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Proterozoic–early Paleozoic ophiolites of the Andean basement of southern South America

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ABSTRACT

We describe a series of Middle Proterozoic to early Paleozoic ultramafic and mafic rocks in the basement of the Central Andes that have different geochemical attributes and paleogeographic settings. Several ophiolitic belts are identified on the basis of lithologic assemblages and geochemical characteristics, but only the most important belts are described here: the Western and Eastern Córdoba (Early Cambrian), Pie de Palo (Middle Proterozoic), Western Precordillera (Middle Ordovician), and eastern Cordillera Frontal (Proterozoic) belts. Most ophiolites in the Central Andean basement belong to one of two types: the harzburgite type and the lherzolite type. For example, in the metamorphic basement in the Western Córdoba belt of the Eastern Sierras Pampeanas, a harzburgite-type ophiolite is associated with important podiform chromite deposits whereas a lherzolite-type ophiolite of the Eastern Córdoba belt was emplaced in a backarc setting. The most ancient ophiolites at these latitudes are exemplified by the Middle Proterozoic Pie de Palo ophiolite, part of the Cuyania terrane, which is a Laurentian-derived block accreted to the protomargin of Gondwana during early Paleozoic time. The ophiolitic assemblage of the Western Precordillera includes serpentinized peridotites, ultramafic cumulates, layered gabbros, diabases, and basaltic pillow lavas. The ophiolites of the eastern Cordillera Frontal are emplaced within three distinctive belts in Precambrian metamorphic rocks. The dominant assemblage of the eastern Cordillera Frontal includes serpentinized peridotites, gabbros, basaltic dikes, and pillow lavas. As a whole, these ophiolite belts represent a complex system of sutures that record the accretionary history of the basement of the Central Andes in several tectonic episodes.

INTRODUCTION

The basement of the Central Andes of Argentina, situated within the flat segment of subduction between lat 27°S and 33°S, exposes a series of ophiolitic belts. Some of these belts were described in the early work of Borrello (1969) and in the review of ultramafic and mafic rocks of Villar (1975). The ophiolitic belts have received increasing attention in recent years as they have been interpreted as marking possible sutures of a collage of terranes accreted to the protomargin of Gondwana during Proterozoic–early Paleozoic time (Ramos et al., 1984, 1986). The current distribution of these possible sutures and the outline of the suspected allochthonous terranes are shown in Figure 1, along with the main geologic provinces of the Central Andes.

Present information on these belts is inhomogeneous; some of them are known at a reconnaissance level, whereas others are better studied. The objective of this overview is to describe these poorly known belts in order to call attention to their lithologic assemblages, ages, distribution, and local features and thus to encourage future studies.

ULTRAMAFIC AND MAFIC BELTS AND OPHIOLITE ASSEMBLAGES

The early reviews of Villar (1975, 1985) focused on the petrographic attributes and the Alpine-type settings of these ultramafic-mafic belts. The lithology, the complex tectonic emplacement, and the belts' general association with mylonitic rocks prompted her to

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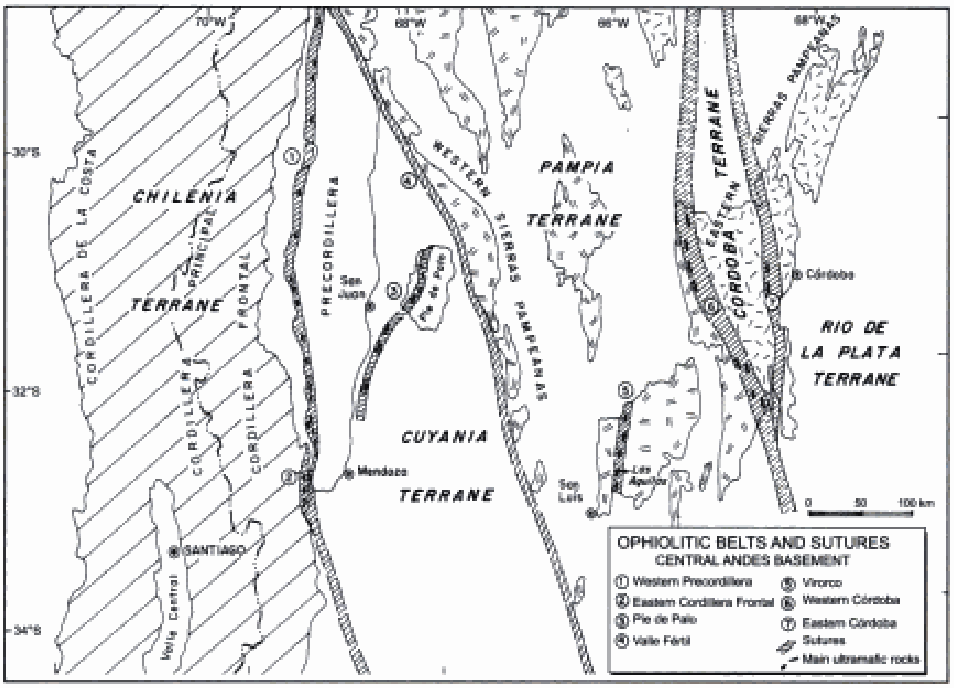

Figure 1. Ultramafic and mafic rocks interpreted as ophiolitic belts, possible sutures among Proterozoic–early Paleozoic allochthonous suspect terranes, and main geologic provinces within the flat subduction segment of the Central Andes (modified from Ramos, 1988, 1994, 1995).

interpret some of them as ophiolitic assemblages. These belts are interpreted to have been obducted onto the Río de La Plata craton successively from east to west (Ramos, 1988). We describe them in this order.

1. The Precambrian–early Paleozoic basement of the Sierras Pampeanas is exposed in a series of mountain blocks uplifted during the Andean orogeny. These mountains expose two belts of ultramafic and mafic rocks of Late Proterozoic age: the Eastern Córdoba belt and Western Córdoba belt (Fig. 1) within the Eastern Sierras Pampeanas, which separate the Córdoba terrane from Pampia terrane and the Río de La Plata craton (Kraemer et al., 1995). These belts are well developed along the uplifted basement of the east-central part of the Andes. Several ophiolitic thrust sheets have been recognized within the Late Proterozoic–early Paleozoic metamorphic basement. Since the early work of Villar (1985), the existence of two separate belts in the Eastern Sierras Pampeanas has been recognized, but Kraemer et al. (1995) were the first to focus on their tectonic importance.

2. Another tract of ultramafic and mafic rocks known as the Virorco belt is developed within the Pampia terrane, north of the city of San Luis (Fig. 1). Elongated bodies of mafic and ultramafic rocks, up to 3.5 km in length and up to 500 m width, crop out within a 50-km-long, north-northeast–trending belt. These rocks, first described by González Bonorino (1962), are characterized by ultramafic and mafic bodies metamorphosed to granulitic facies. Dominant rock types include dunites, pyroxenites, hornblendites, and amphibolites (Bjerg et al., 1996). A felsic segregation in the ultramafic rocks at Las Aguilas dated by U-Pb in zircon separates yielded a value of 478 ± 6 Ma that was interpreted by Sims et al. (1997) as a crystallization age. The extensively boudinaged rocks display a foliation parallel to the stretching lineation in the enclosing pelitic gneisses. These mafic-ultramafic bodies are associated with platinum-group minerals in Las Aguilas (Gervilla et al., 1992; Mogessie et al., 1995) and have been interpreted as a series of linear intrusions unrelated to an ophiolite assemblage (Villar, 1985), as a suture of a backarc basin (Ramos, 1988), or more recently, as a series of mafic, ultramafic, and amphibolite rocks emplaced synchronously with regional deformation in a backarc or frontal island-arc setting (Sims et al., 1997). Although geologic studies are scarce and the precise nature of this belt is unknown, it is worth mentioning that Kostadinoff et al. (1999) have shown a large positive magnetic anomaly, which coincides with the trace of this belt that has been interpreted as a major crustal discontinuity.

3. A major lineament, known as the Valle Fértil megashear, coincides with a belt of mylonitic rocks that show a conspicuous ductile deformation of Middle Ordovician age (Schmidt et al., 1995; Ramos et al., 1998). There are some ultramafic and mafic rocks along this possible suture (Mirré, 1976). Harzburgites, norites, and pyroxenites are described by Villar (1985) in the Sierra de Valle Fértil, along with other peridotites and amphibolites in the Sierra de La Huerta (Vujovich et al., 1994; Castro de Machuca et al., 1996). These units are better developed in the Sierras de Maz, Umango, and Espinal (see Villar, 1985) to the north outside of the study area. These mafic and ultramafic rocks consist of partially serpentinized peridotite associated with asbestos mines, amphibolites, and metagabbros. Protoliths

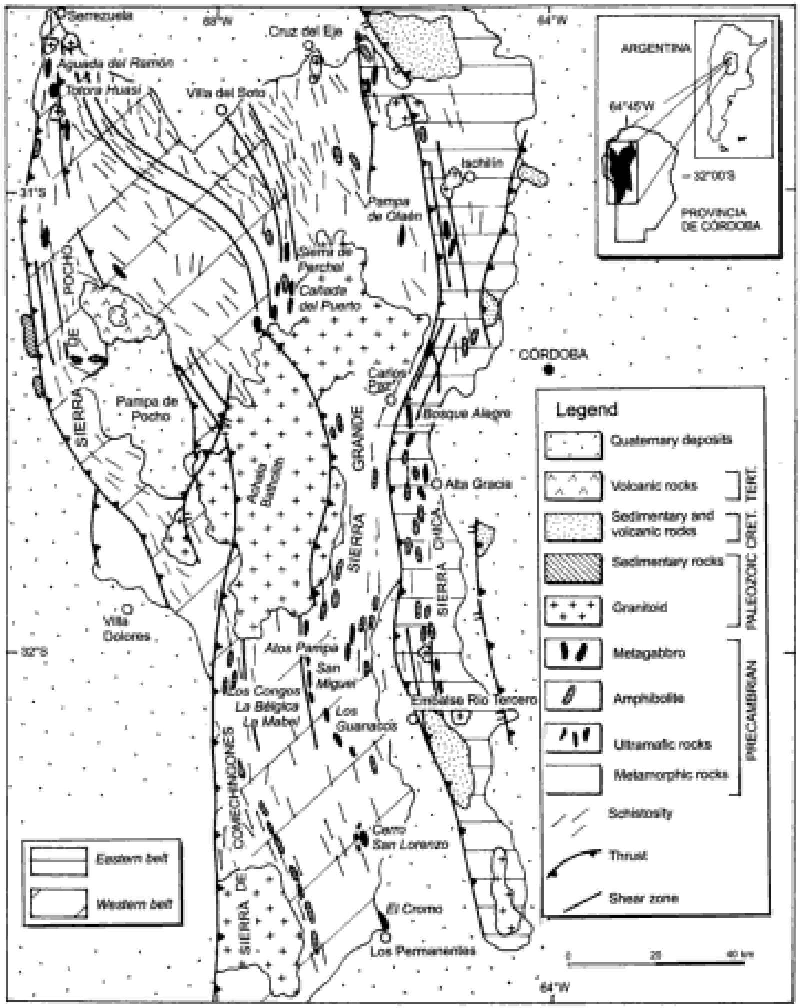

Figure 2. Generalized geologic map of the Sierras de Córdoba, showing the location of the Western and Eastern Córdoba belts of ultramafic and mafic rocks (modified from Mutti, 1992, 1997, and Escayola, 1994).

of most of these amphibolites and metagabbros are interpreted to have formed in an island-arc or backarc setting (Vujovich, 1993; Vujovich and Kay, 1996). Within the study area, the Valle Fértil lineament coincides with major gravity and magnetic anomalies that have been modeled as large ultramafic bodies emplaced in the middle to upper crust (Giménez, 1997; Martínez, 1997). This belt coincides with the proposed suture between the Cuyania and Pampia terranes (Ramos, 1995; Kay et al., 1996; Astini et al., 1996; Rapela et al., 1998).

4. Another belt of ophiolites separates the Precordillera and Pie de Palo terranes, within the Cuyania composite terrane (Fig. 1). Vujovich and Kay (1998) suggested that this belt represents a Middle Proterozoic ophiolite.

5. The westernmost tract of ultramafic and mafic rocks between lat 30°S and 34°S is represented by the Western Precordillera–eastern Cordillera Frontal belt that separates the Chilenia and Cuyania terranes. The belt was emplaced during Devonian time (Ramos et al., 1984).

The paucity of structural and petrologic data precludes a detailed description of some of these belts. We focus our discussion on the Western and Eastern Córdoba, Pie de Palo, and Western Precordillera–eastern Cordillera Frontal belts, for which critical data exist in support of their origin as ophiolitic assemblages.

EASTERN CORDOBA BELT

Eastern Córdoba ophiolites

This belt—exposed along a reverse fault that uplifted the Sierra Chica de Córdoba during the Tertiary (Fig. 2)—extends for 100 km from Ischilín in the north to Embalse Río Tercero in the south. The main exposures included the Pampa de Olaen district, the Bosque Alegre and Alta Gracia bodies, and several other minor bodies of ultramafic and mafic rocks (Mutti, 1987).

Villar (1985) described the ultramafic and mafic rocks in this belt as a typical Alpine-type assemblage. Ramos (1988) interpreted this ultramafic assemblage as an ophiolitic belt emplaced in the suture between the Río de La Plata craton and the allochthonous terranes located to the west. Structural studies of Kraemer et al. (1995) demonstrate the west vergence of the ophiolite emplacement.

The Bosque Alegre ophiolite, southwest of Córdoba city on the western slope of Sierra Chica (Mutti, 1992) constitutes the main exposure in this belt. It is characterized by an elongate body up to 2 km long with an average width of 0.8 km and is bounded on the west by a ductile shear zone associated with a highly schistose amphibolite a few centimeters thick. Ophiolitic rocks are associated with mylonitic belts in a series of west-vergent thrust sheets (Bonalumi and Gigena, 1987). The country rock is composed of schists and tonalite gneiss with a mineral assemblage of plagioclase + quartz + K-feldspar + biotite + garnet, indicating an amphibolite metamorphic facies. Dominant rocks types are lherzolite, subordinate harzburgite, pyroxenite, and gabbro, intruded by leucocratic rocks. The lherzolite has a layered structure and consists of olivine (Fo_{88} to Fo_{90}), orthopyroxene (En_{87} to En_{90}), diopside, amphibole, magnetite, ilmenite, and chromite. The harzburgite displays cumulate textures and consists of olivine, orthopyroxene, spinel, magnetite, ilmenite, chromite, and phlogopite and is intruded by numerous plagiogranite, olivine and hornblende pyroxenite, and gabbro dikes (Mutti, 1992).

Geochemical characteristics of the Eastern Córdoba ophiolites

The peridotites of the Eastern Córdoba belt have SiO_2 contents between 41.99% and 46.80% and MgO contents between 42% and 46%. In the MgO-Al_2O_3-CaO diagram, the peridotites plot in the cumulate peridotitic field, whereas the amphibolites plot in the mafic cumulate field. In the FeO/MgO vs. SiO_2 diagram, the amphibolites plot as calc-alkalic rocks (Mutti, 1992). Among the trace elements when compared to chondrites (Wood et al., 1979b), the Rb and Ba have high relative values (10 × chondrites), as well as Th and Nb. Most of the Eastern Córdoba belt amphibolites show strong affinities with backarc basalts (see Table 1 and Fig. 3B), and hence we interpret them as backarc ophiolites (Mutti, 1992; Escayola et al., 1996).

Tectonic setting

Escayola (1994) identified the Eastern Córdoba belt as a typical lherzolite ophiolite in the sense of Boudier and Nicolas (1985), distinct from the typical Western Córdoba belt of harzburgitic type.

The inferred back-arc origin of the Eastern Córdoba belt led Kraemer et al. (1995) to interpret the basement of the Córdoba terrane as part of the Río de La Plata craton. On the basis of this interpretation, Ramos (1995) recognized the Córdoba terrane as a parautochthonous unit that has been incorporated into the craton as a result of the closure of a backarc basin during the latest Proterozoic to Early Cambrian.

WESTERN CORDOBA BELT

Western Córdoba ophiolites

The ultramafic and mafic rocks exposed along the western flank of Sierra Grande de Córdoba delineate a 150-km-long discontinuous belt that crops out in the Proterozoic metamorphic basement of Sierras Pampeanas (Fig. 2). This belt extends from Cruz del Eje in the north to Los Permanentes in the south.

The host rocks of the ultramafic and mafic units consist of medium- to high-grade metamorphic rocks that broadly correspond to the Brasiliano cycle (900 to 500 Ma). The metamorphism is characterized by two prograde episodes (Escayola et al., 1996) that are associated with an intense deformation that produced an axial-planar foliation. Ages obtained by Rb/Sr and K/Ar methods range from 550 to 640 Ma (Cingolani and Varela, 1975; Caminos et al., 1982). Tonalite and granodiorite stocks and granitic veins and pegmatites intrude these units. The latest granitic intrusion of the Brasiliano cycle has been dated between 530 and 520 Ma by U-Pb in zircons (Rapela et al., 1998). This date indicates a Cambrian age for the syncollisional intrusions. Mylonitization and retrograde metamorphism followed late high-grade metamorphism associated with migmatization. Dominant types are quartz + feldspar, quartz + mica + feldspar, and quartz + garnet gneisses and schists, along with migmatites and subordinate amphibolites, marbles, and kinzigites. Their protoliths have been interpreted as quartzofeldspathic and quartz-rich clastic rocks, shales, graywackes, shelf carbonates, and basaltic rocks (Mutti et al., 1997). Ultramafic rocks are bounded by reverse to dextral strike-slip faults marked by ductile shear zones (Martino et al., 1995).

In the northern segment of the Western Córdoba ophiolites, Villar (1985) recognized a series of mafic to ultramafic bodies such as Totora Huasi, Agua de Ramón, Sierra del Perchel, and Cañada del Puerto (Fig. 2). There are no detailed studies of these rocks.

The Western Córdoba ophiolites south of the Achala batholith occur in four distinctive ways: (1) metamorphic peridotites that are composed mainly of depleted harzburgite with concordant to subconcordant podiform chromite ore bodies; (2) transition-zone harzburgites, lherzolites, and websterites intruded by sills and pods of spinel dunites; (3) a layered complex composed mainly of cumulate harzburgite and gabbros; and (4) a cordierite + garnet + anthophyllite association that could represent the basaltic pillow-lava section. These rocks have been recognized in Atos Pampa–San Miguel, Los Congos, La Bélgica, Los Guanacos, Cerro San Lorenzo, El Cromo, and Los Permanentes (see locations in Fig. 2) (Fernández Gianotti, 1979; Escayola, 1994; Mutti 1994, 1997).

Metamorphic peridotites

Metamorphic peridotites occur as elongated lenses that were emplaced along ductile shear zones traceable for more than 40 km (Massabie et al., 1994). The main foliation azimuth ranges from N40°W to N40°E, and the regional structure is characterized by a series of west-vergent thrust sheets that dip between 50° and 70° to the east (Dalla Salda, 1984). Individual peridotite bodies reach up to 1700 m in length and 800 m in width. The dominant rock type as inferred from mineral relicts and pseudomorphic textures is harzburgite with Mg# [Mg/(Mg + Fe)] between 0.87 to 0.84, alumina content <2%, and alkalis content <0.2% (Mutti, 1992; Escayola, 1994; Escayola et al., 1996). The metamorphic assemblage in these rocks includes antigorite + brucite + tremolite + lizardite + chrysotile. The lack of layered textures indicates that these bodies are not cumulate rocks (Escayola, 1994).

Most of the ultramafic rocks are associated with podiform chromite bodies within the basal units, which have been interpreted as mantle tectonites (Mutti et al., 1997). In most cases, the chromitite is enclosed in an intensely sheared dunitic or orthopyroxenitic host rock. A few Fo_{94} to Fo_{92} olivine relicts occur in the serpentinized dunite mesh. Three types of chromite deposits are present: concordant, subconcordant, and, rarely, discordant with penetrative foliation and lineation. The latter is strongly deformed (Mutti and Fernández, 1999). The chromite grains vary from subhedral to anhedral and range from 20 μm to 5 mm. Microscopic examination of the samples shows dark brown spinels with exsolution textures and a wide variety of mineral

TABLE 1. REPRESENTATIVE ANALYSES OF EASTERN AND WESTERN CORDOBA BELTS

	Eastern Córdoba ophiolite backarc amphibolites*					Western Córdoba ophiolite							Western Córdoba ophiolite					
						Arc amphibolites							Harzburgites†		Spinel dunites†		Gabbroic dikes†	
Sample	104	M311	16	M262	M259	44	M220	M200	M241	SE6	SU4	SE8						
SiO_2	46.77	40	48.65	45.52	46.62	52.02	46.68	48.35	47.74	43	40.43	45.36	46.46	43.92	22.89	27.61	41.12	39.83
TiO_2	1.93	0.63	1.58	1.47	1.15	0.6	0.66	0.49	0.61	0.85	0.62	0.71	0.41	0.86	5.23	1.63	0.72	0.74
Al_2O_3	13.86	14.74	14.25	14.87	12.24	13.57	12.84	18.38	13.12	13.45	14.74	15.7	0.73	2.71	15.79	18.76	15.55	17.3
FeO	13.1	10.54	10.01	12.45	12.72	12.15	8.83	7.3	11.91	11.76	11.4	12.66	8.06	10.07	35.83	17.94	11.27	12.17
MnO	0.23	0.16	0.17	0.16	0.21	0.01	0.18	0.13	0.19	0.2	0.3	0.18	0.13	0.13	0.33	0.2	0.2	0.21
MgO	8.61	11.78	5.81	7.56	8	8.15	8.72	6.55	7.26	8.82	11.21	12	43.8	42.09	19.73	33.37	13.57	12.05
CaO	12.73	15.86	13.03	14.22	13.9	9.11	18.9	14.66	13.26	18.06	16.84	10.14	0.28	0.11	0.1	0.19	16.49	16.56
Na_2O	1.81	2	2.78	1.65	1.86	1.76	0.84	1.36	1.78	0.91	0.41	1.13	0.1	0.07	0.05	0.16	0.77	0.78
K_2O	0.37	1.07	0.53	0.5	0.65	1.2	0.21	0.28	0.24	0.22	0.19	0.23	0.01	0.01	0.03	0.02	0.27	0.3
P_2O_5	0.2	0.06	0.13	0.13	0.15	0.04	0.05	0.03	0.06	0.07	0.06	0.05	0.02	0.02	0.02	0.11	0.03	0.05
LOI	2.5	2	2.81	1.45	2.5	b.l.	1.58	1.27	2.5	2.5	3.49	1.34						
Total	102.11	98.84	99.75	99.98	100.00	98.61	99.49	98.8	98.67	99.84	99.69	99.5	100.00	99.99	100.00	99.99	99.99	99.99
Cr	321	850	170	360	200		300	289	400	280	320	480	2734	1647	68		372	308
Ni	93	341	73	216	51	500	131	103		117	154	209	2225	1235	203	775	114	96
Co	49	60	46	56	37	57	39	40	52	50	54	59	112	86	125	180	53	61
Sc	50	38	44	40	45	61	33	31	49	46	47	58	8	31	86	91	53	47
V	401	200	299	270	292	55	257	128	257	336	280	293	29	160	1376	78	282	226
Rb	15	15	33	20	15	259	20	20	15	15	18	20	2	2	16	b.l.	7	5
Cs	1	1	1	1.2	1	58	1	1	1	1	1	1	0.52	0.2	1.67	b.l.	0.09	0.01
Ba	50	370	79	70	270		102	122	50	50	19	17	9	38	111	0.43	38	23
Sr	190	81	252	416	163	470	53	116	44	65	41	79	b.l.	b.l.	8	30	418	493
Ga						95										98		
Ta	0.32	<0.50	<1	<1	<0.50	<0.50	<0.50	<0.50	0.56	0.5	0.5	0.5	0.04	0.01	0.04	0.12	0.08	0.07
Nb	8.3												25.5	21.7	33	b.l.	15.7	16.8
Hf	2.6	2	3.4	1.6	2	1	0.7	0.8	1	1	0.5	1.1	0.08	0.15	0.52	1.94	1.17	1.1
Zr	102		112	73			23	31			20	25	b.l.	b.l.	b.l.	65	96	51
Y	32	24	35	24	30	18	25	15	23	35	20	30	20	6	6	b.l.	11	13
Th	0.95	1.2	0.5	0.9	0.2	<0.50	<0.50	0.5	0.5	0.5	0.5	0.5	0.04	b.l.	0.17	b.l.	0.1	b.l.
U	0.42	0.5	0.5	0.5	1.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1	0.38	0.15	0.32	b.l.	0.06
La	7.8	4.1	5.8	7.3	7.4	1.3	1.3	1	2.2	1.0	0.9	0.8	0.2	0.22	0.13	0.82	1.61	1.47
Ce	19	13	15	19	23	3	4	3	3	5	5	7	0.95	1.26	0.81	2.13	4.44	4.58
Nd	5	5	10.16	8	18	5	5	5	5	5	5	5	0.73	0.63	0.35	3.45	5.16	4.19
Sm	4	2.3	3.68	3	5.1	1	1.2	1	1.6	1.8	1.1	1.9	0.03	0.07	0.12	1.84	2	1.87
Eu	1.9	0.7	1.28	1.1	1.4	0.5	0.5	0.4	0.8	0.6	0.7	0.7	0.02	0.02	0.05	0.26	0.78	0.76
Gd													0.05	b.l.	b.l.	3.37	2.9	2.69
Tb	1.1	0.5	0.82	0.5	0.9	0.5	0.5	0.5	0.5	0.5	0.5	0.9	0.01	0.03	0.16	0.67	0.54	0.52
Ho													b.l.	b.l.	0.33	1.12	0.92	0.8
Tm													b.l.	b.l.	0.21	0.5	0.43	0.4
Yb	4.1	2.9	3.45	2.5	3.5	2.9	2.7	1.6	3.5	3.5	2.6	3.8	0.08	0.36	1.49	3.06	2.69	2.59
Lu	0.63	0.48	0.51	0.34	0.49	0.4	0.39	0.25	0.6	0.08	0.39	0.51	0.01	0.06	0.26	0.47	0.4	0.37

Note: Blank—not determined; b.l.—below limit of detection. Values are weight percent for oxides, parts per million for trace elements.

* This paper.

† Escayola et al. (1996).

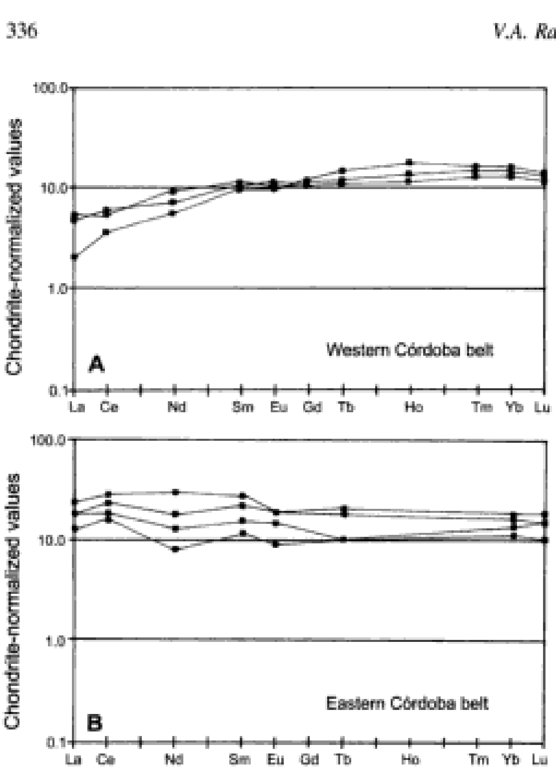

Figure 3. REE pattern (normalized to chondrites) of representative mafic rocks of the Córdoba belts. A, Western Córdoba (modified from Escayola et al., 1996; normalization factor after Wood et al., 1979b). B, Eastern Córdoba (modified from Mutti, 1997; normalization factor after Sun and McDonough, 1989).

inclusions such as olivine (Fo_{96} to Fo_{98}), orthopyroxene ($En_{98.0}$ to $En_{93.5}$), clinopyroxene ($En_{69.5}Fs_{2.4}Wo_{7.9}$ to $En_{52.0}Fs_{26.0}Wo_{22.0}$), millerite, and bornite (Mutti, 1995). The analyses for PGEs (platinum-group elements) show a concentration in the chromite dunite of 30.7 to 980 ppb, whereas the concentration in the harzburgites ranges from 1.7 to 4.9 ppb. The chondrite-normalized patterns range from highly fractionated to flat PGE profiles (Mutti and Fernández, 1999).

Transition-zone peridotite

The transition zone between the mantle and crustal units is well represented in the Western Córdoba belt of the Sierras de Córdoba and locally contains cumulate tectonized peridotites with thick, layered, gabbro sills and numerous small gabbro dikes and veins. Dominant lithologies include harzburgite, dunite, pyroxenite, and gabbro as well as intensively serpentinized amphibolites. The gabbros show relict layering ranging in thickness from 0.01 to 20 m. Transition-zone peridotites have a characteristic Mg# between 0.77 and 0.70 (though some values fall between 0.64 and 0.50) and higher alumina (>2%) and alkalis (>0.2%) contents than the metamorphic peridotites. Olivine ($Fo_{91.0}$ to $Fo_{86.8}$) and orthopyroxene ($En_{88.0}$ to $En_{86.5}$) are richer in Fe than the basal peridotites. Intercumulus clinopyroxene grains and clinopyroxene lamellae in orthopyroxene range from $En_{67.9}Fs_{2.0}Wo_{30.1}$ to $En_{50.5}Fs_{40.0}Wo_{45.5}$. Hornblende, ferrotschermakite, pargasite, and edenitic hornblende are also common (Mutti and Fernández, 1999).

In some other areas, metamorphosed websteritic dikes in the harzburgites, up to more than 4 m wide, have an antigorite + diopside + tremolite assemblage with a relict igneous texture and display diffuse contacts with the peridotite, in places with interlayered dunites. The harzburgitic rocks are also intruded by sills and pods, arranged as boudins of lherzolitic rocks with the metamorphic association of olivine + tremolite. Spinel dunite dikes, 0.5 to 3 m thick, intrude the harzburgites subconcordantly and are composed of olivine + spinel + chromite ± orthopyroxene.

Layered complex

The mafic layered section is well represented in Cerro San Lorenzo (Fig. 2) and in a few other localities as isolated lenses up to 2700 m long and 1600 m thick. In addition to the layered facies, several concordant, ~1-m-thick, lensoid dikes are observed. These quartz-bearing gabbro dikes are composed of plagioclase, clinopyroxene, quartz, hornblende, apatite, titanite, and opaque minerals. Layers containing three types of cumulate facies are common (Chincarini et al., 1996).

Plagioclase-olivine cumulate. This is the most abundant lithology of the gabbroic complex and is characterized by 2-mm-thick layers of plagioclase and subordinate olivine. It is a fine- to medium-grained rock; the anhedral olivine is generally rimmed by orthopyroxene (bronzite coronas), hornblende, and spinel, together with subhedral plagioclase and interstitial clinopyroxene and minor hypersthene surrounding olivine grains. Bronzite-hornblende coronas are interpreted as metamorphic, whereas the hypersthene coronas could be relict igneous textures.

Plagioclase-clinopyroxene cumulate. These gabbros consist of subhedral plagioclase and clinopyroxene with a well-developed layering up to 50 cm thick, interbedded with hornblende-rich layers up to 7 cm thick.

Plagioclase-clinopyroxene-orthopyroxene cumulate. These gabbronorites are locally present and are less common than the other two facies. Although these rocks underwent an amphibolite-facies metamorphism, they still show well-preserved igneous textures.

Mineral chemistry. The plagioclase composition ranges from An_{83} to An_{78} in the olivine gabbros and from An_{78} to An_{63} in the gabbro dikes. The Mg# of the cumulate rocks ranges from 0.80 to 0.65.

Basaltic section

Amphibolites, mafic schists, and gneiss constitute a widespread assemblage in the Western Córdoba belt (Fig. 2). Mutti (1997) has interpreted them as the metamorphic equivalent of the upper section of the ophiolite. Metapelites and metavolcanic rocks are the dominant protoliths, whereas the quartz + plagioclase + almandine + biotite + K-feldspar + sillimanite + staurolite + cordierite assemblage characterizes the upper-amphibolite metamorphic facies in these rocks. East of the peridotite exposures of La Mabel (see location in Fig. 2) are cordierite + garnet + anthophyllite rocks that have been interpreted as the metamorphosed basaltic section of the sequence (Escayola, 1994).

Geochemical characteristics of the Western Córdoba ophiolites

Harzburgites of the western belt are rich in MgO (42.09%–43.8%), higher than spinel harzburgites (31.3%) and spinel dunites (19.73%–33.37%). MgO contents of cumulate gabbros range from 6.04% to 16.13%. Scarce aluminous spinel–bearing dunites and harzburgites with Al_2O_3 contents of 14.0%–17.6% and FeO contents of 25.1%–31.7% are between the metamorphic and transition-zone peridotites (Escayola, 1994; Escayola et al., 1996). TiO_2 is less than 0.12% in harzburgites and lherzolites (Mutti, 1997) and 0.80% in gabbros. Escayola (1994) found higher TiO_2 contents than in the aluminous spinel facies and gabbros (Mutti, 1997).

Trace elements normalized (after Wood et al., 1979b) either to chondrites or MORB (mid-oceanic-ridge basalt) show Nb, Sr, Rb, and Ba positive anomalies (Escayola, 1994) with REE (rare earth element) patterns characteristic of mid-ocean ridges (Table 1, Fig. 3A). In the harzburgites, REEs show patterns between 0.5 and 2 times chondrites with relative depletion in light REEs (LREEs). The La/Sm ratio >1 is similar to other basal tectonites associated with mid-ocean ridges (Sun and McDonough, 1989). On the other hand, spinel dunites and spinel harzburgites are depleted in LREEs relative to heavy REEs (HREEs) and show a typical negative Eu anomaly (Escayola, 1994).

The southern sector of this western belt has somewhat different geochemical attributes according to Mutti and DiMarco (1998). In this sector, a series of northwest-trending thrust sheets with southwest vergence repeats mafic and ultramafic bodies. The amphibolites have REE contents (see Table 1) similar to those of the arc tholeiites of the South Sandwich Islands described by Pearce et al. (1984, 1995). On the other hand, the ultramafic rocks of Los Guanacos and Cerro San Lorenzo areas show some suprasubduction affinities (Mutti and DiMarco, 1998).

These characteristics as a whole show mid-ocean ridge affinities for the Western Córdoba belt, although the southern sector appears to have a more complex suprasubduction setting, possibly an intraoceanic arc (Mutti, 1995; Escayola et al., 1996).

Tectonic setting

Kraemer et al. (1995) and Ramos (1995) interpreted this belt as a mid-ocean ridge–derived ophiolite emplaced during the Brasiliano (Pampean) deformation that occurred from the end of the Proterozoic to Early Cambrian time, as a result of the accretion of the Pampia terrane to the Río de La Plata craton. In the northern and central sector, the ophiolites are associated with pelitic gneisses derived from accretionary-prism turbidites (Escayola et al., 1996). The southern sector is related to orthoamphibolites derived from a metavolcanic protolith with intraoceanic arc affinity (Mutti and DiMarco, 1998).

PIE DE PALO BELT

This Middle Proterozoic belt is exposed along the western flank of Sierra de Pie de Palo, one of the westernmost ranges of Sierras Pampeanas (Fig. 1). The belt continues farther south in the Cerros Barboza and Valdivia (Ramos and Vujovich, 1995), reaching more than 90 km in length (Fig. 4). The outcrops of Sierra de Pie de Palo and the Cerros Barboza and Valdivia collectively make up the Pie de Palo complex, characterized by schists and gneisses that include a belt of mafic and ultramafic rocks identified as an Alpine-type belt (Villar, 1985). The metamorphic grade has been determined as greenschist to amphibolite facies by Dalla Salda and Varela (1984), Castro de Machuca and Conte-Grand (1994), and Ramos and Vujovich (1995). Vujovich and Kay (1998) presented geochemical data showing that the Pie de Palo Complex is one of the best exposed juvenile Middle Proterozoic oceanic arc or backarc complexes on Earth.

The primary igneous characteristics are obliterated by the extreme deformation of the basement associated with greenschist- to amphibolite-facies metamorphism. In the southernmost part of the range, granulite-facies metamorphism is reported (Dalla Salda and Varela, 1984). The country rock in which the ophiolites are emplaced constitutes most of the central part of the Sierra de Pie de Palo and is composed of biotite + muscovite + garnet + oligoclase schists and gneisses. The protoliths of these country rocks are inferred to have been mainly silicic magmas and immature graywackes (Ramos et al., 1993; Vujovich and Kay, 1998). The protoliths of the mafic-ultramafic belt were ultramafic and mafic cumulates and lava flows. Dominant rock types include serpentinite, metagabbro, metadiorite, amphibolite, and various mafic schists. The majority of the outcrops are chlorite, talc + chlorite, and amphibolite schists with nematoblastic to decussate textures. The most important minerals are tremolite-actinolite, talc, chlorite, albite, and epidote. Cataclasis and protomylonitization are common.

Most of the mafic-ultramafic units are exposed in almost continuous belts between the Quebrada de Guayaupa and Quebrada Piedras Pintadas (Fig. 4). The mafic-ultramafic rocks are part of imbricate thrust sheets that override the Pie de Palo Complex on the siliciclastic and carbonate platform facies of the Caucete Group (Ramos et al., 1996). The northwest-vergent thrust sheets are preserved in a series of klippen along the Quebrada de Pirquitas such as the one seen in Figure 5.

The Middle Proterozoic Grenville ages for the Pie de Palo Complex were established by McDonough et al. (1993) on the basis of U-Pb zircon ages in gneisses. Different varieties of gneisses range in age from 1090 to 1060 Ma, whereas zircons from metarhyolites yield ages near 1080 Ma. Metamorphic zircons from amphibolites gave ages of 1066 Ma (McDonough et al., 1993). A Rb/Sr reference isochron age of 1027.6 Ma from Varela and Dalla Salda (1993) also suggests a Grenvillian age. Some new dates from Cerro Barboza indicate a preliminary $^{207}Pb/^{206}Pb$ age of 1118.2 Ma (Vujovich and Kay, 1998). Minimum $^{40}Ar/^{39}Ar$ hornblende ages ranging from 1030 to 650 Ma from Cerro Valdivia are reported by Ramos et al. (1998). All these data are consistent with a Grenvillian age for the igneous and metamorphic episodes that formed the mafic and ultramafic rocks in this belt.

Geochemical characteristics of the Sierra de Pie de Palo ophiolites

The ultramafic group is composed primarily of serpentinite and metapyroxenite bodies, mainly exposed in imbricated thrust sheets in Quebrada del Gato and Quebrada Piedras Pintadas. These units were interleaved with massive metagabbros, metadiorites, amphibolites, and garnet amphibolite bodies. Chemical analyses of these rocks support an ultramafic cumulate protolith on the basis of the presence of chromite, relict olivine, and pyroxene grains. They have high Cr (4700 ppm) and Ni (1800 ppm) and low REE concentrations (see Table 2). In Cerro Valdivia, ultramafic and mafic cumulate protoliths display compositional and grain-size layering with orthopyroxene, clinopyroxene, olivine, and Cr-rich spinel as cumulate phases. The REE patterns are consistent with intercumulus liquid and support an arc origin (Vujovich and Kay, 1998; Fig. 6A). Similarly, the high La/Ta ratios (>98) of these rocks are also consistent with an arc environment. On the basis of its chemical characteristics, Cerro Barboza amphibolite is interpreted as an amphibole + plagioclase + iron-titanium oxide cumulate (Vujovich and Kay, 1998). Thus an origin as an island-arc cumulate section is well established for the Quebrada

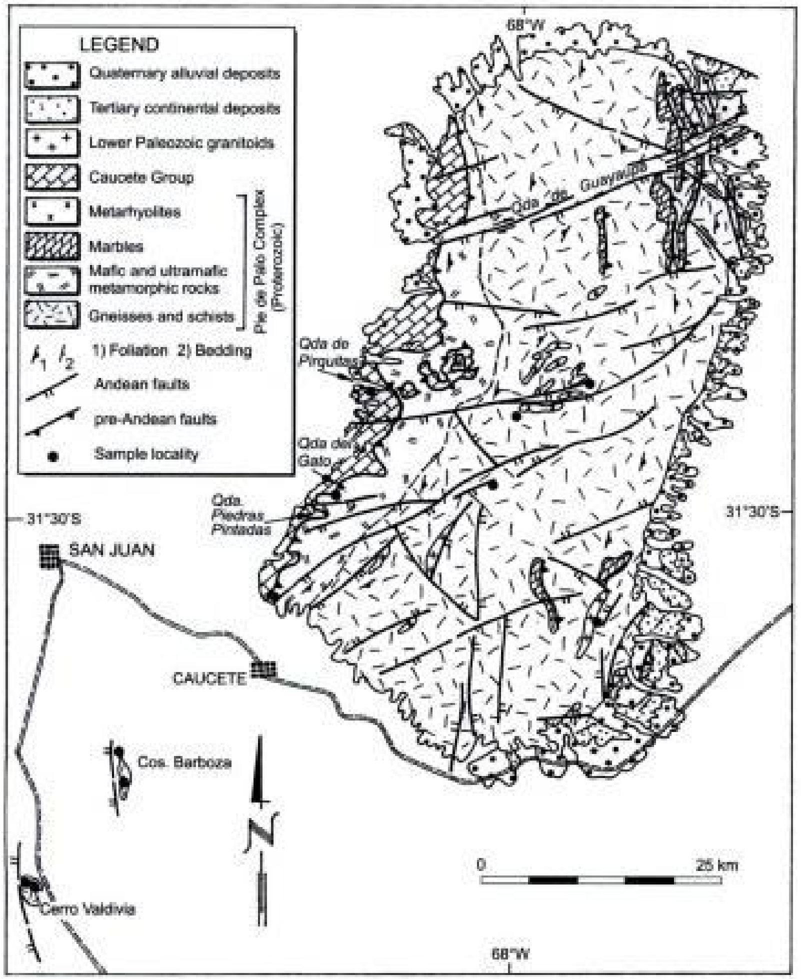

Figure 4. Generalized geology of Sierra de Pie de Palo, showing the mafic and ultramafic belt along its western side and its continuation in Cerros Barboza and Valdivia (modified from Ramos and Vujovich, 1995).

Figure 5. Ophiolitic rocks in a klippe at Quebrada de Pirquitas (view to the south). The oceanic rocks are thrust over quartzites of the Caucete Group platform.

del Gato, Cerros Barboza, and Cerro Valdivia ultramafic rocks (Vujovich and Kay, 1998).

A metamorphosed mafic sequence occurring in Las Pirquitas displays the characteristic textural field relationships of a possible sheeted-dike complex (Vujovich and Kay, 1998). These amphibolites have a distinctive pattern like N-MORB (normal MORB), characterized by LREE depletion and Ta and Th abundance (Fig. 6B). Cr (80–310 ppm) and Ni (45–80 ppm) concentrations are consistent with fractionation of olivine under the low-pressure crystallization conditions typical of N-MORB. The gabbros have typical cumulate-dominated trace element patterns with low REE concentrations and positive Eu anomalies. Vujovich and Kay (1998) correlated these rocks on geochemical grounds with the Lau Basin sequences described by Hawkins (1995a, 1995b).

In the central part of Sierra de Pie de Palo, the amphibolites are interpreted as originating in an arc or backarc environment. The country rocks consist of biotite + muscovite + oligoclase + garnet schists and appear to have a siliciclastic origin, although a magmatic origin for their protolith cannot be ruled out (Ramos et al., 1993; Vujovich and Kay, 1998).

TABLE 2. REPRESENTATIVE ANALYSES OF PIE DE PALO BELT

	Cerros Barboza and Valdivia mafic-ultramafic cumulates*					Quebradas Las Pinquitas and El Quemado amphibolites*			
Sample	V42	V43	V44	V45	B23		QQ2	PR-3	PR4a
SiO_2	53.18	51.94	51.30	52.05	42.31				
TiO_2	1.01	1.22	0.75	1.14	4.87				
Al_2O_3	3.43	4.46	13.60	15.01	12.67				
FeO	9.27	9.15	7.98	8.20	17.92	10.09	11.23	11.95	10.22
MnO	0.21	0.14	0.15	0.12	0.16				
MgO	19.52	17.79	11.51	10.53	6.87				
CaO	12.83	14.00	10.79	7.54	10.50				
Na_2O	0.33	0.69	2.40	3.55	2.50	4.64	2.54	2.63	2.49
K_2O	0.07	0.20	0.72	0.47	0.22				
P_2O_5	0.16	0.36	0.26	0.26	0.45				
Total	100.01	99.95	99.46	98.87	98.47				
Cr	2462	3172	916	584	11	311	138	77	309
Ni	403	245	130	142	24	79	55	44	72
Co	61	42	42	44	80	47	48	49	43
Sc	53.8	46.8	34.3	31.6	51.6	40.4	41.5	42.5	43.4
Cs	b.l.	0.02	0.10	0.12	0.06	0.06	b.l.	0.46	0.72
Ba	13	50	268	143	73	10	32	41	83
Sr	257	309	859	847	858	139	112	145	223
Ta	b.l.	0.11	0.05	0.10	0.26	0.05	0.06	0.07	0.06
Hf	1.1	2.1	1.7	1.6	1.2	1.1	1.4	1.6	1.3
Th	0.02	0.3	0.4	0.4	0.1	b.l.	0.1	0.1	0.1
U	0.01	0.26	0.27	0.30	0.14	0.03	b.l.	0.18	0.09
La	3.97	10.6	9.13	10.0	5.75	1.24	1.51	1.77	1.92
Ce	15.1	33.3	24.0	26.7	16.7	4.48	4.84	5.74	6.61
Nd	12.0	20.8	12.8	15.9	13.0	4.36	4.52	5.09	5.57
Sm	3.82	5.45	3.35	4.02	3.97	1.72	2.26	2.31	1.93
Eu	1.18	1.90	1.35	1.44	2.10	0.651	0.810	0.874	0.778
Tb	0.571	0.737	0.498	0.555	0.698	0.583	0.749	0.797	0.660
Yb	0.920	1.06	1.19	1.22	1.41	2.66	3.33	3.53	2.87
Lu	0.133	0.144	0.157	0.182	0.198	0.390	0.472	0.534	0.430

Note: Blank—not determined; b.l.—below limit of detection. Values are weight percent for oxides, parts per million for trace elements.
* Vujovich and Kay (1998).

As a whole, the ophiolitic rocks of Pie de Palo exhibit a typical suprasubduction affinity in the sense of Pearce et al. (1984) as depicted in Figure 7.

Tectonic setting

The petrologic, geochemical, isotopic, and geochronologic similarities between the basement of Sierra de Pie de Palo and the basement of the Precordillera led Kay et al. (1996) and Vujovich and Kay (1998) to correlate both basements and interpret them as having been derived from Laurentia. These terranes collectively constitute the Cuyania composite terrane that docked against the protomargin of Gondwana during the Middle Ordovician (Ramos et al., 1998). In this scenario, the Pie de Palo ophiolites are interpreted as the suture zone between the Middle Proterozoic Precordillera and the Pie de Palo terranes, which were amalgamated prior to the collision with the Gondwana protomargin (Vujovich and Kay, 1998). This last Ordovician collision uplifted and exposed the basement and the old suture as evidenced by the $^{40}Ar/^{39}Ar$ crystallization history (Ramos et al., 1998).

On the basis of the dominant west vergence of the ductile deformation preserved in these rocks, as well as the geochemical and petrologic characteristics, the Middle Proterozoic subduction is interpreted as east dipping (present coordinates). The Pie de Palo ultramafic-mafic assemblage is therefore explained as a disrupted ophiolite that evolved in an intraoceanic arc and/or backarc setting (Vujovich and Kay, 1998).

WESTERN PRECORDILLERA OPHIOLITE

The ophiolitic nature of the mafic and ultramafic belt of Western Precordillera has been established since the early work of Borrello (1963, 1969). This belt, extending over 900 km from south of lat 26°S to north of lat 33°S, was recognized by Haller and Ramos (1984) as the Famatinian ophiolites emplaced during the early Paleozoic.

The Western Precordillera ophiolite is represented by a series of discontinuous exposures of mafic and ultramafic rocks preserved in the western slope facies of the carbonate platform of the Precordillera (Fig. 8). The ultramafic rocks are more abundant toward the south, whereas pillow lavas and mafic and ultramafic sills are preserved in the northern sector together with distal limestone turbidites, or pelagic limestones, and locally with chert.

The northern sequences

The structural relationships of the clastic strata with the mafic and ultramafic igneous rocks are well exposed in a section along Río Jáchal, near lat 30°15′S (Ramos et al., 1984). In the western part of the section, a massive sequence of basaltic lavas crops out along an unconformity at the base of the Tertiary strata. The basalts occur as pillow lavas and columnar-jointed flows that are steeply folded with a westward vergence. The eastern part of this section consists of graywackes, shales, and local conglomerates containing angular sedimentary clasts, intruded by sills of mafic and ultramafic composition. The eastern unit is tightly folded, and on the basis of graded beds, a

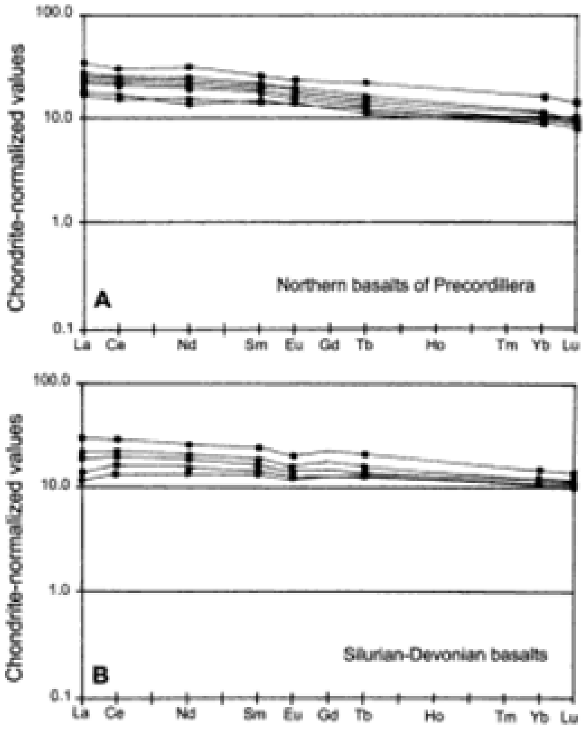

Figure 9. REE pattern normalized to chondrites from representative basalts of Precordillera. A, Ordovician basalts from the northern sector (Kay et al., 1984). B, Silurian–Devonian basalts from the southern sector (modified from Cortés and Kay, 1994). REEs in both plots were normalized to the Leedy chondrite.

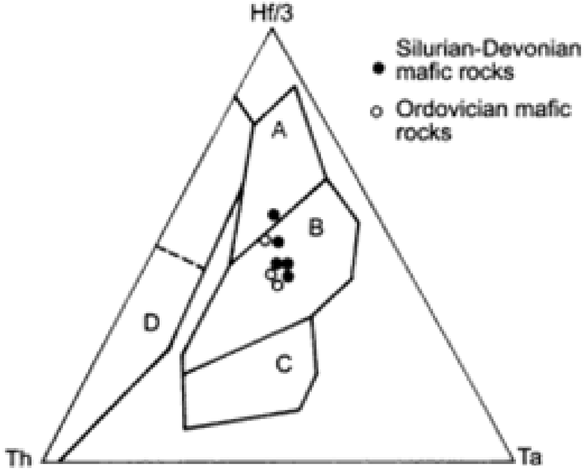

Figure 10. Hf-Th-Ta diagram of basalts from Western Precordillera (from Wood et al., 1979a). Both Ordovician and Silurian–Devonian rocks have E-MORB affinities (modified from Cortés and Kay, 1994). Fields: A—N-MORB, B—E-MORB, C—alkalic within-plate, and D—arc.

lished an age range from 353.1 to 399.6 Ma on the basis of K/Ar dating of 2–6 μm interlayered illite/muscovite separated from the metasedimentary rocks. These ages were interpreted as dating the neocrystallized phase of white mica associated with syndeformational metamorphism. On the basis of new ^{40}Ar/^{39}Ar and structural data, Davis et al. (1999) interpreted the metamorphic age of the metasedimentary sequence as 384.5 ± 0.5 Ma. These ages are all consistent with interpreting the main phase of deformation and regional metamorphism as Early Devonian, as was proposed by Astini et al. (1996).

Rock types in the ophiolitic units constitute a complete ophiolite pseudostratigraphy, as established by Coleman (1977), Moores (1982), and Nicolas (1989). The ultramafic rocks consist of highly serpentinized bodies, with a few relict peridotites. Each thrust sheet is composed of serpentinized ultramafic rocks, ultramafic cumulates, and layered gabbros that represent the mantle and lower-crustal part of a classic ophiolite sequence (Davis et al., 1995a, 1995b). Despite extensive serpentinization, these authors were able to distinguish relict clinopyroxene, chromite, spinel, and minor amounts of olivine and orthopyroxene. They used these data to identify wehrlite, harzburgite, lherzolite websterite, and veins of dunite crosscutting wehrlite. In some areas, mantle tectonite textures were recognized in the ultramafic rocks (Haller and Ramos, 1984).

Coarsely crystalline ultramafic cumulates are associated with the base of the layered gabbro section, which ranges from a few meters up to 150 m in thickness. High-grade metamorphism of the layered gabbro complex converted the mineral assemblage to mafic garnet granulite (Davis et al., 1999).

Microgabbros and fine-grained diabase in tectonic contact with the cumulates and layered gabbros reach several hundred meters in thickness. In some areas, rusty-orange ophicalcites are exposed. They consist of pervasively sheared and cataclastic serpentinite and mafic garnet granulite with a calcitic to dolomitic matrix and extensive carbonate veining.

West of the Cortaderas section, basalt flows up to 20 m thick are interfingered with Silurian–Devonian sandstones and shales. There are pillow lavas and sheet flows that are heavily deformed with conspicuous boudinage and pinch-and-swell structures (Cortés, 1992). These units are interpreted as the upper part of a complex accretionary prism developed during the Ordovician and Middle Devonian.

Geochemical characteristics of the southern sequences

Preliminary trace and REE analyses of samples from the mafic rocks of the Cortaderas section indicate an E-MORB or within-plate origin (Davis et al., 1995a, 1995b). Geochemical analyses from the gabbros of Cortaderas show the P-MORB signatures of anomalous oceanic crust formed in a plume or plateau setting (Haller, 1995).

The most complete geochemical study is that of Cortés and Kay (1994) in the Silurian–Devonian pillow lavas west of Cortaderas (see Table 3). The Eu anomaly and the low concentration of Ni (<104 ppm) indicate low-pressure crystallization of olivine and plagioclase, characteristic of mid-ocean ridges. The REE, Ta, Th, and Hf contents indicate a nonarc oceanic source for these mafic rocks. The La/Ta ratios (13 to 15) are within the range of those in mid-ocean ridges, but much lower than those in island arcs (La/Ta > 20 to 25). In the Wood et al. (1979a) diagram, the samples are typical of N-MORB and E-MORB (Fig. 10), and the REE patterns are consistent with a mid-ocean ridge or enriched source origin (Fig. 9B).

The isotopic study of Cortés and Kay (1994) confirmed the oceanic nature of these Silurian–Devonian lavas as well as that of the

Ordovician basalts of the northern sequences. The ϵ_{Nd} for these lavas ranges from +7.1 to +8.6. These values fall within the range of the early Paleozoic depleted mantle (Cortés and Kay, 1994). The $^{87}Sr/^{86}Sr$ ratios (0.7051 to 0.7095) of the Silurian–Devonian lavas, although higher than normal oceanic crust, are similar to the Bay of Islands ophiolite of Nova Scotia described by Jacobsen and Wasserburg (1979). These wide ranges have been interpreted in both cases as produced by seawater addition.

Tectonic setting

The Western Precordillera mafic and ultramafic belt with its almost complete pseudostratigraphic sequence is interpreted as a disrupted ophiolite (Haller and Ramos, 1984, 1993) emplaced along a suture zone between the Chilenia and Precordillera terranes (Ramos et al., 1984, 1986).

Davis et al. (1999) challenged this interpretation on the basis of different ages for the ultramafic and lower mafic sequence (Middle Proterozoic) compared to the upper mafic sequence (early Paleozoic) and suggested the occurrence of two different ophiolite assemblages along the suture. However, recent studies in the Ligurian ophiolites show similar contrasts in ages within different sections of an ophiolite assemblage (see Rampone and Piccardo, this volume). This situation can be explained as a result of the continental upper mantle and lower crust interleaving with the upper oceanic crust trapped in the collision.

The east vergence of the early ophiolite emplacement proposed by Davis et al. (1995a) could be compatible with a late, west-verging emplacement if flake tectonics in the sense of Oxburgh (1972) is applicable. Several ophiolites in the Variscan sutures of the southwestern Iberian massif recorded such a change in vergence, as proposed by Ferreira da Fonseca (1995).

EASTERN CORDILLERA FRONTAL OPHIOLITES

Along the eastern slope of the Cordillera Frontal, a series of ophiolite assemblages, emplaced in Precambrian metamorphic rocks, is preserved south of lat 33°S (Polanski, 1964). Villar (1975, 1985) has described these rocks as ultramafic Alpine-type belts. The age of their country rock is poorly defined. U-Pb data from zircons from Cordón del Portillo yielded an age of 1069 ± 36 Ma (Ramos and Basei, 1997), indicating a basement of possible Grenvillian age.

Three belts have been recognized from west to east—Los Metales, the Central, and the Eastern belt (Fig. 11)—that could represent either a thrust-sheet repetition of a single ophiolite or different ophiolites.

Los Metales belt

These rocks are exposed along the Río de Las Tunas and have been recently described by Gregori and Bjerg (1997). This belt, 8 km long and 1.5–2 km wide, is composed of serpentinized peridotites, altered gabbros, basaltic dikes, and pillow lavas. The ultramafic and mafic rocks on the Precambrian metamorphic basement have been emplaced along a west-dipping conspicuous shear zone.

An extensive serpentinized peridotite exposure interpreted as a basal tectonite is in contact with the metamorphic rocks. Pyroxene-bearing gabbros and gabbroid rocks are scarce. The pillow lavas are in tectonic contact with the ultramafic rocks. There are two types of dikes: deformed metabasalts in greenschist metamorphic facies and basalts with no deformation and slight metamorphism. The metamorphosed mafic dikes have a regional trend parallel to the fabric of the metamorphic rocks, they are up to 20 m thick, and some are folded and faulted. The country rocks consist of amphibolites, biotite + garnet, and quartz + feldspar schists. Dikes of a second type are up to 50 m thick, have chilled margins, and preserve their original textures and mineral assemblages.

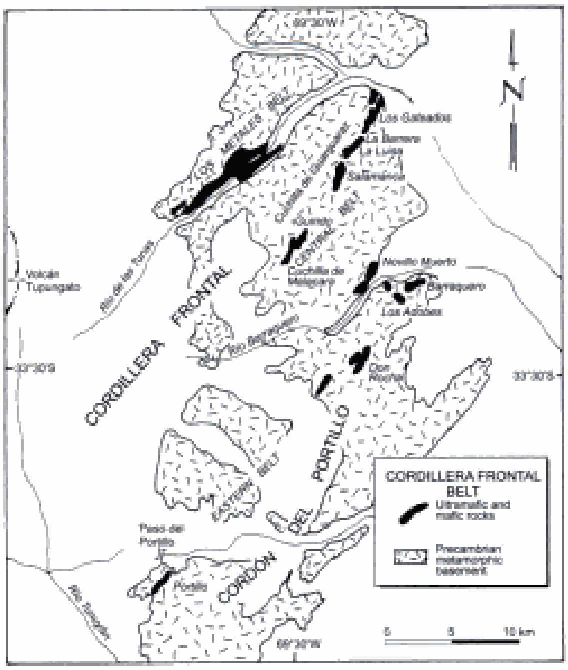

Figure 11. Different ophiolitic belts in the eastern slope of Cordillera Frontal (modified from Polanski, 1964; Haller and Ramos, 1993; and Gregori and Bjerg, 1997).

The chemical analyses of the basaltic rocks (Table 4, Fig. 12A) indicate that the metabasites have an E-MORB affinity, whereas the basaltic dikes have geochemical signatures typical of ocean-island basalts (OIBs) (Gregori and Bjerg, 1997).

Central belt

This belt is exposed along the eastern flank of Cuchilla de Guarguaráz, and consists of a series of ultramafic bodies, such as La Barrera, Salamanca, Los Gateados, and other lenses up to the Cuchilla de Malacara bodies (Fig. 11). These bodies are mainly composed of serpentinite with scarce relicts of wehrlites, lherzolites, and dunites, associated with rare bodies of gabbros and lenses of amphibolites of variable sizes. The country rocks are metasedimentary rocks. Serpentinites contain talc, concentrated along shear zones, and include carbonate-rich bodies with brucite and epidote. In some areas like Los Gateados, the ultramafic rocks are heavily deformed in an antiformal structure and contain sulfides and Cr-rich spinel (Villar and Donnari, 1989a, 1989b). Layered gabbros are commonly metamorphosed to amphibolite facies. The gabbros have geochemical affinities with E-MORB with a slight N-MORB trend (Table 4, Fig. 12B). Villar (1998) has interpreted these rocks as part of an ophiolitic assemblage.

TABLE 5. MAIN OPHIOLITE BELTS OF SOUTHERN SOUTH AMERICA

Ophiolite	Age	Country rocks	Remarks	Tectonic setting
Eastern Córdoba	Late Proterozoic	Schists and tonalite gneiss. Amphibolite metamorphic facies	Lherzolite, subordinate harzburgite, pyroxenite, gabbros. Intruded by leucocratic rocks	Backarc basin
Western Córdoba	Early Cambrian	Quartz + feldspar, quartz.mica + feldspar, quartz + garnet gneisses and schists; migmatites, amphibolites, marbles, and kinzigites. Amphibolite to granulite metamorphic facies	*Metamorphic peridotites*: harzburgites, metamorphosed ultramafic rocks. Chromite bodies	Mid-ocean ridge ophiolite
			Transition zone: Cumulate tectonized peridotites (harzburgites, dunites, pyroxenites, gabbros). Gabbro sills, dikes, and veins. Websteritic and spinel + dunite dikes in the harzburgites. Harzburgite boudins in lherzolitic rocks	
			Layered complex: Gabbroic cumulate complex with plagioclase-olivine, plagioclase-clinopyroxene, and plagioclase-clinopyroxene- orthopyroxene cumulates. Quartz-bearing gabbro dikes	
			Basaltic section: Amphibolites, mafic schists, and gneisses derived from basaltic lavas	
	Ordovician?	Metapelitic schists and gneisses and amphibolites	Dunites, pyroxenites, hornblendites, amphibolites. Felsic segregation associated with ultramafic bodies	Backarc or frontal island arc setting
Virorco		Amphibolite to granulite metamorphic facies		
Valle Fértil	Middle Ordovician Middle Proterozoic	Metapelitic gneisses. Upper-amphibolite to granulite metamorphic facies	Pyroxenites, peridotites, gabbros, hornblendites, amphibolites	Island arc setting
Pie de Palo	Middle Proterozoic	Metapelitic schists and gneisses, graphite and amphibolite schists. Greenschist to amphibolite metamorphic facies	Sepentinized peridotites, pyroxenites, gabbros, diorites, amphibolites	Island arc and backarc setting
Western Precordillera				
Northern sequences	Middle Ordovician to Devonian	Greywackes and shales with local conglomerates	Clinopyroxene-bearing basaltic lavas, mafic to ultramafic sills	Anomalous enriched mid-ocean ridge
Southern sequences	Middle Ordovician to Devonian	Metasandstones and metasiltstones interlayered with metavolcanic flows and tuffs	Serpentinized peridotites (wehrlites, harzburgites, lherzolites, websterites, and veins of dunite crosscutting wehrlite), ultramafic cumulates, layered gabbros to microgabbros, diabase	Anomalous enriched mid-ocean ridge and lithospheric mantle granulites
Eastern Cordillera Frontal				
Los Metales belt	Middle Ordovician to Devonian	Amphibolites, biotite + garnet and quartz + feldspar schists. Greenschists to amphibolite metamorphic facies	Serpentinized peridotites, gabbros, basaltic dikes, basaltic lavas	Enriched mid-ocean ridge basalts and oceanic island basalts
Central belt	Middle Ordovician to Devonian	Actinolite + tremolite schists, muscovite + biotite + garnet schists. Amphibolite-epidote to amphibolite metamorphic facies	Serpentinites. Scarce wherlites, lherzolites, dunite, gabbros, amphibolites. Associated with basaltic dike swarms	Enriched mid-ocean ridge to normal mid-ocean ridge
Western belt	Middle Ordovician to Devonian	Quartz + biotite + feldspar schists, biotite + garnet schists, amphibolite schists. Amphibolite metamorphic facies	Dunites, harzburgites, wehrlites, orthopyroxenites, associated with ophicalcites	Cumulate peridotite-gabbro section of amid-ocean ridge

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