Journal of South American Earth Sciences, Vol. 6, No. 1/2, pp. 97–104, 1992
Printed in Great Britain

0895-9811/92 $5.00+.00

Age and petrogenesis of the Sarmiento ophiolite complex of southern Chile

C. R. STERN[1], S. B. MUKASA[2], and R. FUENZALIDA P.[3]

[1]Department of Geological Sciences, University of Colorado, Boulder, CO 80309-0250, USA;
[2]Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109-1063, USA;
[3]Empresa Nacional del Petroleo, Casilla 11135, Santiago, Chile

(Received September 1992; Revision Accepted November 1992)

Abstract—Zircon fractions separated from fine-grained plagiogranites, interpreted to be cogenetic with the mafic rocks of the Sarmiento ophiolite complex in southern Chile, yield slightly to grossly discordant age patterns for which the lower concordia intercept U-Pb ages of 140.7 ± 0.7 Ma (Lolos Fjord) and 137.1 ± 0.6 Ma (Encuentro Fjord) are well constrained. These dates are interpreted as formation ages for the northern portion of the igneous floor of the Rocas Verdes basin, and they are younger than the age of 150 Ma determined for a more southern portion of the floor of this basin on South Georgia Island. Coarse-grained trondhjemites within the gabbro units of the Sarmiento complex yield a lower concordia intercept U-Pb age of 147 ± 10 Ma and a poorly defined upper intercept reflecting an inherited zircon component, possibly of Proterozoic age. These rocks are interpreted as remobilized fragments of country rocks entrapped within the essentially mantle-derived rocks of the ophiolite complex.

Resumen—Fracciones de zircón separadas de plagiogranitos de grano fino, que han sido interpretados como cogenéticos con las rocas máficos del Complejo Ofiolítico Sarmiento en el sur de Chile, arrojan patrones de edades levemente a fuertemente discordantes para las cuales el valores de intersección de la concordia inferior de edades U-Pb están bien definidos y corresponden a 140.7 ± 0.7 Ma (Fjordo Lolos) y 137.1 ± 0.6 Ma (Fjordo Encuentro). Estas edades se interpretan como edades de formacón de la zona norte del fondo ígneo de la cuenca de Rocas Verdes y son más jóvenes que la edad de 150 Ma determinada para la zona sur del fondo de esta cuenca en la Isla South Georgia. Trondjomitas de grano grueso dentro de la unidad de gabro del Complejo Sarmiento entregan una intersección de la conordia inferior de edades U-Pb de 147 ± 10 Ma y un valor de intersección superior debilmente definido, posiblemente reflejando una componente de zircón heredada de edad Proterizoica. Estas rocas se interpretan como fragmentos removilizados de la roca de caja, atrapados en rocas ofiolíticas derivadas esencialemente del manto.

INTRODUCTION

THE BELT of dominantly mafic Rocas Verdes igneous complexes in the southernmost Andes (Fig. 1A) represents the uplifted, but autochthonous, igneous floor of an Early Cretaceous back-arc basin (Dalziel *et al.*, 1974) or Gulf of California type ensialic basin (Alabaster and Storey, 1990). The ages of the Rocas Verdes mafic complexes of southern Chile are constrained by stratigraphic data (Bruhn *et al.*, 1979; Fuenzalida and Covacevich, 1988) but have not previously been determined isotopically, in part because of extensive spilitization related to hydrothermal metamorphism, and in part because rocks with minerals suitable for dating are scarce. Zircon U-Pb age determinations are presented here for two petrologically distinct suites of silicic rocks which are important components of the Sarmiento complex, the northernmost of the Rocas Verdes ophiolite complexes. These silicic rocks include plagiogranites, which have previously been interpreted as cogenetic with the mafic rocks of the Sarmiento complex, and trondhjemites, which have been interpreted as remnants of older continental crust engulfed within this ophiolite complex (Stern, 1979; Saunders *et al.*, 1979; De Wit and Stern, 1981).

SAMPLE DESCRIPTION AND GEOCHEMISTRY

The Sarmiento complex consists of gabbros and of mafic dikes and pillow lavas interpreted to represent the upper sections of an ophiolitic sequence formed along an oceanic-type spreading center which rifted the South American crust during the Late Jurassic and Early Cretaceous to produce the Rocas Verdes basin (Dalziel *et al.*, 1974, Bruhn *et al.*, 1978). Geochemical studies of mafic rocks from the Sarmiento and other Rocas Verdes complexes indicate close similarities with ocean ridge basalts (Stern, 1979, 1980, 1991; Alabaster and Storey, 1990).

The samples of silicic plagiogranites and trondhjemites analyzed in this study were collected from exposures along the northern shores of Lolos and Encuentro Fjords, which cut perpendicularly across the regional north-south strike of dikes within the Sarmiento complex (Fig. 1B). At these localities the lower 500-800 m of outcrop is formed by the plutonic unit of the ophiolite, including mafic gabbros and diorites as well as leucocratic plagiogranites and trondhjemites described below (Fig. 2). The upper portions of these sections consist of the sheeted dike complex of the ophiolite, which grades upward into pillow lavas and breccias.

Address all correspondence and reprint requests to Dr. Charles R. Stern: telephone [1] (303) 492-8141; fax [1] (303) 492-2606.

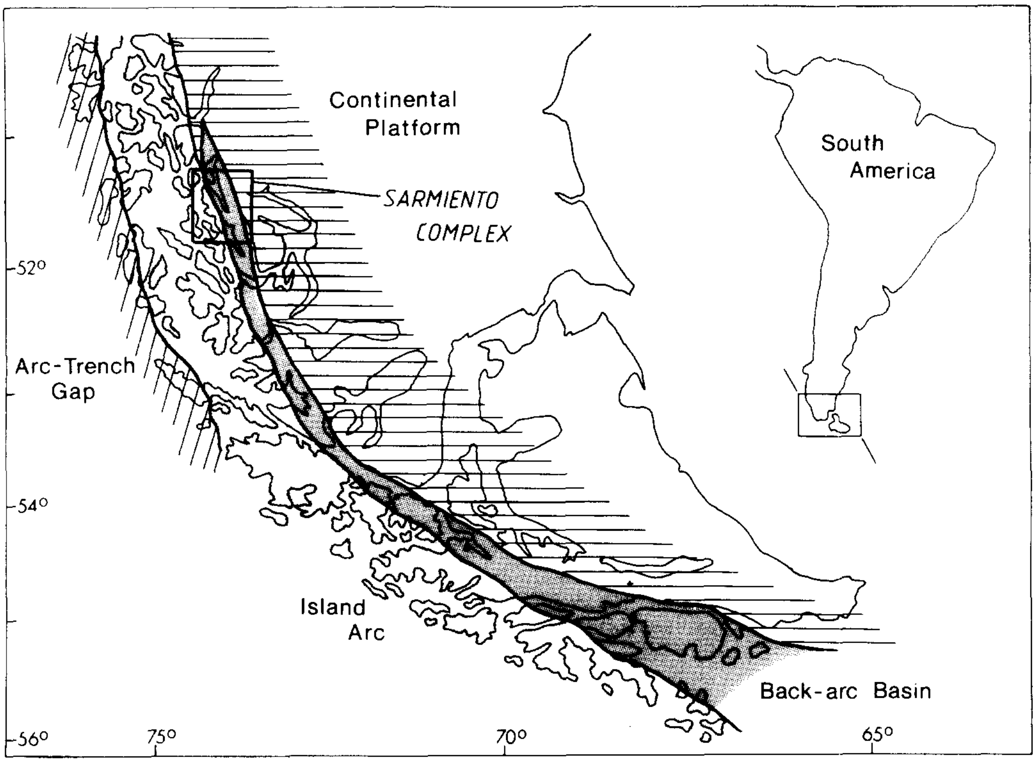

Fig. 1A. Map showing the location of the Sarmiento complex within the context of the major lithotectonic units of the southernmost Andes during the late Mesozoic (Dalziel *et al.*, 1974).

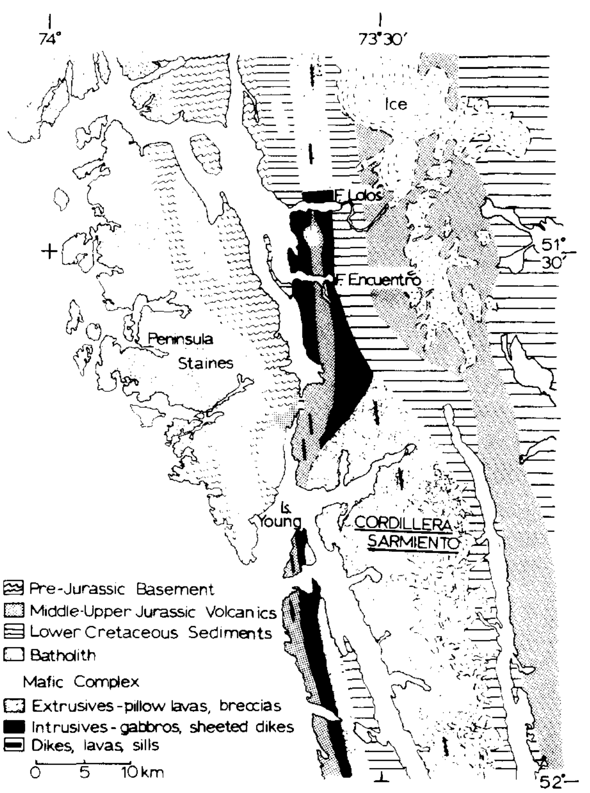

Fig. 1B. Map showing the distribution of the main rock types of the Sarmiento ophiolite complex (Stern, 1979). Samples for dating came from the northern shores of Lolos and Encuentro Fjords.

Plagiogranites in the Sarmiento ophiolite occur as fine-grained leucocratic rocks either in a plutonic body intruding the sheeted dike complex, or as dikes within the sheeted dike complex and the overlying pillow lavas (Fig. 2; Stern, 1979; De Wit and Stern, 1981). The plagiogranite plutonic body, which marks the contact between the lower plutonic unit of the ophiolite and the sheeted dike complex, intruded the sheeted dike complex by magmatic stoping. It is approximately 50-100 to m thick and grades downward across a diffuse boundary into trondhjemite, diorite, and gabbro. The pluton itself is cut by later mafic dikes, indicating that the plagiogranites are contemporaneous with the mafic magmatic activity which produced the Sarmiento ophiolite complex.

Hydrothermal "ocean-floor" metamorphism at greenschist facies conditions (200-500°C) has modified the original mineralogy and geochemistry of the plagiogranites (Stern *et al.*, 1976; Stern and Elthon, 1979; Elthon *et al.*, 1984). The concentrations of mobile major and trace elements, particularly alkali elements such as K and Rb, have been significantly modified, in both mafic rocks and the plagiogranites, by this metamorphism. However, the concentrations of immobile trace elements, such as rare-earth elements (REE) and high-field-strength elements (HFSE; Nb, Zr, Ti, Y) do not appear to have been affected (Stern and Elthon, 1979). The immobile elements exhibit coherent trends through the basalt-ferrobasalt-andesite-plagiogranite sequence of the complex (Fig. 3; Stern, 1979; Saunders *et al.*, 1979). These coherent chemical trends among the immobile trace elements suggest that the plagiogranites are cogenetic with the associated mafic rocks

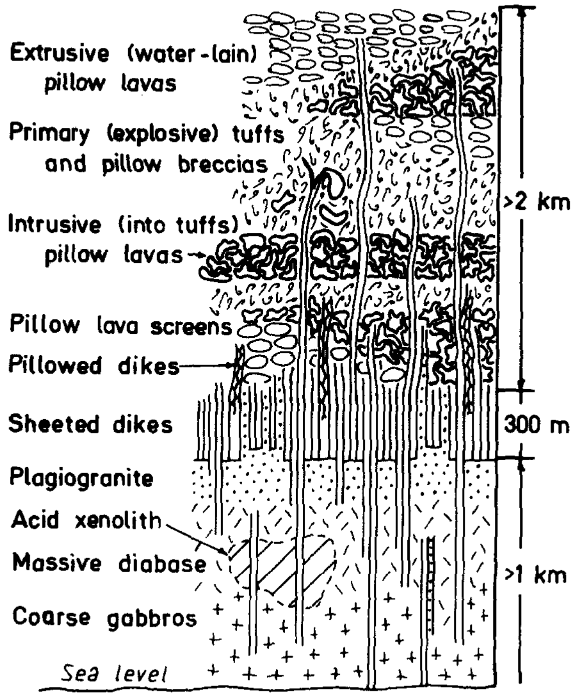

Fig. 2. Pseudostratigraphic cross-section of the Sarmiento ophiolite complex showing the mutually intrusive inter-relation of mafic dikes and plagiogranites, which imply contemporaneity of these two units, and the typical location of trondhjemites (labled as "acid xenolith") within the plutonic unit of the ophiolite (Stern, 1979).

of the complex. They are interpreted to have formed from mafic magmas by closed-system igneous fractionation involving the crystallization and separation of the large proportion of Fe-Ti oxides found concentrated in ferrogabbros within the gabbro unit of the Sarmiento complex (Stern, 1979; Saunders *et al.*, 1979).

Table 1 presents seven new chemical analyses of plagiogranites which formed a portion of the large sample (>50 kg) collected from Encuentro Fjord for zircon dating. These samples exhibit relatively high Zr (Fig. 3), Nb, and Y contents, compared with the associated mafic rocks of the Sarmiento complex, which is consistent with the plagiogranites being the end-product of extensive crystal-liquid fractionation of these mafic rocks (Stern, 1979). They also have the anomalously low K and Rb contents previously noted from other Sarmiento plagiogranites and explained as a result of removal during hydrothermal metamorphism (Stern and Elthon, 1979; Saunders *et al.*, 1979).

Trondhjemites of the Sarmiento complex are coarse-grained leucocratic rocks which occur between the plagiogranites and the underlying mafic gabbros (Fig. 2). The trondhjemites typically crop out over a vertical distance of 100 to 200 m, but both their upper and lower boundaries are diffuse and difficult to identify in the field. They are cut by numerous mafic dikes, as is the plagiogranite. In thin section, trondhjemites are quite distinct from plagiogranites, being coarser grained and containing

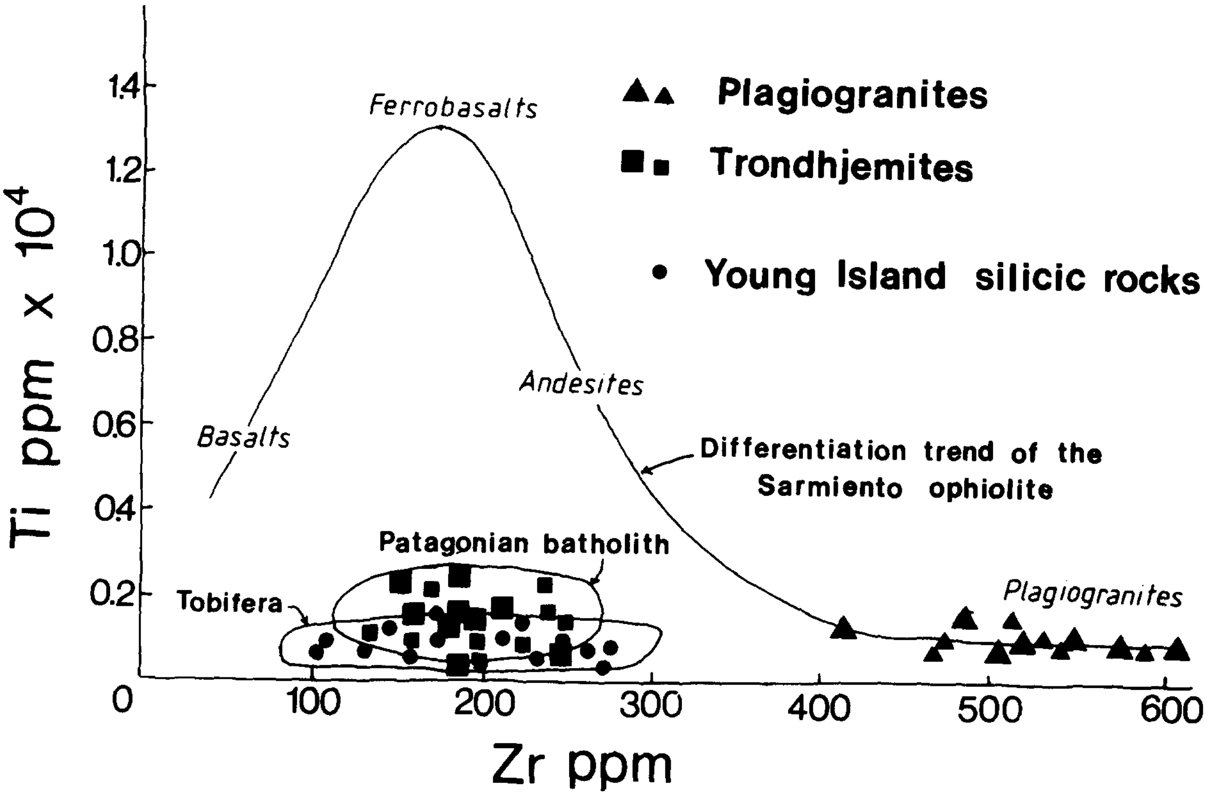

Fig. 3. TiO_2 *versus* Zr content for plagiogranites (triangles) and trondhjemites (squares) from the Sarmiento complex. Larger symbols are new data (Table 1) and smaller symbols are previously published data (Stern, 1979; Stern and Elthon, 1979; Saunders *et al.*, 1979). Trend for basalt-ferrobasalts-andesites-plagiogranites from the Sarmiento complex is taken from Stern (1979). Fields for silicic Tobifera volcanic rocks and plutons of the Patagonian batholith, as well as analyses of silicic rocks engulfed in mafic igneous rocks on Young Island (circles) to the south of Lolos and Encuentro Fjords (Fig. 1B), are taken from De Wit and Stern (1981).

Table 1. Major and trace element composition of plagiogranites and trondhjemites from the Sarmiento ophiolite complex at Encuentro Fjord.

	Plagiogranites							Trondhjemites									
	43A	43B	43D	44B	44D	44E	49A	46	53	58	59	64	65	66	67	71	78
SiO_2	72.99	71.70	72.94	73.48	74.03	74.04	74.75	66.99	69.97	71.35	70.38	71.71	72.17	71.15	70.54	72.97	68.91
TiO_2	0.20	0.32	0.22	0.22	0.22	0.22	0.27	0.27	0.40	0.30	0.35	0.32	0.33	0.32	0.14	0.05	0.52
Al_2O_3	13.28	13.80	13.43	13.51	12.62	13.30	12.20	14.96	13.62	13.90	14.17	14.24	13.88	14.24	14.24	14.28	15.38
Fe_2O_3	1.51	1.54	2.20	1.39	1.76	1.52	1.57	1.18	2.78	1.17	1.11	0.84	0.98	1.36	1.56	1.18	1.16
FeO	2.15	1.87	0.96	0.88	1.68	0.75	1.55	1.43	2.25	1.42	2.47	2.09	1.59	1.66	2.03	1.77	3.01
MnO	0.04	0.05	0.04	0.03	0.01	0.03	0.03	0.08	0.04	0.04	0.03	0.04	0.03	0.04	0.04	0.04	0.06
MgO	0.35	0.51	0.27	0.20	0.25	0.15	0.15	0.78	0.32	0.63	0.80	0.61	0.58	0.56	0.71	0.53	0.86
CaO	3.08	3.79	4.42	3.29	3.96	3.32	3.40	3.83	5.72	4.85	2.88	4.43	3.93	4.94	3.47	3.72	3.83
Na_2O	5.00	4.70	4.76	5.89	4.31	5.81	5.51	4.52	2.83	3.36	3.72	3.80	3.44	3.29	3.24	2.98	3.71
K_2O	0.19	0.70	0.23	0.04	0.06	0.05	0.14	2.28	0.57	0.52	2.16	0.37	2.04	0.70	2.51	0.95	1.10
P_2O_5	0.04	0.07	0.04	0.04	0.04	0.03	0.03	0.11	0.07	0.29	0.07	0.07	0.07	0.08	0.08	0.06	0.12
LOI	1.07	1.18	0.78	0.72	0.98	0.80	0.88	4.30	1.32	2.25	1.44	1.50	0.99	1.36	1.25	1.38	1.45
Total	99.90	100.23	100.11	99.69	99.88	100.22	100.22	99.83	99.89	100.09	100.04	100.02	100.04	99.69	100.01	99.91	100.11
Rb	<	<	<	<	<	<	<	59	22	27	54	19	51	24	67	20	23
Sr	234	279	313	251	281	270	241	177	155	171	232	184	256	189	212	197	189
Ba	80	90	100	20	40	40	60	700	140	510	1400	390	1400	340	1300	650	500
Zr	412	485	526	606	501	575	543	174	156	196	192	161	211	207	245	197	182
Y	89	97	112	143	106	119	99	24	27	31	30	29	31	29	33	23	25
Nb	17	18	18	24	21	23	22	8	9	9	11	10	12	7	9	9	10

Major elements (wt%) determined by wet chemical techniques in the laboratories of the Servicio Nacional de Geología y Minería, Santiago.
Trace elements (ppm) determined by XRF at the USGS Isotope Branch, Denver; < indicates below detectability of 3 ppm.

a somewhat higher proportion of mafic minerals such as biotite, chlorite, and epidote, as well as alkali feldspar. Also, trondhjemites characteristically contain quartz orbicules and both myrmekitic intergrowths between quartz and plagioclase and graphic intergrowths of quartz and alkali feldspars.

Petrologically, these trondhjemites resemble remobilized xenoliths of older silicic country rocks, either Tobifera Formation silicic volcanic or granites of the Patagonian batholith, found cut by numerous mafic dikes and intruded by gabbros along the margins of the Sarmiento complex, such as on Young Island (Fig. 1B; De Wit and Stern, 1981). The trondhjemites exposed in Lolos and Encuentro Fjords have also been interpreted as remnants of remobilized country rocks engulfed in the mafic rocks of the ophiolite. This interpretation is supported by geochemical data which indicate that compared to the plagiogranites, these trondhjemites have lower HFSE contents (Fig. 3) and higher La/Yb ratios and more closely resemble both the granitic plutons of the Patagonian batholith and silicic volcanic rocks of the Jurassic Tobifera Formation, which are suggested as their possible precursor lithologies (De Wit and Stern, 1981).

Table1 presents analyses of eleven samples of trondhjemites which formed a portion of the large sample (>50 kg) collected in Encuentro Fjord for zircon U-Pb dating. These samples have lower and more variable SiO_2, higher MgO and K_2O, and significantly lower Zr (Fig. 3) and Y contents than plagiogranites. Also, their Ba contents are higher than plagiogranites, and some samples, which also have high K_20, have extremely high Ba. Chemically similar samples have been referred to previously as the granophyre phase of the trondhjemites (Saunders *et al.*, 1979), and they may have formed by concentration of partial melts derived from the precursor trondhjemite lithology. These samples contain abundant graphic intergrowths of quartz and alkali feldspar.

RESULTS AND DISCUSSION

The analytical techniques, data, and calculated ages for samples of plagiogranites and trondhjemites from both Lolos and Encuentro Fjords are presented in Table 2. Figure 4 presents these data on concordia diagrams.

Zircons separated from plagiogranites collected in Lolos and Encuentro Fjords are slightly to grossly discordant, yielding lower intercept ages of 140.7 ± 0.7 and 137.1 ± 0.6 Ma, respectively (Fig. 4A). W e interpret these as formation ages for these outcrops of the Sarmiento complex. Although the plagiogranites are cut by some later mafic dikes, these ages are considered to be close to the minimum age for the igneous activity that formed this portion of the floor of the Rocas Verdes basin. Upper intercept ages for these rocks range from Proterozoic to Archean but have large errors that reduce their chronological significance.

Fuenzalida and Covacevich (1988) established a minimum stratigraphic age of late Tithonian, or 145 ± 5 Ma, for mafic lavas of the Sarmiento complex on Peninsula Taraba south of Lolos and Encuentro Fjords. The small differences between this age and the isotopic ages for the two plagiogranite bodies in Lolos and Encuentro Fjords may reflect the actual time that elapsed while different portions of the Sarmiento complex formed by extension-related igneous activity.

Trondhjemites from Lolos Fjord yield a lower intercept age of 147 ± 10 Ma (Fig. 4B). The points for the Lolos Fjord trondhjemites are not strictly linear, which may be explained by either inherited zircons in each fraction having slightly different thermal histories or by different samples having different ages. These data are consistent with the suggestion that the trondhjemites represent remobilized fragments of country rock engulfed within the essentially mantle-derived ophiolite complex. The upper intercept for these samples is 2935 Ma, but the error for this age is excessively large. A younger Proterozoic age for the inherited zircons is supported by other U-Pb studies of igneous rocks from the Austral Andes (Hervé *et al.*, 1991; Mukasa and Dalziel, 1992).

Field and petrochemical data suggest that the Rocas Verdes back-arc basin widened and its mafic igneous floor became more oceanic in character south of the Sarmiento complex (Stern, 1979, 1980, 1991; De Wit and Stern, 1981). An age of 150 ± 1 Ma has been obtained for the igneous floor of a more southern portion of the Rocas Verdes basin now exposed on South Georgia Island (Mukasa and Dalziel, 1992). This older age suggests that the basin may have opened by unzipping from south to north, with the more southern portions beginning to form earlier, and developing more extensively in an oceanic setting, than the northern portion of the basin in the vicinity of the Sarmiento complex. Alternatively, the greater width and more oceanic character of the southern part of the Rocas Verdes basin may reflect regional differences in spreading rate rather than the duration of extension-related igneous activity associated with the basin's development. In this case, each of the different ages reported here and by Mukasa and Dalziel (1992) may represent only specific events within a longer time period during which extension-related igneous activity produced the different parts of the mafic floor of the Rocas Verdes basin.

Alabaster and Storey (1990) reported chemical data suggesting that the Rocas Verdes basin did not develop in a back-arc supra-subduction-zone setting but rather in an oblique-slip margin akin to that of the Gulf of California. However, Halpern (1973) and Bruce *et al.* (1991) have dated a number of I-type plutons of the southern Patagonian batholith, south and west of the Rocas Verdes ophiolite belt, in the age range 151 to 138 Ma, contemporaneous with the mafic igneous activity that formed these ophiolites. The Patagonian batholith has been interpreted as the roots of a convergent plate boundary magmatic arc (Dalziel *et al.*, 1974; Stern and Stroup, 1982; Bruce *et al.*, 1991). The presence in this batholith of plutons of similar age to the mafic floor of the Rocas Verdes basin is consistent with the original suggestion of Dalziel *et al.* (1974) that this was a back-arc basin, the development of which rifted the continental crust north and east of a contemporaneous magmatic arc active along the continental margin.

Table 2. U-Pb analytical data and apparent ages.

Wt (mg)	Size (μm)	Concentration (ppm)		Isotopic Compositions			Apparent Ages (Ma)		
		^{238}U	$^{206}Pb^*$	$^{204}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$
Plagiogranite from Lolos Fjord (solid circles in Fig. 4A)									
4.43	75 - 150	494.0	9.477	0.00037	0.05461	0.28505	141.3	142.3	159.2
2.73	42 - 75	488.6	9.345	0.00029	0.05365	0.28115	140.9	142.2	164.5
4.11	< 42	588.5	11.389	0.00022	0.05390	0.28857	142.5	147.3	223.9
Plagiogranite from Encuentro Fjord (solid triangles in Fig. 4A)									
3.61	75 - 150	275.5	5.187	0.00004	0.05335	0.30885	138.7	149.0	316.5
1.80	42 - 75	321.1	6.063	0.00119	0.07090	0.36717	139.1	151.6	352.4
1.87	< 42	476.2	9.445	0.00020	0.07239	0.32282	146.0	201.7	915.3
Trondhjemite from Lolos Fjord (solid circles in Fig. 4B)									
7.79	> 150	546.8	12.232	0.00023	0.06996	0.19423	164.5	216.4	827.0
8.37	75 - 150	481.3	9.827	0.00027	0.05972	0.16889	150.3	169.2	443.3
7.68	42 - 75	532.9	10.904	0.00046	0.05763	0.21798	150.6	155.7	234.1
Trondhjemite from Encuentro Fjord (plot not shown)									
8.90	75 - 150	752.1	13.848	0.00010	0.05228	0.13395	135.7	141.0	230.7
5.76	42 - 75	820.0	15.758	0.00016	0.05284	0.14419	141.6	146.1	220.9

*Denotes radiogenic Pb. Note: All zircon fractions are non-magnetic at 1.8 amperes, 2-degree side slope, 15-degree forward slope on a Frantz magnetic barrier separator. Isotopic compositions and concentrations were measured statically on a VG Sector thermal ionization mass spectrometer. The measured blank for this study was 0.05 nanograms (*i.e.*, <0.5% of the total Pb). The within-run precisions for zircon Pb isotopic ratios were generally around ±0.04% (1σ), except for $^{204}Pb/^{206}Pb$, which reached ±0.3% for the highest ratios, where ages were insensitive to ^{204}Pb. Precision on the Pb and U concentrations are ±0.1% or better. Errors on Pb/U isotopic ratios reach a maximum of ±0.2% (1σ) and are calculated using the Ludwig (1982) program, which propagates analytical errors of the U and Pb concentrations. All isotopic ratios have been normalized for mass-dependent fractionation using factors of 0.08 ± 0.02% per atomic mass unit (a.m.u.) for Pb and 0.06 ± 0.02% per a.m.u. for U. Common Pb corrections have been based on one analysis of feldspar from the freshest Encuentro Fjord plagiogranite for which $^{206}Pb/^{204}Pb = 18.423 \pm 4$, $^{207}Pb/^{204}Pb = 15.581 \pm 3$, and $^{208}Pb/^{204}Pb = 37.845 \pm 8$. Constants used: $\lambda\ ^{235}U = 9.8485 \times 10^{-10}\ yr^{-1}$; $\lambda\ ^{238}U = 1.55125 \times 10^{-10}\ yr^{-1}$; $^{238}U/^{235}U = 137.88$.

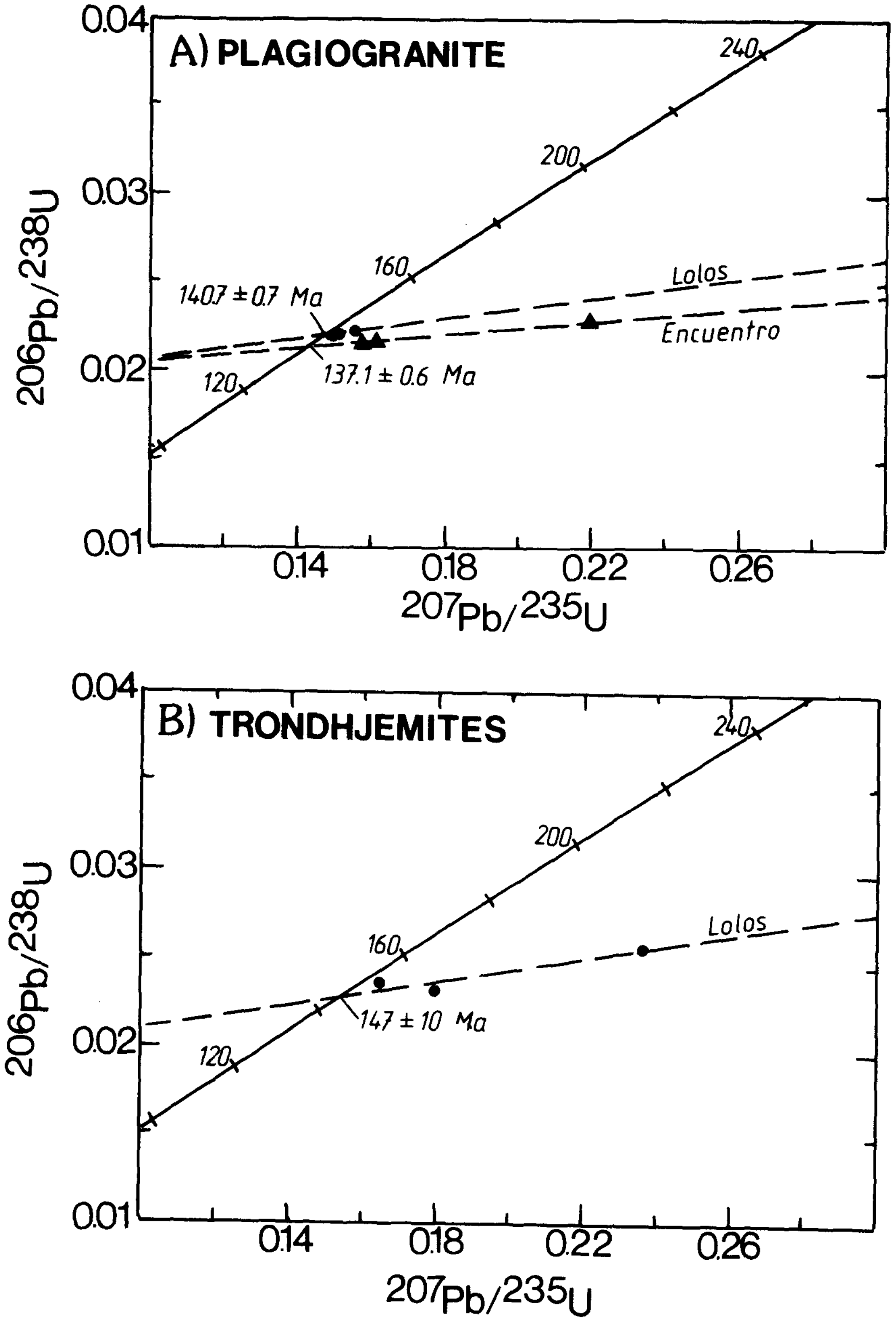

Fig. 4. U-Pb concordia diagrams showing the lower intercepts for samples of (A) plagiogranites from Lolos (circles) and Encuentro (triangles) Fjords, and (B) trondhjemites from Lolos Fjord. Error ellipses for each data point are smaller than the symbols used. The concordia upper intercepts are not included on the diagrams because they have large errors and no particular chronological significance other than to broadly constrain the age of inherited zircon components as Precambrian.

Aknowledgments—We thank the Empressa Nacional del Petroleo, Chile, for logistic support. The isotopic work was supported in part by National Science Foundation grant DPP-8643441.

REFERENCES

Alabaster, T., and Storey, B. C., 1990. Modified Gulf of California model for South Georgia, north Scotia Ridge, and implications for the Rocas Verdes back-arc basin, southern Andes. *Geology* **18**, 497-500.

Bruce, R. M., Nelson, E. P., Weaver, S. G., and Lux, D. R., 1991. Temporal and spatial variations in the southern Patagonian batholith: Constraints on magmatic arc development. In: *Andean Magmatism and Its Tectonic Setting* (edited by R. S. Harmon and C. W. Rapela). Geological Society of America, Special Paper **265**, 1-13.

Bruhn, R. L., Stern, C .R., and De Wit, M. J., 1978. Field and geochemical data bearing on the development of a Mesozoic volcano-tectonic rift zone and back-arc basin in southernmost South America. *Earth and Planetary Science Letters* **41**, 32-46.

Dalziel, I. W. D., De Wit, M., and Palmer, K. F., (1974. Fossil marginal basin in the southern Andes. *Nature* **250**, 291-294.

De Wit, M. J., and Stern, C.R., 1981. Variations in the degree of crustal extension during the formation of a back-arc basin. *Tectonophysics* **72**, 229-260.

Elthon D., Lawrence, J. R., Hanson, R. E., and Stern, C. R., 1984. Modelling of oxygen isotope data from the Sarmiento ophiolite complex, Chile. In: *Ophiolites and Oceanic Lithosphere* (edited by I. Gass, S. Lippard, and A. Shelton), pp. 185-197. Blackwell Scientific Publications, London, England, UK.

Fuenzalida, R., and Covacevich, V., 1988. Volcanismo y biostratigrafía del Jurásico y Cretácico Inferior en la Cordillera Patagónica, Región de Magallanes, Chile. *Actas, V Congreso Geológico Chileno, Santiago* **3**, H159-H183.

Halpern, M., 1973. Regional geochronology of Chile south of 50°S latitude. *Bulletin of the Geological Society of America* **84**, 2407-2422.

Hervé, F., Loske, W. P., Miller, H., and Pankhurst, R. J., 1991. Chronology of provenance, deposition and metamorphism in the southern limb of the Scotia Arc. In: *Geologic Evolution of Antarctica* (edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson), pp. 429-435. Cambridge University Press, Cambridge, England, UK.

Mukasa, S. B., and Dalziel, I. W. D., 1992. Southern Andes and South Georgia Island, north Scotia Ridge: Zircon U-Pb and muscovite ^{40}Ar/^{39}Ar age constraints on the kinematic evolution of southwestern Gondwanaland. *Tectonics*, in press.

Saunders, A. D., Tarney, J., Stern, C. R., and Dalziel, I. W. D., 1979. Geochemistry of Mesozoic marginal basin floor igneous rocks from southern Chile. *Bulletin of the Geological Society of America* **90**, 237-258.

Stern, C. R., 1979. Open and closed system igneous fractionation within two Chilean ophiolites and the tectonic implications. *Contributions to Mineralogy and Petrology* **68**, 243-258.

Stern, C. R., 1980. Geochemistry of Chilean ophiolites: Evidence of the compositional evolution of the mantle source of back-arc basin basalts. *Journal of Geophysical Research* **85**, 955-966.

Stern, C. R., 1991. Isotopic composition of Late Jurassic and Early Cretaceous mafic igneous rocks from the southernmost Andes: Implications for sub-Andean mantle. *Revista Geológica de Chile* **18**, 15-23.

Stern, C. R., and Elthon, D., 1979. Vertical variations in the effects of hydrothermal metamorphism in Chilean ophiolites: Their implications for ocean floor metamorphism. *Tectonophysics* **55**, 179-213.

Stern, C. R., and Stroup, J. B., 1982. The petrochemistry of the Patagonian batholith, Ultima Esperanza, Chile. In: *Antarctic Geoscience* (edited by C. Craddock), pp. 135-142. University of Wisconsin Press, Madison, WI, USA.

Stern, C. R., De Wit, M. J., and Lawrence, J. R., 1976. Igneous and metamorphic processes associated with the formation of Chilean ophiolites and their implications for ocean floor metamorphism, seismic layering and magnetism. *Journal of Geophysical Research* **81**, 4370-4380.