrosa Formation, here named the Lago Grey-fault-zone (LGFZ). At the western lake and in outcrops south of the lake the regional axial plane cleavage (s_1) was bent and a new foliation was formed (s_3, Fig. 5c). S_3 strikes NNW-SSE and dips steeply (65-78°) to the southwest. The zone in which two foliations exist is more than 1 km wide and strikes NNW-SSE, *i.e.*, parallel to the bedding planes s_0. The bending of s_1, in addition to the small-scale folding and the lineation perpendicular to the fold axis, indicate left-lateral sense of shear with a strong component of high-angle reverse faulting, in which the northwestern part was thrust onto the southeastern part (Fig. 5c). Therefore, the Lago Grey-Fault zone is a convergent strike-slip fault, indicating deformation under transpressive conditions. Rare isoclinally folded neptunian dikes occur (Fig. 5d). In addition, s_3 parallel faults south of Lago Grey cut andesitic to basaltic dikes and display the same kinematics as s_3 and the Lago Grey-fault zone. To the south, the LGFZ has a probable continuation as indicated by the fault-parallel Río Grey, covered by alluvial sediments (Fig. 2).

At the Lago Grey-fault zone, south of the steep slopes of the Cordillera del Paine, a large-scale northeast-trending fault zone developed. This fault zone is partially covered by the Lake Lago Nordenskjøld, and here named Lago Nordenskjøld-fault zone (LNFZ). The fault zone is composed of a system of faults, probably displaced by a transfer fault, located below the Lago Nordenskjøld (Fig. 2). To the west, at least two branches exist (Fig. 4). Katz (1962) first described the fault zone as a single fault. Based on the observation that two folds, one of each side of the Lago Nordenskjøld, originally belonged to one fold, Katz (1962) described the LNFZ as a right lateral strike-slip fault zone with a moderate component of high-angle normal faulting. Katz (1962) postulated that the northwestern part was the downthrown side, whereas the present study reveals the downthrown side to be the southeastern part. Along the western branches of the LNFZ, south of Lago Skottsberg, the fault shows a downward 'jump' of the southeastern part. In addition, the LNFZ cuts and bends the Lago Skottsberg-fault zone, indicating a right lateral movement of up to 200 m. Therefore, the authors conclude that the LNFZ is a right lateral strike-slip fault zone with a component of high-angle normal faulting. The authors interpret the LNFZ as an antithetic branch of the Lago Grey-fault zone. Smaller faults of the same orientation and kinematics occur south of the Torres del Paine granite and west of the Lago Grey-fault zone. In very rare cases, small-scale faults of the same trend show left-lateral sense of movements.

Large morphological depressions occur west of the investigated area (*e.g.*, Lago Azul, Laguna Amarga). They form NNW-trending large scale valleys. Hence they are very similar to the Lago Grey-Lago Nordenskjøld system.

Mafic dikes of unknown age intruded into the Cretaceous sediments parallel to the Lago Nordenskjøld- and parallel to the Lago-Grey fault system. Strike-slip and normal faults exclusively disected these dikes.

POST-INTRUSIVE FAULTS

SE- and E- trending left-lateral strike-slip faults. Moderate to steeply dipping, southeast- trending faults are frequent. In contrast to the fault zones described above, they are of minor geographic extension. Larger ones are often overprinted by weathering phenomena and form valleys, furrows or deep trenches. In most cases, fault planes, bent layers, and striae indicate left-lateral movements with a gentle component of normal faulting, in which the southern part moves down to the east (Figs. 5e, f). The faulting is the result of transtensional conditions. In rare cases, small-scale faults of the same trend show right-lateral sense of movements. This type of faults crosscuts the 'external' gabbros northwest of the eastern end of Lago Nordenskjøld (Fig. 2). Southeast-trending left-lateral strike-slip faults often cut the northeast-trending right-lateral faults described above.

A remarkable feature is the intrusion of numerous mafic dikes parallel to these faults. Some of these dikes clearly show en-echelon structures (Fig. 3e). These structures are typical of regions with extensional dynamics having a component of strike-slip faulting (*e.g.*, Nairn and Cole, 1981). Some of the dikes are cross-cut by southeast-striking dikes and faults, pointing to an intrusion before these faults were active.

A few east-trending, left lateral strike-slip faults with a slight component of normal faulting are exposed. Cross-cutting relationships indicate, that these faults are younger than those described above. Their trend deviates by *ca.* 20°. This displays similar kinematics as for the ESE-striking faults and reflects a clockwise rotation of the P (compression) and T (tension) axes (Table 2).

RIO PAINE- AND VAL FRANCES-FAULT ZONE

Northwest of the Lago del Toro at the western and eastern river banks of the Río Paine river a gabbro sill is displaced along faults indicating a left-lateral sense of shear with a moderate component of high-angle normal faulting, in which the southwest moved down. The faults strike to the north and dip steeply to the west. To the north, some small faults with the same orientation and sense of displacement are observed. They are probably part of a large scale fault zone, the Val Francés-fault zone (Fig. 2). The faults of this zone show a slightly different strike direction from the Río Paine-fault zone, but have the same sense of displacement. The Val Francés-fault zone strikes towards the NNW. Furrows, valleys, outcrops, the NNW-trend of the western part of the Lago Nordenskøld and the Valle Francés indicate a continuation of the Val Francés-fault zone. The fault zone clearly displaces and, therefore, post-dates steeply dipping faults striking 120°. In addition, it displaces the northeast trending right-lateral Lago Nordenskøld-fault zone (Fig. 2). Satellite images and air photographs indicate, that the fault zone displaces the Torres del Paine granite with the same sense of shear. Therefore, this fault system was active after the intrusion of the Paine granite. The Río Paine- and Val Francés-fault zones form divergent strike-slip faults, formed in a transtensional stress regime.

NE-trending steeply dipping normal faults, northeast-trending normal faults form dominant fault systems in the investigated area. They are parallel to the Lago Nordenskjøld-fault zone. However, they cross cut the western part and, therefore, post-date the LNFZ, which is interpreted as an antithetic branch of the Lago Grey-fault zone. They are more frequent, but not restricted, to the region east of the Lago Grey-fault zone. The faults can be observed directly by crosscut relations and as strong lineaments in satellite images and air photographs. In most cases, the single faults show displacements of centimetres to tens of meters. The faults dip steeply to the southeast. However, this type of fault probably reactivates the Lago Nordenskjøld fault as indicated by normal faults on both sides of the lake.

In some places, they overprint the Lago Skottsberg- and Lago Grey-fault zones. Faults are vertically or subvertically dipping to the southeast. The fault planes, bent sedimentary layers and striae indicate down to the south movements. Only few faults dip moderately to the southeast (Fig. 5g). Often, waterfalls (Fig. 5h) mark them.

NNW-trending steeply dipping normal or reverse faults. These faults are vertical or dip steeply to the northeast. Along the fault planes top-to-northeast movements are obvious. Striae on the fault planes are oriented nearly vertical.

STRUCTURAL AND KINEMATICAL EVOLUTION OF THE TORRES DEL PAINE FORELAND AND THEIR RELEVANCE FOR MAGMA EMPLACEMENT

The results of the structural analyses indicate the following relationships between kinematics, dynamics, and magma emplacement (Table 2):

- The oldest magmatic activity in the Torres del Paine area is represented by 'external gabbros'. At the Río Paine, southeast of Lago Pehoe and southwest of Laguna Amarga, large-scale folding of the gabbros occurs. Biotites of the 'external gabbro', located northeast of the eastern end of Lago Nordenskjøld, give an Oligocene age (29 Ma). Biotite is of late magmatic *i.e.*, hydrothermal origin.

- The emplacement of the Paine gabbroic and granitic magma clearly post-dates the folding, reverse faults and most of the convergent sinistral faults (*e.g.*, Lago Skottsberg-fault zone). The root is spatially connected with the convergent strike-slip Lago Grey-fault zone. The intrusion clearly pre-dates all divergent strike-slip and normal faults, which overprint the Lago Grey-fault zone. Therefore, the intrusion must be placed in the time span after activation of the Lago Skottsberg-fault zone and before the sinistral strike-slip faults post-dating the Lago Grey-fault zone. Therefore, the emplacement of the gabbros and granites of the Torres del Paine laccolith occurred during the change from compressional to tensional tectonics.
- Most of the mafic dikes of the foreland post-date the granite intrusion and intruded parallel to the trend of the major fault systems. From structural and cross-cutting observations the following chronology can be obtained:

Dikes parallel to the Lago Grey- and Lago Nordenskøld-fault zone are probably the oldest dikes observed. These dikes were cross-cut by most fault systems younger than the LGFZ.

Dikes parallel to the ESE-striking sinistral strike-slip faults, which are often cut by these faults. En-echelon structures indicate tensional stress during emplacement.

ENE-striking dikes are the youngest dikes, observed. They are parallel to subparallel to the strike-slip faults, post-dating the granite intrusion. These dikes were cross-cut by normal faults.

DISCUSSION AND CONCLUSIONS

During Oligocene to recent times the foothills of the Torres del Paine intrusive complex were affected by a minimum of three magmatic pulses (external gabbros, Torres del Paine Intrusive Complex, dikes). Magmatic activities are related to compressional dynamics as well as to periods in which a change from compressional to transtensional tectonics occurred.

The Oligocene 'external gabbros' are the first intrusions in the study area. Assignment of a tectonic setting is not obvious based on their alkaline chemistry (*e.g.*, Wilson, 1989). The Balmaceda pluton to the south is of similar age as the external gabbros, but detailed work on its geotectonic setting is lacking. However, north of the study area in the foothills of the Miocene Fitz Roy pluton, compressional dynamics throughout Cretaceous to Miocene are suspected (*e.g.*, Coutand *et al.*, 1999). Therefore, emplacement in a compression dominated crust is probable for the external gabbros of the Torres del Paine area.

The emplacement of the 'external gabbros' is followed by compressional and transpressional tectonics, expressed by large scale folding and faulting with subhorizontal ENE- to east-striking shortening axes (Table 2). Shortening axes are compatible with the relative plate velocities of the Nazca- and the South-America plate.

The magmas of the Miocene Torres del Paine laccolith used a pathway close to the Lago Grey-Fault zone for ascent and intrusion. It intruded during a phase of kinematic changes from left-lateral convergent strike-slip faulting to left-lateral divergent strike-slip faulting. This marks the change from transpressional to transtensional dynamics, probably resulting from plate tectonic reorganization during the Miocene. The Chile ridge collided obliquely with western Tierra del Fuego about 14 Ma ago. The triple point subsequently migrated northwards to its present position at about 47°S (Fig. 1). Consequently, the southern tip of South America has experienced a rapid oblique convergence (ENE-WSW at about 9 cm/yr) between Nazca and South America plates, followed by slow frontal convergence (east west at about 2 cm/yr) between Antarctica and South America (*e.g.*, Coutand *et al.*, 1999). The triple point must have collided with the trench west of the Torres del Paine region at about 12 Ma, according to the data of Gorring *et al.* (1997). The change in convergence rate is a possible mechanism to produce a change from compressional to tensional stresses. A similar scenario has been described for the central Andes (Scheuber, 1994; Taylor *et al.*, 1998).

The 'magmatic root zone' of the Torres del Paine intrusions possibly coincides with the intersection of the (subducted) Madre de Dios oceanic transform fault or fracture zone with the Lago Grey-Fault zone, when projecting its position during the time of magma ascent onto the continent (Fig.1; Gorring *et al.*, 1997). The structural control of the upper plate by subducted oceanic fracture zones is well known from other regions (*e.g.*, Carr, 1984). Although the area above the Madre de Dios fracture zone is not characterized by a major fault zone at the present surface, a structural inhomogeneity in this region is probable, as expressed by the present deeply eroded morphology. Therefore, the magma ascent of the Torres del Paine laccolith was possibly controlled by the intersection of the LGFZ and the Madre de Dios transform fault. The study does not reveal clear evidence for the tectonic role of the northeast-striking San Lorenzo-Balmaceda-Lineament. The major structural elements controlling the pathway for magma ascent in the studied area are the 30°NW striking LGFZ and probably the fossil oceanic Madre de Dios 70°NE striking transform fault. A hypothesis to explain the San Lorenzo-Balmaceda Lineament (SLB) by authors' new data and published data on the San-Lorenzo Batholith is a possible north-south trending strike-slip (?) fault zone in the deeper crust. This lower crustal zone enhanced magma ascent to the upper crust, in which the pathways are controlled by NW-trending and NE-trending faults.

One of the main unresolved questions about magmatic arcs concerns the mechanisms by which large volumes of granitic melts intrude the upper crust. The recognition that oblique plate convergence may have been associated with voluminous granitic magmatism, *e.g.*, in the Cretaceous plutons in California (Glanzer, 1991), suggests that there is a genetic link between strike-slip tectonism and granitoid emplacement. Therefore, observed divergence of the SLB as a possible strike-slip fault in the lower and/or middle crust, and the upper faults controlling magma ascent is possibly a function of shear partitioning.

The numerous mafic dikes of the foreland intruded mostly parallel to faults and fault zones. They are parallel to the LGFZ and younger faults. Therefore, a genetic relationship with the mafic magmas of the Paine laccolith is possible, although dike formation outlasted the ascent of the Paine intrusion.

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