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PALEOZOIC TERRANES OF THE CENTRAL ARGENTINE-CHILEAN ANDES

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Abstract. The recognition of accreted terranes and their importance in orogenesis has spurred the search for allochthonous fragments along the western and southern margins of South America. Here we present stratigraphic and petrologic data from Chile and Argentina between 29° and 33°S latitude that demonstrate the "suspect" nature of several major terranes, which we infer to have been accreted during the Paleozoic. Three lower-middle Paleozoic terranes are described (from east to west): (1) the Pampeanas terrane, a Cambrian-Devonian magmatic and metamorphic province built on late Precambrian basement at the margin of South America, (2) the Precordillera terrane, a Cambrian-Devonian shelf-slope-oceanic basin assemblage bounded by mélanges on both sides and bearing many stratigraphic similarities to the lower-middle Paleozoic of the Northern Appalachians, and (3) the "Chilenia" terrane, which has largely been obliterated by late Paleozoic magmatism and metamorphism. The distribution of Carboniferous continental, deltaic, and marine strata demonstrates that these three terranes were sutured together and part of South America by the end of the Devonian. Subsequent Permo-Carboniferous plate interactions more closely resembled the modern Andean margin, with eastward subduction, accretionary prism formation, and minor terrane emplacement exposed along the present coast of Chile and eastward migrating arc magmatism from the present coast of Chile to western Argentina.

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INTRODUCTION

The role of accreted or "suspect" terranes as an important geodynamic process of continental accretion has been brought into focus recently [Coney et al., 1980]. The western and southern margins of South America have attracted much interest because accreted terranes and collisional tectonics, which now are known to be important components of orogenesis in many of the world's major mountain belts, are seemingly absent from the modern tectonics of the region. Thus, much current endeavor is directed toward the discovery of terranes accreted during the formation of the Andes Mountains [e.g., Ben Avraham et al., 1981]. However, the Andes, which are Jurassic to Recent in age, represent only the latest orogenic cycle to have affected the western edge of the continent. Two earlier cycles—Carboniferous through Triassic and Cambrian through Devonian—also molded the character of the continent and formed the basement on which the Andes are built.

We describe the tectonics of these two orogenic cycles for a segment of South America between 29° and 33°S latitude (Figure 1) with emphasis on the earlier cycle because it contains the best evidence for major terrane accretion during the formation of the continental margin [Coira et al., 1982; Allmendinger et al., 1983; Ramos et al., 1984]. Terranes of lesser importance probably were also accreted during the Carboniferous to Triassic orogeny [Helwig, 1972; Mpodozis and Forsythe, 1983]. In contrast, geologic synthesis and recent preliminary paleomagnetic data indicate that terrane accretion was least important during the Jurassic to Recent Andean Orogeny, at least south of 15° S latitude [Palmer et al., 1980; Coira et al., 1982; Dalziel, 1985; Heki et al., 1984; May and Butler, 1985; Turner et al., 1984; Jordan and Gardeweg, 1986].

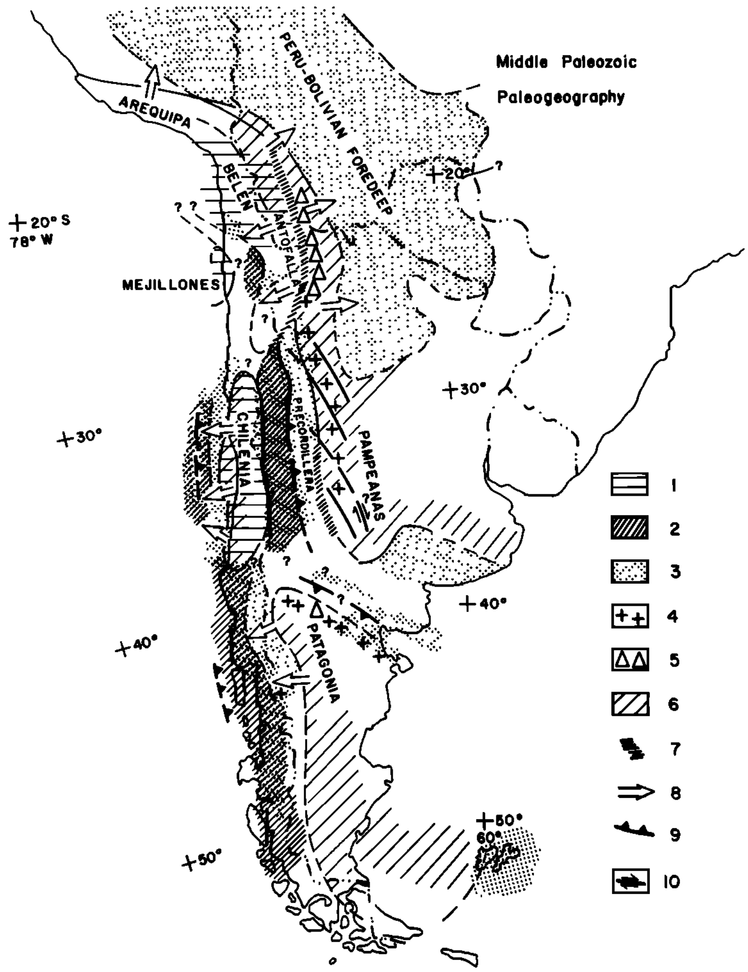

Fig. 1. Generalized paleotectonic map of western South America for the Paleozoic, showing the generalized loca - tions of terranes discussed in this paper. Map is on a nonpalinspastic base and thus is distorted by the much younger Andean (Jurassic-Recent) shortening. The box shows the location of the paleogeographic maps in Figures 3-5, 8, 11, 12. Key to the symbols used: (1) continental basement of the allochthonous blocks, (2) zones of deep ocean basins, (3) clastic sediments, (4) granitoids, (5) volcanic axis, (6) emergent areas, (7) suture zones, (8) directions of sediment transport, (9) paleo-trenches, (10) zones of folding, and (11) strike-slip faults. Based on works by Borrello [1969], Martínez [1980], Dalmayrac et al. [1980], Pacci et al. [1979], Allmendinger et al. [1982], Coira et al. [1982], Carlier et al. [1982], Mpodozis et al. [1983], and Ramos [1984].

The lower and middle Paleozoic rocks of the Central Andes can be divided into several important complexes whose characteristics fit those outlined by Coney, Jones, and Monger [1980]: The terranes have "internal homogeneity and continu - ity of stratigraphy, tectonic style and history" and boundaries that are "fundamental discontinuities in stratigraphy that cannot be explained easily by conventional facies changes or unconformities." By this definition, there are three major, dintinctive terranes of pre-Carboniferous age in the area between 29-33°S. We must emphasize that these terranes are recognized solely on stratigraphic and petrologic bases (implicit in the above definition). A single preliminary paleomagnetic study in these complexes suggests either rotation or latitudinal displacement of a poorly dated volcanic sequence, but the results are under revision at present (Vilas and Valencio, personal communication, 1982). Furthermore, the tectonic setting of the terranes—in particular the plate geometry, the role of major strike-slip faulting during or subsequent to emplacement, and the nature of the basement of the terranes—remain important unresolved problems. Thus, this paper serves only as an introduction to the "suspect" terranes of the central Argentine-Chilean Andes rather than as a fully developed, let alone tested, model.

The three terranes, "Chilenia," the Precordillera terrane, and the Pampeanas terrane, and the key stratigraphic relations that define them are illustrated in Figure 2. The Pampeanas terrane is a distinct metamorphic and plutonic province that was probably part of the South American continent by the start of

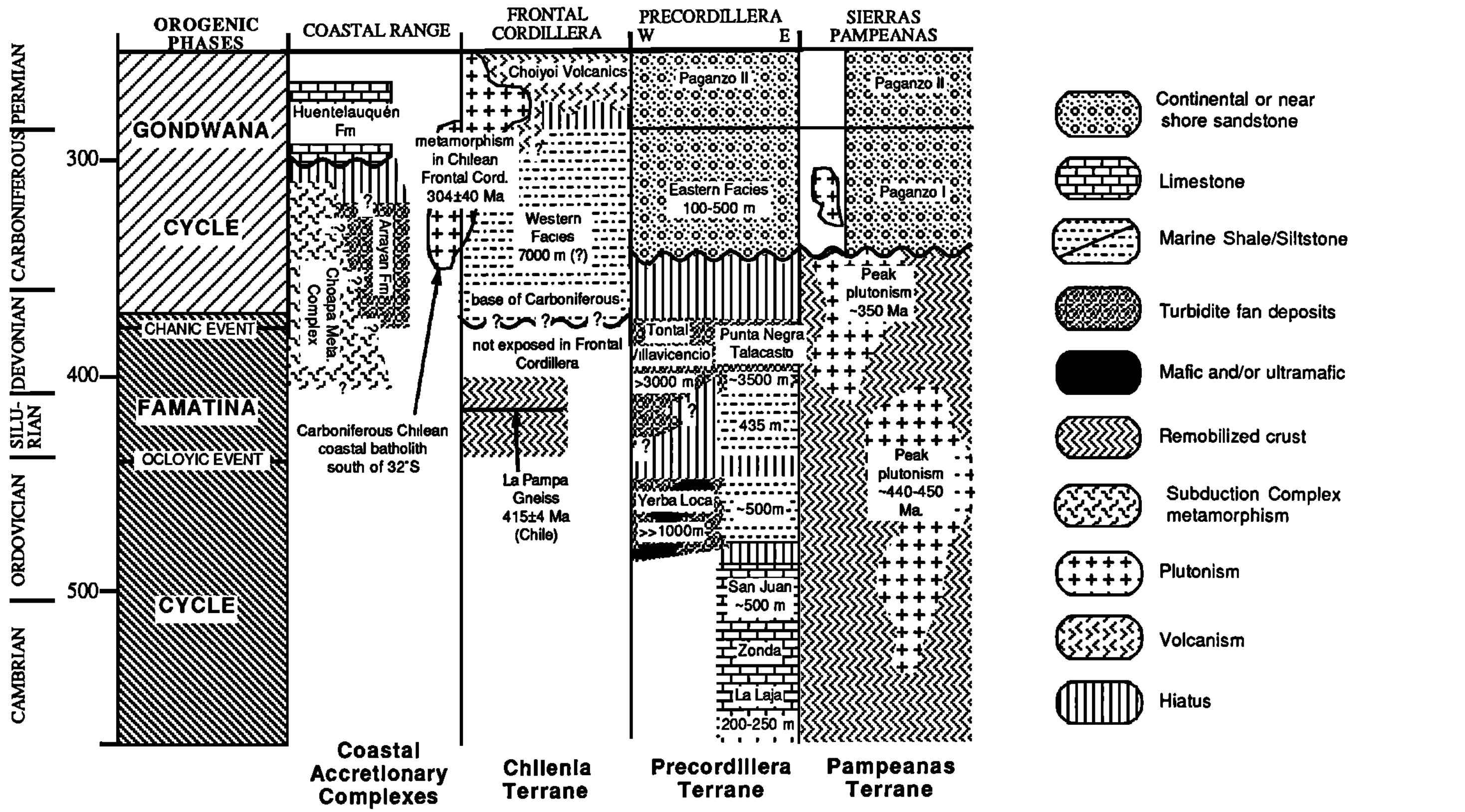

Fig. 2. Tectono-stratigraphic diagram for the Paleozoic of western South America at the latitude of 31°S, in the middle of the study area. Geologic time is on the vertical axis; first column shows terminology of orogenic phases commonly used in Chile and Argentina, the next four columns constitute a west to east transect across the region. Labels at the tops of the columns show the names of the Andean morphotectonic provinces in which the relations are preserved; labels at the bottoms of the columns show the names of the Paleozoic terranes used in this paper. Characteristic stratigraphic thicknesses are shown, and some isotopic age data are summarized. Note the continuous overlap of Carboniferous strata across the three eastern terranes.

the Phanerozoic. The suspect nature of the two other terranes during the Ordovician to Devonian is hypothesized on the basis of (1) the lack of continuity of sedimentary units found in western Argentina, (2) the existence of oceanic basalts, ultramafic rocks, and relatively deep marine facies sedimentary rocks during the Ordovician, presently located more than 300 km east of the continental margin in western Argentina [Borrello, 1969; Kay et al., 1984; Haller and Ramos, 1984], and (3) Devonian clastic facies indicative of relatively deep marine conditions also located 300 km east of the present continental margin in the zone between 30° and 32°S [González Bonorino, 1975]. The oldest strata that extend across these diverse lower to middle Paleozoic features are Carboniferous in age.

We will describe the rocks in two separate parts, corresponding to the Cambrian to Devonian orogenic cycle (Famatina Cycle) and the Carboniferous to Triassic orogenic cycle (Gondwana Cycle) (Figure 2). These are differentiated because loci of magmatism and facies and areas of deposition differed radically between the two cycles.

We focus on the segment of the Andes between 29° and 33° S because of its excellent exposures, its well known geology, and its relative accessibility. The data and hypotheses presented here are based largely on numerous previous geologic and tectonic studies in this part of the Andes Mountains with additional field reconnaissance by the authors. The area discussed spans the region from the central cratonic area of Argentina to the present Pacific continental margin. At these latitudes the Andean orogenic belt consists of, from west to east, the Coastal, Principal (south of 31°) and Frontal Cordilleras, the Calingasta Valley, the Precordillera (the foothills to the main Andes), and the broad Sierras Pampeanas region of widely separated basement uplifts (Figure 3). The Precordillera can be divided into Western, Central, and Eastern belts which have both neotectonic and, of particular importance for this paper, paleotectonic significance. The Cenozoic geology and tectonic setting of these morphotectonic provinces has been reviewed by Jordan et al. [1983a, b]. Neogene and Quaternary thrust faulting has caused as much as 50% east-west shortening in the Precordillera, and elsewhere, smaller amounts of shortening are known; distances given in this paper are for present geography and thus understate the Paleozoic distances.

THE PRE-CARBONIFEROUS TERRANES AND THE FAMATINA TECTONIC CYCLE

Pampeanas Terrane

There are two different basement domains in the Pampeanas terrane. In the eastern domain (Figure 4), basement is characterized by an isochemical high grade metamorphism and partial anatexis that culminated in the late Precambrian [Gordillo, 1984]. Radiometric ages for the high-grade metamorphic rocks of the eastern Pampeanas terrane range in age between 650 and 900 Ma, with sparse ages between 1000 Ma and 1800 Ma obtained from granulite facies rocks [Cingolani and Varela, 1975; Caminos et al., 1982]. The western domain (Figure 4) has a Precambrian regional metamorphism of low to very low grade [Caminos, 1979a; Dalla Salda and Varela, 1982]. In the central part of the western region an allochemical, high temperature, middle pressure metamorphism and metasomatism is associated with syn- and late-kinematic magmatism of early Paleozoic age [Caminos et al., 1982].

Unmetamorphosed, pre-Carboniferous sedimentary rocks are completely lacking in the Pampeanas terrane. Highly deformed marbles are a minor component of the bedrock in the western part of the terrane in the present ranges of Pie de Palo and Sierra de Valle Fértil (Figure 3). Bastías et al. [1984] have speculated that some of these marbles could be correlative with the Paleozoic Precordillera sequence, and Linares et al. [1982] proposed, on the basis of oxygen isotope studies, that they are the metamorphic equivalents of Cambrian and Ordovician limestones of the Precordillera. Others, however, have pointed out that the marbles show a distinctive deformational and metamorphic evolution and are more likely to be Precambrian in age [Dalla Salda and Varela, 1982]. These two occurrences of marble of uncertain age are the only evidence of overlap of sedimentary sequences between the Precordillera and Pampeanas terranes prior to the Carboniferous. In the northern Sierras Pampeanas (Sierra Famatina, Figure 3), Early and Middle Ordovican shales, metamorphosed as much as greenschist facies [de Alba, 1979], are dissimilar to correlative strata of the Eastern and Central Precordillera, but their paleogeographic significance is poorly known.

Early and Middle Paleozoic Magmatism. Between 29° to 33° S latitudes, two compositional suites of lower Paleozoic granitoids are recognized. Available chronological data suggest that magmatism was most widespread during the Late Ordovician [Ramos and Ramos, 1979]. Granitoids and migmatites occur in the western Sierras Pampeanas [Caminos, 1979a], and the granites occur in the eastern Sierras Pampeanas (Figure 5).

The granitoids of the western Sierras Pampeanas vary in composition from tonalites to granodiorites, with an important late granitic phase. The plutons are associated with similar composition cogenetic migmatites and medium-grade metamorphic rocks [Zuzek, 1978; Caminos, 1979c; Coira and Koukharsky, 1979; Ramos, 1982]. The western plutonic belt probably extends north of the study area [Rapela, 1976; Toselli et al.,1978; Knüver and Miller, 1981; Knüver and Reissinger, 1981], and sparse outcrops of this plutonic belt extend south of the Sierras Pampeanas to 38°S [Linares et al., 1980]. Despite abundant geochronologic data, the ages of the western plutonic belt are not conclusively defined, and the complete magmatic history remains poorly constrained. Important activity existed between the Cambrian and middle to late Ordovician, then declined during the Silurian, and was minor during the Devonian [Ramos and Ramos, 1979; Forsythe, 1982; Caminos et al., 1982]. The western belt of plutons and associated migmatites can be interpreted as the traces of a magmatic arc, whose composition and evolution are characteristic of other circum-Pacific orogenic granitoids [Pitcher, 1982]. Volcanic remnants of this arc have not been found in the Sierras Pampeanas.

The plutons of the eastern Sierras Pampeanas are mostly posttectonic granites [Gordillo and Lencinas, 1979; Rapela, 1982]. Rb/Sr isochrons from the only well-dated batholith in the eastern belt indicate an age of 399±25 Ma (Early Devonian) [Rapela et al., 1982]. The eastern belt granites can

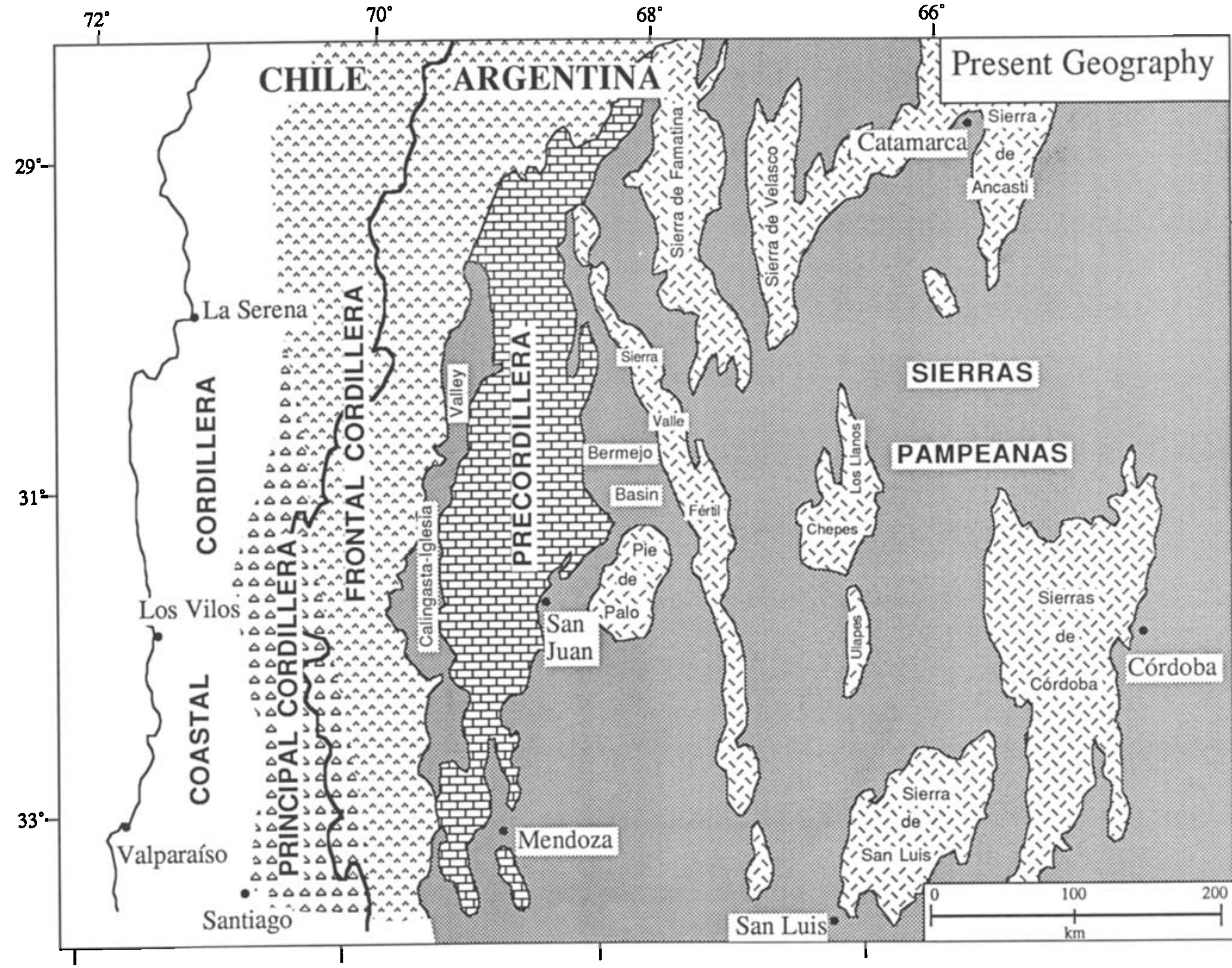

Fig. 3. Present geography of western South America between 29° and 33°S, showing the modern morphotectonic provinces, major geographic features, and principal cities in western Argentina and Chile. This map is the base for those in Figures 4, 5, 8, 11, and 12.

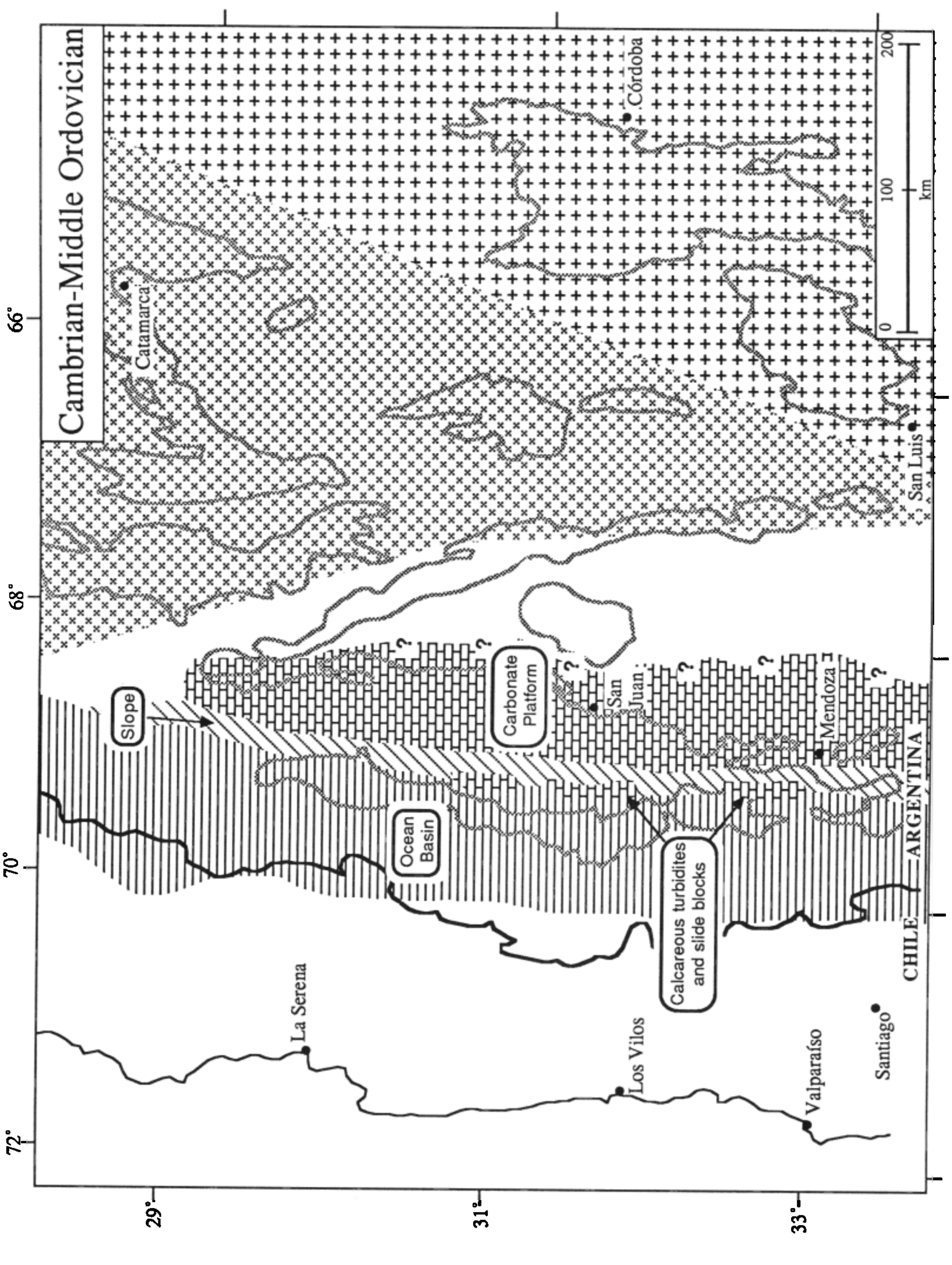

Fig. 4. Cambrian-Middle Ordovician paleogeography: nonpalinspastic, outline base from Figure 3. The two patterns in the eastern half of the map correspond to the eastern and western basement types and eastern and western belts of lower Paleozoic intrusions discussed in text.

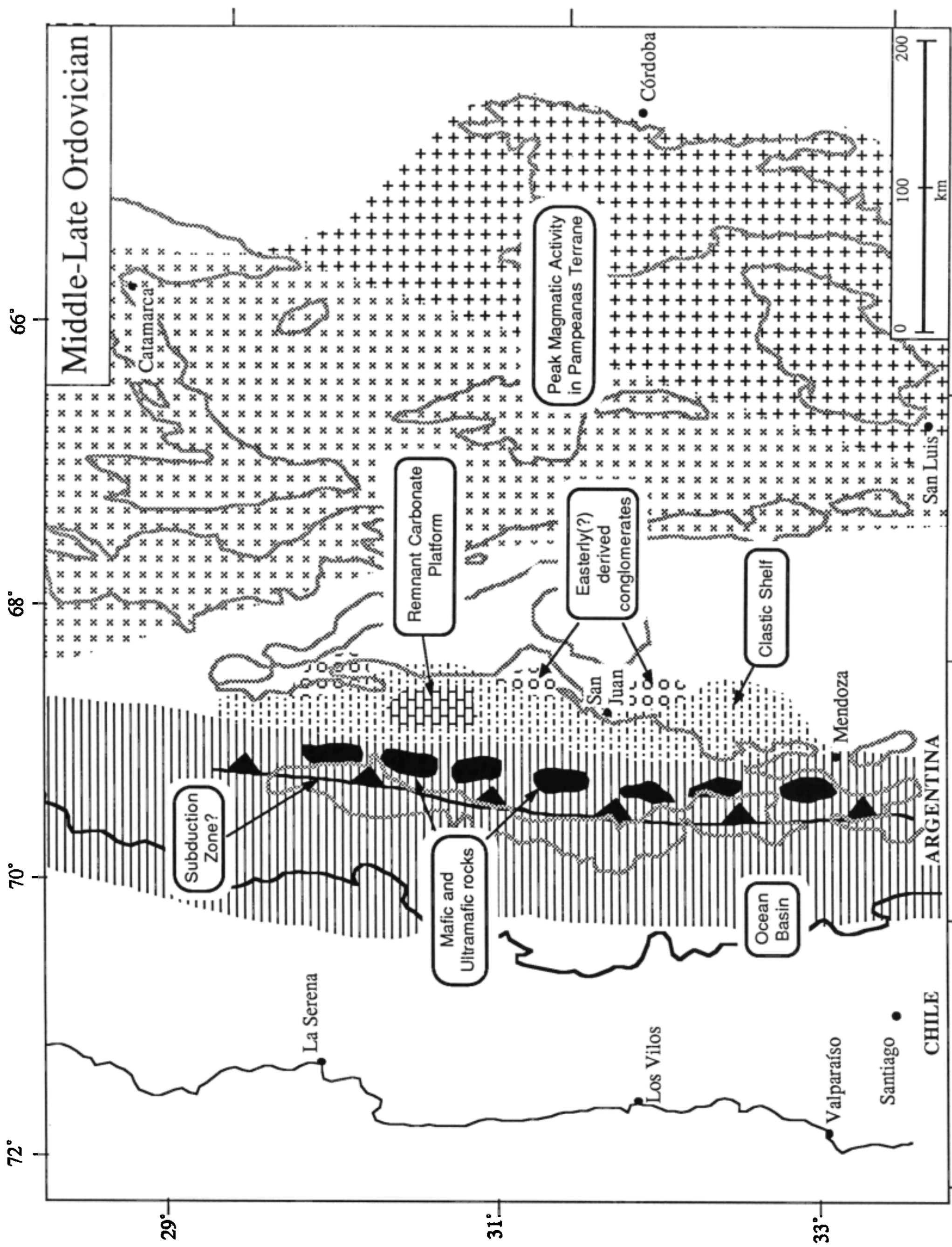

Fig. 5. Middle-Late Ordovician paleogeography; nonpalinspastic, outline base from Figure 3. The two patterns in the eastern half of the map correspond to the eastern and western basement types and eastern and western belts of lower Paleozoic intrusions discussed in text.

be differentiated from the western tonalites or granodiorites on the basis of petrochemical characteristics. The more homogeneous and acidic eastern belt granites constitute a typical calcalkaline peraluminous facies, characterized by high K_2O and incompatible trace element abundances, low K/Rb ratios, and the absence of Ca-rich rocks of low silica content [Rapela, 1982]. Their low $^{87}Sr/^{86}Sr$ ratio (0.7048) [Rapela et al., 1982] is clearly different from the initial isotopic ratios of the wall rock (0.710) [Cingolani and Varela, 1975]; thus the granites were not produced by anatectic melting of supracrustal metamorphics but are more likely derived directly from a lower crust depleted in lithophile elements or from the upper mantle [Rapela, 1982]. They could represent a late retroarc magmatic association.

Precordillera Terrane

The Argentine Precordillera forms the keystone of our interpretation of the pre-Carboniferous tectonics of the region. The Precordillera contains the most complete exposures of lower and middle Paleozoic strata and in addition produces the most compelling structural and petrologic evidence for major tectonic boundaries between the Argentine craton and the rocks of the main Andes. Crystalline basement rocks are nowhere exposed in the Precordillera, and thus the nature of the basement of this terrane is virtually unknown. Xenoliths in some of the Miocene andesites of the Precordillera [Leveratto, 1968; S. M. Kay, unpublished field data, 1984, 1985] appear lithologically similar to the metamorphic basement rocks of the Sierras Pampeanas. They serve as indirect evidence of the basement below the Precordillera, but the age and affinity of these crystalline rocks and whether they are genetically related to the Pampeanas basement are unknown.

Cambrian-Ordovician Stratigraphy of the Precordillera. The principal Cambrian units recognized in the area are a transgressive limestone sequence [Borrello, 1969; Baldis et al., 1982] that crops out from 31° to 33°S in the Eastern Precordillera [Ortiz and Zambrano, 1981]. Some limestone and shale in the western Precordillera (32°S) are of Cambrian age, but their extent is not well known [Cuerda et al., 1985b]. Lower Ordovician rocks in the Eastern Precordillera are conformable on the Cambrian units [Baldis et al., 1982] and stretch about 60 km to the west [Cuerda et al., 1985a], where they are in fault contact with Cambrian deposits (Figure 4).

Systematic east-to-west facies changes in the Cambrian and Lower Ordovician strata document an extensive calcareous platform (Figures 2 and 4) that varied from proximal, near-shoreline facies to more distal facies westward [Baldis et al., 1982; Cuerda et al., 1985a]. The carbonate platform limestone was deposited over the broadest zone during the Arenigian (late early Ordovician) and interfingered westward with slope facies limestone and shale [Furque, 1983; Cuerda et al., 1985a.] To the south (32°30'S), metamorphosed limestones and pelites [Harrington, 1971] are inferred to represent a lateral continuation of that depositional system. In the western border of the Precordillera, typical clastic turbidite facies occur in a north trending belt (Figure 4) [Borrello, 1969; Baldis et al., 1982]. This western belt is significantly less well known because graptolite faunas, a key to unraveling the stratigraphy of the marine basinal clastics, have been found and dated in only a few localities. The Cambrian to Lower Ordovician sequences of the Precordillera are interpreted to represent shelf and slope sedimentation on a rifted continental margin, with an oceanic basin to the west and continent to the east.

After the Arenigian, limestone deposition in the Precordillera was restricted to a few isolated structural highs [Baldis et al., 1982]. The remainder of the Precordillera region was dominated by clastic sedimentation (Figures 2 and 5), including black shales with abundant graptolites deposited in restricted environments. The Middle and Upper Ordovician strata of the easternmost Precordillera suggest that local deformation created sufficient relief to shed conglomerates into the sedimentary basin (Figure 5). Upper Ordovician conglomerate near 29°30'S reaches 350 m thickness and includes angular limestone and black shale clasts typical of the underlying Middle Ordovician strata, plus quartz clasts; it is thought to be Llandeillian (Middle Ordovician) in age [Baldis et al., 1982]. Between 31° and 32°S, there are two thin intervals of conglomerate (Figure 5) of Llanvirnian to Caradocian age [Baldis et al., 1982]. The clast types include limestone, quartz, quartzite, and metamorphic basement lithologies.

During the Middle and Late Ordovician, shallow marine shales were deposited in the Eastern Precordillera, and deep marine turbidites were widespread in the west (Figures 2 and 5). The turbidites have yielded mainly Caradocian fossils [Blasco and Ramos, 1976; Aparicio and Cuerda, 1976; Cuerda et al., 1985a]. Over a wide area the western clastic units appear to have been subjected to a very low grade metamorphism, and we interpret somewhat more metamorphosed units to the south (~32°30'S) [Harrington, 1971; Cucchi 1971, 1972] as being correlative deep marine strata.

The clastic deposits of the western Precordillera interfinger with pillow lavas, mafic and ultramafic sills (Figures 2 and 5), distal limestone turbidites, or pelagic limestones, and locally with chert [Quartino et al., 1971; Furque, 1979]. The structural relations of the clastic strata with the mafic and ultramafic igneous rocks are well exposed in a section along the Río Jáchal, near 30°15'S (Figure 6) [Ramos et al., 1984]. In the western part of the section, a massive sequence of basaltic lavas crops out beneath the unconformity at the base of the Tertiary strata. The basalts occur as pillow lavas and columnar jointed flows that are steeply tilted with a westward vergence. The eastern part of this section consists of graywackes and shales with local conglomerate of angular sedimentary clasts, intruded by sills of mafic and ultramafic composition. These sills are concordant with the strata and structure. The eastern unit is tightly folded, and graded beds indicate west vergence. Ultramafic sills occur parallel to the stratification, and one of them occupies the core of a westward overturned syncline. The concordance with the structure and the fact that they are genetically related to the thick pillow lavas (see Figures 6 and 7), indicate that the ultramafic sills were intruded prior to the folding.

The chemistry of the mafic and ultramafic rocks is useful in constraining the tectonic setting and in establishing the existence of oceanic crust west of the Precordillera continental margin at this time. Here we summarize analyses of basaltic and ultramafic samples from the western Precordillera (Figures 7a and 7b and Table 1; see also Kay et al. [1984] and Haller and Ramos [1984]. The basalts from all the studied localities

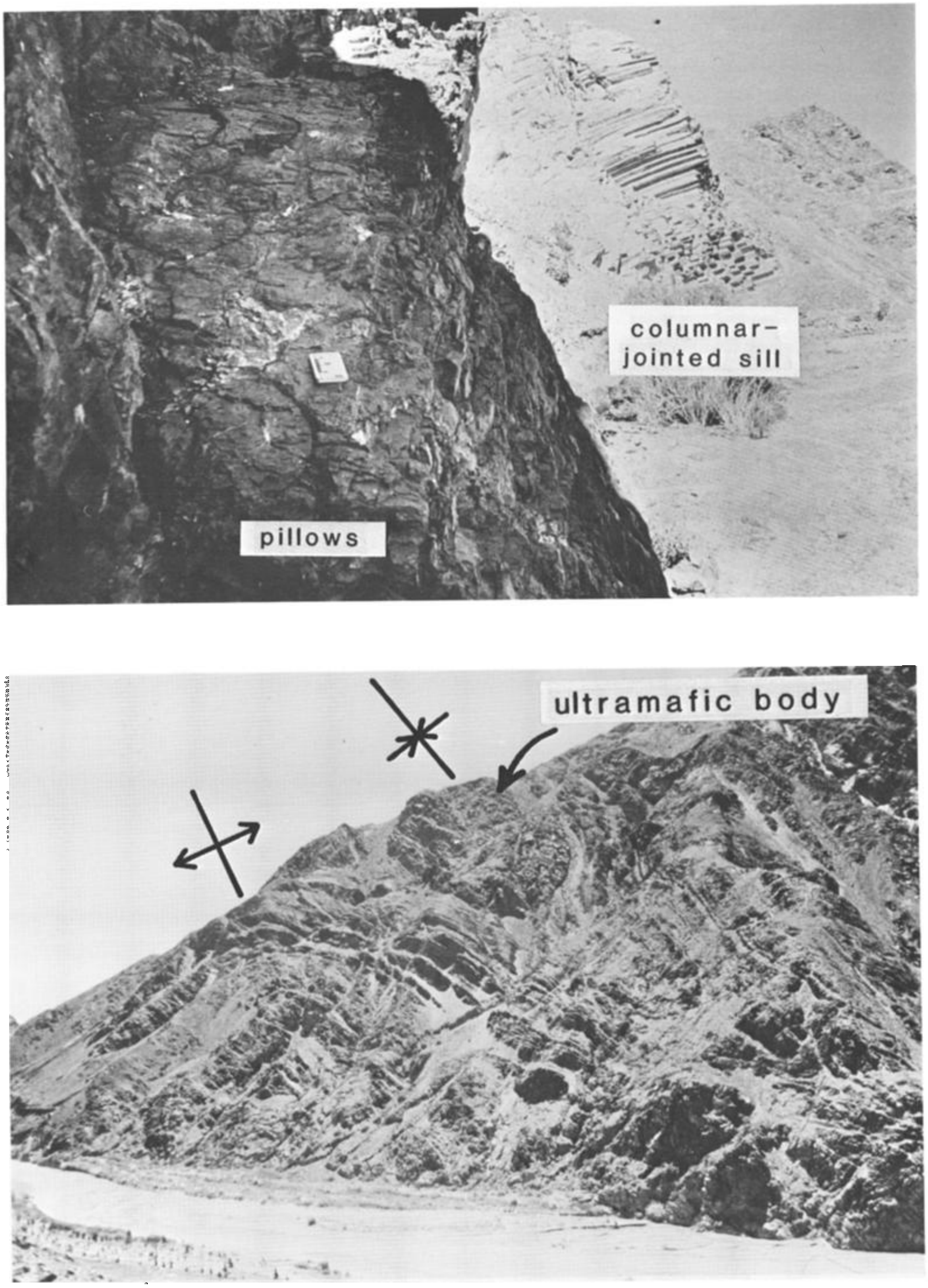

Fig. 6. Field photos illustrating geologic relations along the Río Jáchal on the west side of Precordillera (Figure 3). Top: Pillow basalts (in shadow) and columnar jointed sill, looking south. Bottom: west verging overturned folds of Upper Ordovician strata with concordant mafic and ultramafic sills, looking north. The body in the core of the overturned syncline is a wherlite.

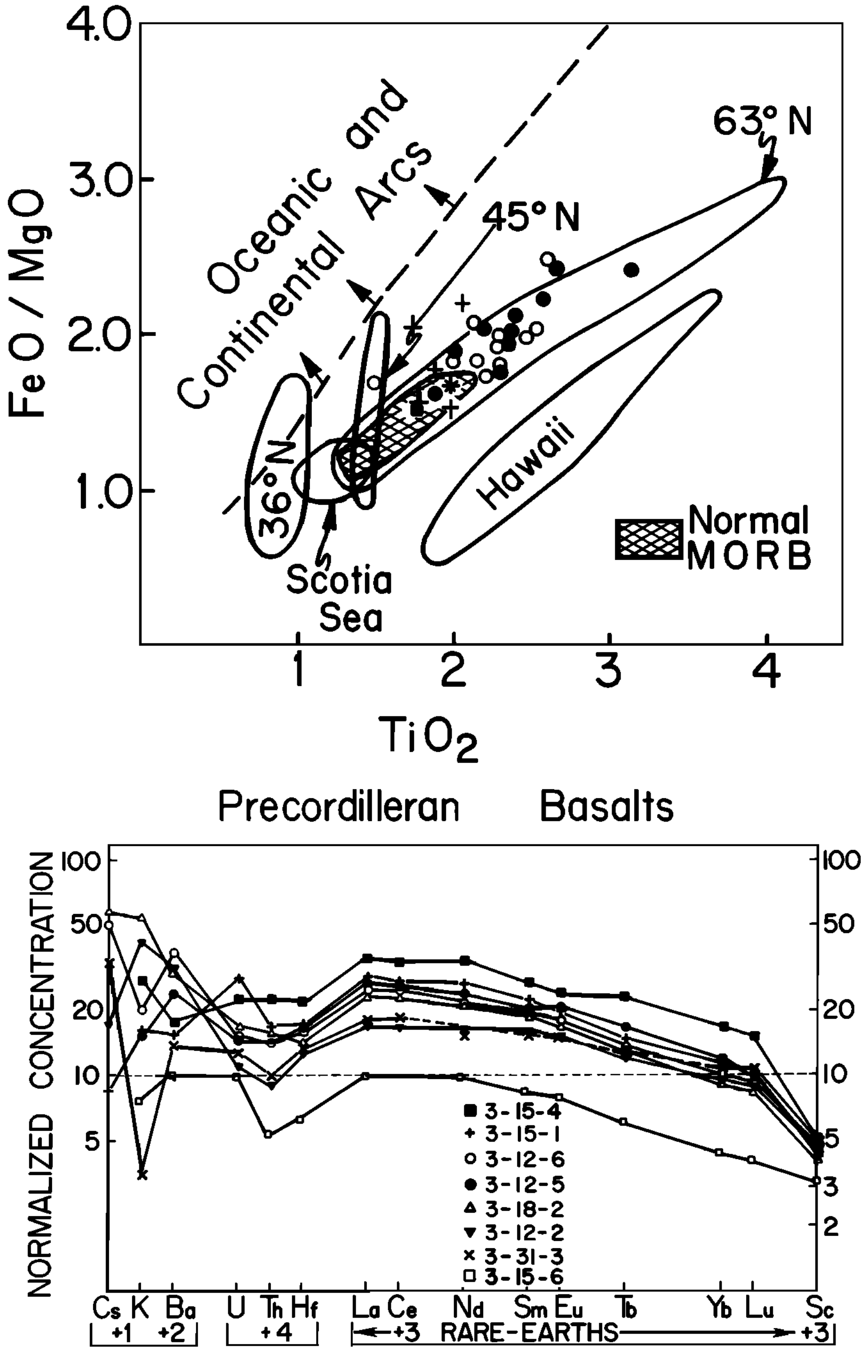

Fig. 7. Top: FeO/MgO ratio versus TiO_2 for Ordovician Precordillera basalts (Table 1) [Kay et al., 1984; Haller and Ramos, 1984], and reference suites of Scotia Sea back-arc basin basalts [Saunders and Tarney, 1979], normal mid-ocean ridge basalts (patterned field)[Bryan et al., 1981], mid-ocean ridge plume and transitional basalts (fields from 36°N, 45°N, and 63°N in the Mid-Atlantic ridge) [Tarney et al., 1979], and oceanic intraplate basalts from Kilauea Volcano ("Hawaii" field) [Basaltic Volcanism Study Project, 1981]. Arc basalts from the Aleutian Islands [Kay et al., 1982] and other arcs plot to the left of the dashed line. The Precordillera basalts are most similar to transitional ocean ridge basalt. Samples from Jáchal (solid circles), Sierra del Tigre (open circles), Calingasta (crosses), Uspallata (star), and Bonete (square). Bottom: Concentrations of REE and Sc (+3 cations), U, Th, and Hf (+4), and Cs, K, and Ba (+1 and +2) in Precordillera basalts (Table 1) normalized to Leedy chondrite and basalt KD–11. All samples show light REE enrichment and other trace element characteristics of transitional ocean ridge basalts, similar to those described by Tarney et al. [1979] from the Mid-Atlantic ridge at 63°N.

TABLE 1. Analyses of Ordovician Basalts From the Western Precordillera

	3-31-3	3-12-2	3-12-5	3-12-6	3-15-1	3-15-4	3-15-6	3-18-2
SiO_2	49.21	48.99	49.20	48.30	47.85	48.89	45.90	49.04
TiO_2	1.78	1.78	2.30	2.28	2.38	2.67	0.93	2.01
Al_2O_3	14.53	16.36	14.08	14.29	15.19	13.55	7.94	14.40
Cr_2O_3	-	-	0.03	-	-	0.01	0.32	-
FeO	11.89	10.29	12.60	12.48	12.96	14.01	11.77	12.59
MnO	0.24	0.21	0.20	0.20	0.21	0.23	0.17	0.20
MgO	7.74	6.58	7.33	6.59	6.19	5.91	24.71	7.65
CaO	10.66	11.29	10.59	12.89	11.39	10.64	7.57	10.59
Na_2O	2.86	3.19	2.48	1.35	2.95	2.46	0.29	2.06
K_2O	0.05	0.60	0.23	0.30	0.23	0.40	0.11	0.74
P_2O_5	0.14	0.14	0.18	0.21	0.19	0.29	0.03	0.16
Total	99.10	99.43	99.22	98.89	99.54	99.06	99.74	99.44
FeO/MgO	1.54	1.56	1.72	1.89	2.09	2.37	0.48	1.65
La	6.89	6.58	10.2	9.52	10.8	13.4	3.81	8.93
Ce	18.5	17.8	25.1	22.9	26.6	31.2	12.4	22.5
Nd	11.1	11.9	16.9	15.7	19.3	24.7	6.45	14.9
Sm	3.65	3.78	4.92	4.71	5.16	6.63	1.96	4.35
Eu	1.35	1.32	1.77	1.56	1.72	2.13	0.688	1.46
Tb	0.809	0.721	0.98	0.801	0.862	1.37	0.357	0.760
Yb	2.70	2.37	2.75	2.49	2.71	4.21	1.10	2.12
Lu	0.405	0.343	0.367	0.350	0.373	0.564	0.155	0.328
Sc	44.6	42.7	41.6	39.9	39.7	46.9	30.4	39.1
Hf	2.96	2.83	3.61	3.58	3.87	4.80	1.38	3.19
Ta	-	0.488	-	1.606	0.865	-	-	0.783
Th	0.507	0.457	0.700	0.709	0.837	1.10	0.233	0.783
U	0.194	0.169	0.220	0.223	0.578	0.350	0.166	0.259
Ba	52.4	120.6	33.8	143.5	61.4	66.8	39.0	117.0
Cs	0.438	0.169	1.4	0.661	0.111	0.339	4.78	0.813

Note: 3-31-3 Sierra de Uspallata (≈ 32.8°S), dike cutting Paleozoic sediments; 3-12-2 town of Calingasta (≈ 31.5°S), pillow lava; 3-12: north end of Sierra de Tigre (≈ 30.6°S); 5, sill; 6, pillow lava; 3-15: Rio Jachal east of Rodeo (≈ 30.2°S); 1, pillow lava; 4, sill; 6, wehrlitic pod. 3-18-2: Rio Bonete (≈ 28.5°S), pillow lava. Analyses done at Cornell University on fused glasses by JEOL733 microprobe and on powders by instrumental neutron activation (INAA). Analytical details in Kay et al. [1984].

are evolved oceanic tholeiites that formed in a similar tectonic environment. Distinguishing characteristics are the presence of clinopyroxene and plagioclase phenocrysts, high TiO_2 contents (1.7-2.4%), light REE enrichment, and a restricted compositional range (Table 1). Basalts from the Sierra del Tigre and Río Jáchal have a greater range of TiO_2 content and FeO/MgO ratios than basalts from the other localities (Figure 7a). A wehrlite from the Río Jáchal section described above and basalts collected between 28°30'-30°36'S have similar trace element distributions (Figure 7b and Table 1) and are more enriched in the light REE than are basalts from farther south (31°30'-32°48'S). On chemical grounds, the Precordillera basalts are not similar to normal ocean ridge basalts, oceanic intraplate magmas, or arc-derived magmas but do have similarities to basalts from unevolved back-arc basins and transitional to plume ridge segments such as the Reykjanes Ridge south of Iceland (Figure 7a). Eruption through continental crust is unlikely both on the basis of field information and low Ba contents. Possible origins consistent with the chemical data include an oceanic rift in an early stage of development, a transitional ridge segment, a back-arc basin, or conceivably some poorly defined setting in a fore-arc region.

Silurian-Devonian Stratigraphy of the Precordillera. In general, during the Silurian and Devonian, the Precordillera region was segmented in three parts (Western, Central, and Eastern) that are reflected today in the Neogene and Quaternary structure of the region (Figure 8). The westward-deepening passive margin sequence that characterized the entire Precordillera during the Ordovician changed by the Silurian. Sandstone and conglomerate were deposited in what had previously been the stable platform [Beresi, 1978]; the depocenter was approximately located in the northern part of the central Precordillera.

The nature of deposition in the westernmost part of the Precordillera during this time interval is not well determined due to the paucity of faunal control. Turbidites with late Silurian-Devonian age plant fossils occur locally [J. M. Cortés, unpublished data, 1985] and other localities have

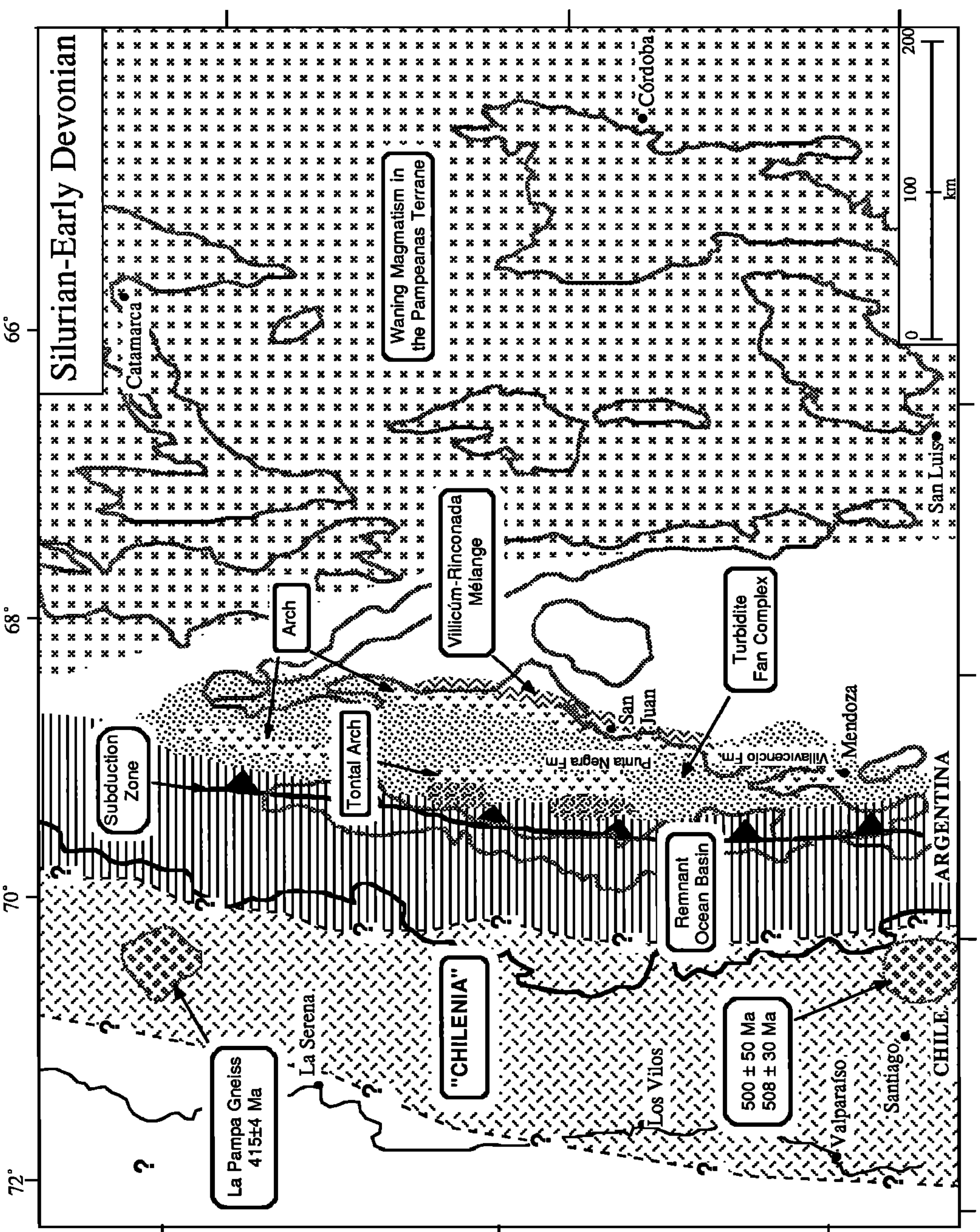

Fig. 8. Silurian-Early Devonian paleogeography: non-palinspastic, outline base from Figure 3. The Tontal Arch is the precursor of the Protoprecordillera. The western extent and character of Chilenia are unknown.

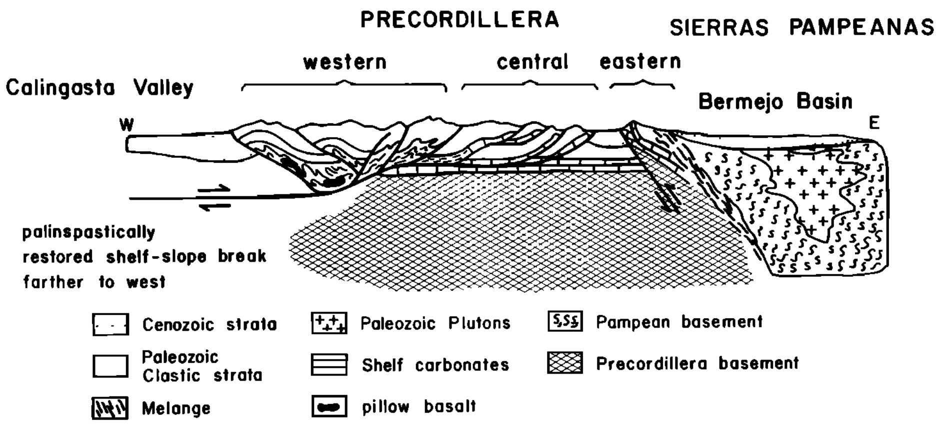

Fig. 9. Schematic cross section of the modern Precordillera showing the three structural belts and the juxtaposition of the Precordillera terrane basement against the Pampeanas basement. Not to scale.

Middle Devonian trilobites (Baldis and Sarudiansky, 1975). Rocks that have been correlated on the basis of similarity of facies locally contain basaltic clasts [Quartino et al., 1971].

Two lithofacies characterize the Silurian and Devonian basin of the Central Precordillera: an early shelf facies and later turbidite deposits (Figures 2 and 8). The shelf facies are represented by widespread Silurian and Lower Devonian shale and fine grained sandstone. Lowest Silurian oölitic ironstones underlie a clastic shelf sequence that Baldis et al. [1982] interpret to have first deepened up-section and then shallowed progressively during the Late Silurian, based on the sequence of trace fossil assemblages and faunal abundance. The Devonian strata are a distinctive, thick assemblage of fine-grained sandstone and siltstone, deposited in a trough between structurally higher north trending basin margins [González Bonorino, 1975]. South of about 31°S, over a 3000-m thickness of strata is composed of turbidites (Figure 8) [González Bonorino, 1975], but the clastic fill shoaled northwestward to nonmarine facies [Furque, 1963]. Plant fossils are common in these strata, but the chronology of the facies development is not known in detail. Volcaniclastic grains are reported in the turbidite sandstones [González Bonorino, 1975].

In the Eastern Precordillera, Silurian and Devonian(?) rocks crop out only from 31° to 32°S. Llandoverian to Ludlovian shale and sandstone [Cuerda, 1981; Peralta, 1984] of turbidite origin, highly folded and locally cleaved, contain large tabular clasts of Ordovician limestone and conglomerate, commonly tens of meters in length. The clasts have been interpreted as olistoliths in a sedimentary mélange (the Villicúm-Rinconada mélange of Figure 8) produced during submarine slumping and transported no more than a few kilometers from a positive area to the west [Amos, 1954; Baldis et al., 1982]. This positive source area would have separated the Silurian basins of the Eastern and Central Precordillera; an erosional unconformity between Ordovician and Silurian units in the Central Precordillera might indicate a source area for the olistoliths [Rolleri, 1947; Baldis et al., 1982]. Alternatively, the source of the limestone blocks could have been to the east; though no suitable source areas are now recognized to the east, later deformation has altered the original spatial relations of the Cambro-Ordovician shelf. Furthermore, the mélange facies rests on a thick sequence of Ordovician strata that does not thin eastward, and thus the limestones may have extended to the east during the Silurian.

A third possibility is that the clasts and the mélange are tectonic in origin, a conclusion reached by Heim [1948]. This alternative is attractive because the mélange belt, traceable for ~75 km along the easternmost Precordillera but elsewhere covered by Tertiary strata, forms the boundary between the Precordillera and Pampeanas terranes. East of the mélange, none of the pre-Carboniferous strata of the Precordillera have been recognized with certainty on Pampeanas basement. We interpret the mélange as being indicative of a major fault zone [e.g., Cowan, 1985], which might also have produced localized uplifts that sourced the conglomerates and olistoliths. This major fault zone forms the boundary between the Pampeanas and Precordillera terranes. Upper(?) Carboniferous strata overlie the deformed mélange rocks across an angular unconformity [Baldis et al., 1982]. The shale and sandstone hosts of the olistoliths are at least in part of Late Silurian age [Peralta, 1984], hence the deformation can be bracketed as Late Silurian to Late Carboniferous.

A few minor stocks in the Central Precordillera predate Carboniferous strata and postdate deformation and therefore are considered to be of Devonian or Late Silurian in age [Furque, 1963; Caminos, 1972; Caminos et al., 1982]. These rocks are granodioritic to granitic in composition, with a more acidic facies associated with quartz porphyries [Rossi, 1947]. These Middle Paleozoic intrusions lie about 250 km west of the Pampeanas magmatic front.

Early and Middle Paleozoic Deformation of the Precordillera Terrane. The three part subdivision of mid-Paleozoic depositional settings in the Precordillera is mimicked in the Famatina cycle deformation. Pre-Carboniferous deformation occurred in the Eastern and Western Precordillera, but there was little deformation in the Central Precordillera (Figure 9) [e.g., Baldis and Chebli, 1969; Baldis et al., 1982].

The first stratigraphic indications of deformation in the Eastern Precordillera are the Middle and Late Ordovician conglomerates. The Silurian and Devonian(?) strata of the Eastern

Precordillera were intensely deformed prior to the deposition of Carboniferous strata, but the age of deformation cannot be more closely constrained. An interpretation combining tectonic and sedimentary origins for the mélange suggests that the deformation was either syndepositional or early post-depositional.

In the Western Precordillera, pre-Carboniferous deformation is also very important. Facies variations in the Carboniferous units indicate that a topographic high existed near the position of the present Western Precordillera, coinciding with the Sierra de Tontal [Baldis et al., 1982], and the Devonian submarine fan facies are consistent with the existence of a subaqueous ridge (Figure 8) [González Bonorino, 1975]. Before Carboniferous strata were deposited, the Devonian units were intensely folded and faulted along the western flank of the basin but not in the eastern part [Baldis et al., 1982], suggesting that the topographic high, referred to as the "Protoprecordillera," was tectonic in origin [Amos and Rolleri, 1965; Rolleri and Baldis, 1969]. West of the Sierra de Tontal the late Ordovician clastic facies (west of the platform and slope facies) are highly deformed; locally they are imbricated with mafic and ultramafic rocks, constituting a tectonic mélange (e.g., Sierra de Cortaderas, 32°15'S [Keidel, 1939; Haller and Ramos, 1984]). On the west side of the southernmost Calingasta Valley, west of the units known to be of Late Ordovician age, Late Silurian-Devonian units are highly deformed [J. M. Cortés, unpublished data, 1985]. If deformation in the Western Precordillera was synchronous with sedimentation from the Late Ordovician onward (ie., a trench was active for that entire time), the westward younging of strata would imply a westward migration of deformation. Although metamorphism is not a common characteristic of this phase of deformation, phyllites in the southern Precordillera at 32°15'S have yielded a K/Ar whole rock date of 350±17 Ma [Cucchi, 1971], suggesting a minimum age of Late Devonian for the deformation.

In summary, the stratigraphy of the Precordillera terrane indicates that there were three tectonostratigraphic belts during the Early and Middle Paleozoic (Figures 4, 5, 8, and 9). The Western belt was first a deep marine basin, affected by mafic volcanism and shallow mafic and ultramafic intrusion. The Central Precordillera was structurally more stable, recording the gradual subsidence from an Ordovician carbonate shelf to a northward shallowing Devonian submarine fan, but with no angular unconformities developed during this time interval. The Eastern Precordillera was initially a part of the stable Cambro-Ordovician carbonate shelf environment, but evolved into a major topographic and structural boundary by the Silurian and Devonian. The correspondence of these Paleozoic belts with modern Andean structural provinces (Figure 9) indicates a strong paleogeographic control on younger structures.

Comparison to North American Appalachian History. The Precordillera stratigraphy cannot be carried either north of 29°S or south of 34°S latitude. However, the lower and middle Paleozoic stratigraphy of the Precordillera terrane is surprisingly similar, both lithologically and faunally, to that of the Northern Appalachians. Features common to both sequences include (Figure 10): (1) Cambrian to Lower Ordovician carbonate shelves grading into shaly slope and basin facies, (2) similar Cambrian trilobite faunas [Baldis et al., 1982], (3) similar tectonic subsidence histories [Bond et al., 1984], (4) a mid-Ordovician to Lower Silurian sequence of sandstones and red and green shales, (5) Silurian ferruginous sandstone and oölitic ironstone, and (6) mafic and ultramafic intrusives and extrusives associated with clastic rocks of Llandeilian to Caradocian age. Plate reconstructions generally do not place South America adjacent to northeastern North America during this time [but see Bond et al., 1984]. The plate reconstructions might be quite different if the Precordillera were treated as a terrane that was distantly allochthonous to South America during the Early and Middle Paleozoic. If during the Early Paleozoic there was a connection between the Precordillera and the Northern Appalachians, it is interesting to note that their stratigraphies diverge sharply in character after the early-mid Silurian (Figure 10). This time may coincide with the formation of the mélange in the easternmost Precordillera.

Chilenia Terrane

The relations that demonstrate the existence of an ocean basin at the west side of the Precordillera terrane provide the strongest evidence for the allochthonous nature of the basement of the Frontal Cordillera, which we call the Chilenia terrane. The abundant upper Paleozoic to Neogene plutons, volcanic rocks, and sedimentary strata of Chile and westernmost Argentina have largely covered or obliterated the rocks that constituted Chilenia. Unmetamorphosed sedimentary rocks of pre-Carboniferous age are completely absent in the Coastal and Principal Cordilleras, and outcrops of any metamorphosed rocks of Devonian or older age are relatively rare in the Frontal Cordillera, the inferred location of Chilenia (Figure 3). There have been few geochronologic and isotopic studies of the pre-Carboniferous metamorphic rocks of the region. Furthermore, the Frontal Cordillera, particularly in Argentina, has had only cursory reconnaissance because of its remoteness and difficult access. Thus little is known of the character or affinity of Chilenia.

South of our immediate region of study, in the Frontal Cordillera of Mendoza (33°-34°S), Caminos et al. [1979] obtained Rb/Sr and K/Ar whole rock isochrons of 500±50 and 508±30 Ma, respectively, from greenschist to amphibolite grade metamorphic rocks that are tectonically interleaved with Devonian to Carboniferous marine sedimentary rocks and are intruded by upper Paleozoic granitoids. The isotopic ages are interpreted to indicate a metamorphic event that overprinted Precambrian rocks [Polanski, 1958]. North of 31°S the Paleozoic rocks of the Frontal Cordillera extend into Chile, where undated pelitic schists of lower(?) Paleozoic age have recently been found (the El Cepo metamorphic complex [Cornejo et al., 1984]). In the Frontal Cordillera at 29°N, Ribba et al. (personal communication, 1985) have discovered mylonitic schists and cataclastic gneisses, one of which has yielded an Rb/Sr age of 415±4 Ma (La Pampa Gneiss, Figures 2 and 8). The above rocks are the oldest known from the Frontal Cordillera and are also the only direct, though inconclusive, evidence for the nature of the basement of Chilenia.

Indirect, but nonetheless important, arguments that Chilenia had an old basement with possible continental affinities are (1) The upper Paleozoic magmatic belt of the Frontal

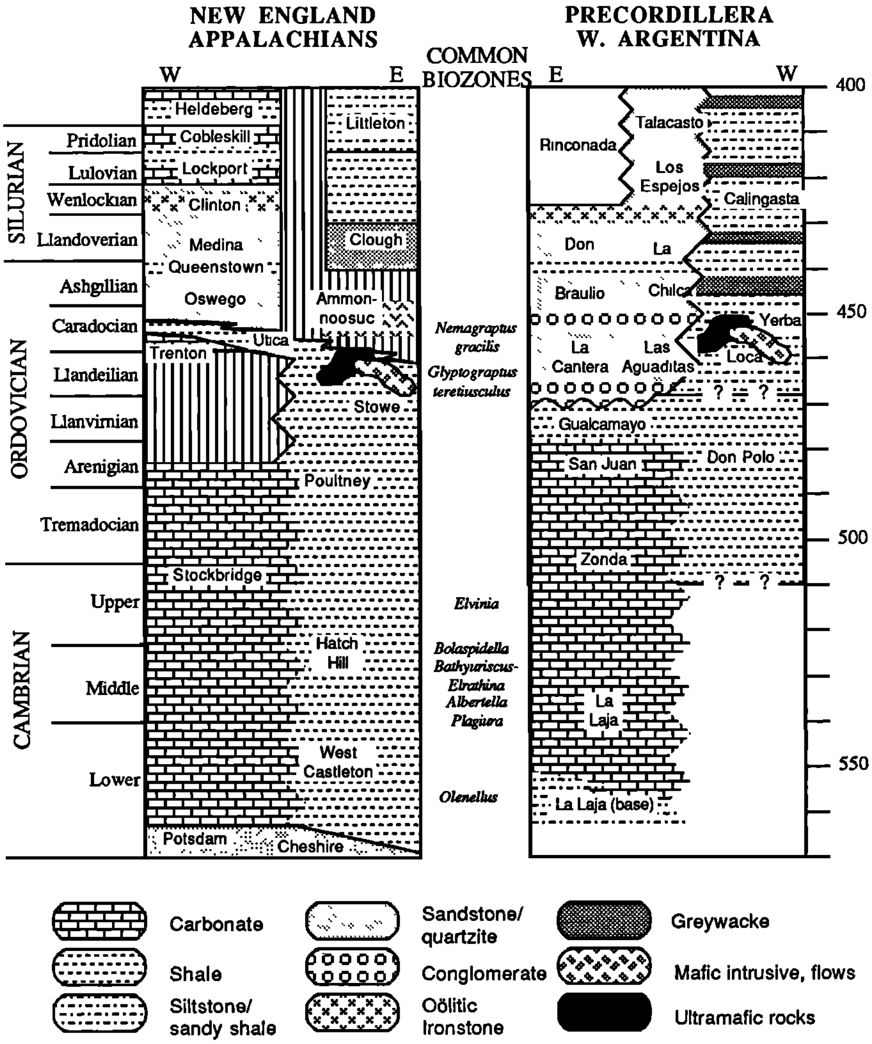

Fig. 10. Comparison of Cambrian to Silurian stratigraphy for the Precordillera terrane (right) and the New England Appalachians (left). Columns constructed based on information in the works by Baldis et al. [1982] and Bird and Dewey [1970]. Note that east (E) and west (W) are reversed for the Precordillera section for the purposes of comparison.

Cordillera includes a thick pile of high silica rhyolites together with large plutons of leucocratic "pink" granites (discussed below). These are interpreted as being produced either by melting of continental crust, or mixing of mantle-derived magmas with previously existing lower Paleozoic or older continental material [Parada, 1984; Mpodozis et al., 1985]. (2) The Devonian to Permian forearc sedimentary and metasedimentary strata in the Coastal Cordillera at 32°S include clasts with granitoid fragments and detrital micas that are inferred to be continentally derived (Arrayan and Huentelauquen Formations, Figure 2) [Sepulveda, 1984]. (3) High initial $^{87}Sr/^{86}Sr$ ratios for the Carboniferous Tanumé metamorphics, south of Santiago, have been interpreted by Hervé et al. [1984] as being indicative of recycled crustal material. These direct and indirect indications of continental basement west of the Precordillera, in combination with the belt of oceanic crustal material of Late Ordovician age lying on the west side of the Precordillera terrane (Figure 5), are the primary evidence that we use to infer the existence of Chilenia.

Contacts Between Terranes

The present nature of the terrane boundaries has been obscured by younger strata and overprinted by upper Paleozoic and Andean deformation. The boundary between the Precordillera and Sierras Pampeanas terranes is locally abrupt, with less than 10 km separating exposures of rocks characteristic of the two provinces, or more commonly is completely hidden beneath a broad alluviated valley (Bermejo Basin, Figures 3, 11). The boundary between Chilenia and the Precordillera terranes coincides with, and is partly obscured by, the Calingasta Valley (Figure 11). Where it is not covered by

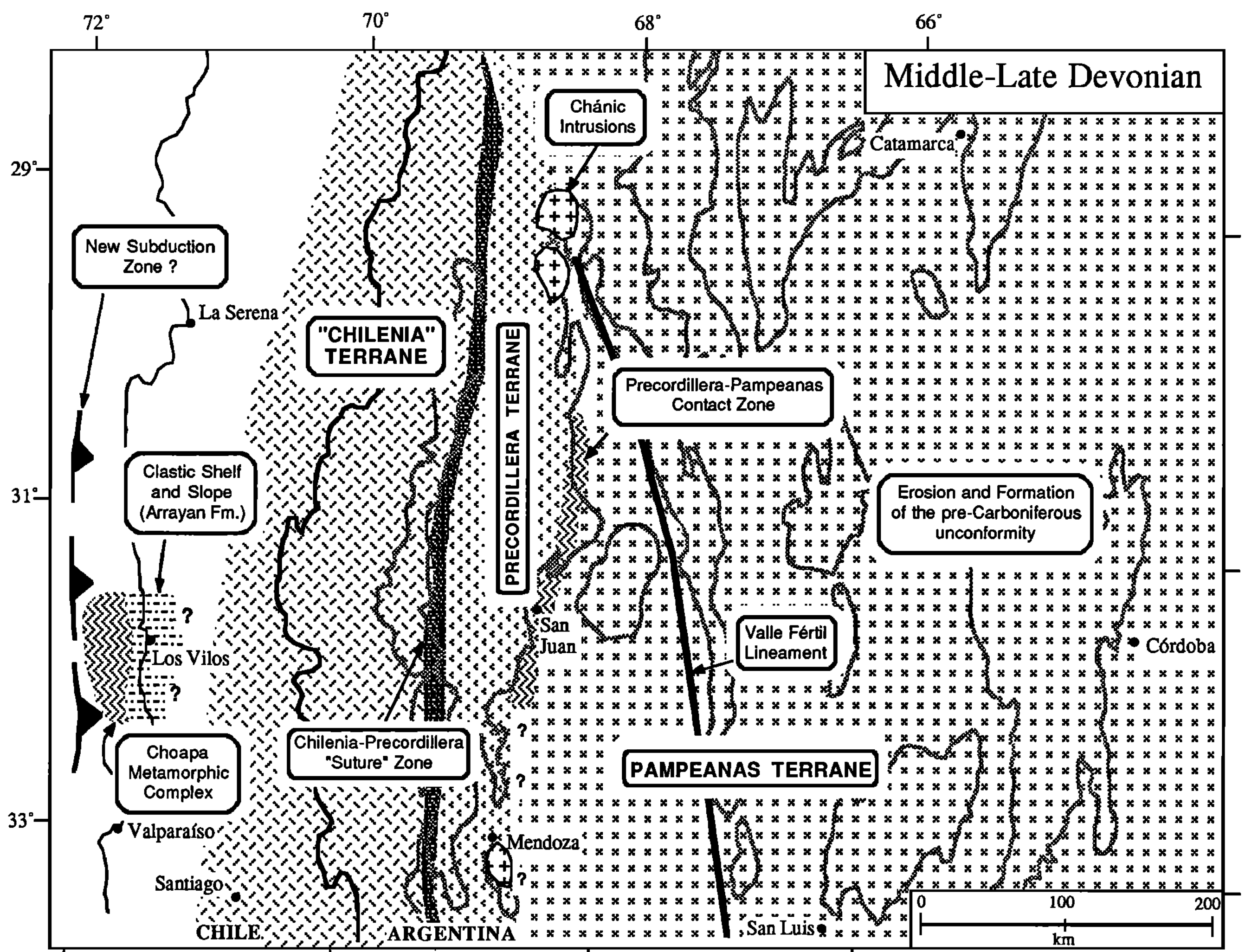

Fig. 11. Middle-Late Devonian paleogeography: non-palinspastic, outline base from Figure 3. Shows relations of the Chilenia, Precordillera, and Pampeanas terranes following the accretion of Chilenia during the Chánic orogeny. The western extent and character of Chilenia are unknown. The Valle Fértil lineament, discussed in the text, may have been active at times other than or in addition to Middle-Late Devonian; its history is very poorly known. Position of the Chilenia-Precordillera suture is shown in the upper plate of Andean thrust faults; its position in the lower plate is probably beneath the Frontal Cordillera.

Quaternary material, it has been crosscut by and is buried beneath Upper Paleozoic plutonic and volcanic rocks.

Between 31° and 32°S the boundary between the Pampeanas and Precordillera terranes is represented by the Silurian-Devonian(?) mélange which separates the shelf sequence to the west from the crystalline metamorphic rocks to the east (Figure 11). Between 29°30'-31°S and south of 32°S, Tertiary and Quaternary sediments cover the possible northern and southern continuations of the mélange. Farther north a major lineament named after the Sierra de Valle Fértil (Figures 3 and 11) coincides with the boundary between the Precordillera and Pampeanas terranes, but Cenozoic shortening across it has obscured the original character of the contact. South of 31°S the lineament, which is today a major reverse fault, lies entirely within the Pampeanas terrane (Figure 11). The Valle Fertil lineament has been proposed as an important paleotectonic feature and may have been active, perhaps as a strike-slip fault, during the early-middle Paleozoic.

The northern limit of the Precordillera terrane is problematical because the characteristic stratigraphy cannot be traced north of 29°S. In the Sierra de Famatina (Figure 2) there is a transitional relationship between greenschist facies strata and sedimentary sections bearing abundant fossil remains of Early to Middle Ordovician age [de Alba, 1979]. The metamorphism is spatially associated with the Famatina Batholith, which is apparently bracketed on stratigraphic grounds as being Late Ordovician in age [Moya and Salfity, 1982]. The north end of the Precordillera carbonate platform overlaps in latitude with the metamorphic rocks of the Famatina Range. The northward extension or termination of the Precordillera terrane, its relationship to the Famatina metasedimentary rocks, and their relationship to the Pampeanas terrane are poorly understood.

The remains of the contact between Chilenia and the Precordillera are presumably mostly buried due to the Late Paleozoic to Miocene magmatic activity and to subsequent deformation. The structural geometry of the Precordillera [e.g., Baldis and Chebli, 1969; Ortiz and Zambrano, 1981] suggests that Cenozoic deformation resulted in thrusting of upper crustal strata eastward above the basement of the Precordillera. Preliminary restoration to the pre-Cenozoic geometry indicates that the basement of the Ordovician carbonate shelf extends as far west as the Frontal Cordillera (R.W. Allmendinger, unpublished data, 1984). Therefore, the suture zone between the Precordillera terrane and Chilenia is probably cut by the younger faults: Its trace in the upper crust is related to the belt of mafic volcanic rocks but is mostly covered by the Calingasta Valley; its trace in the lower plate of the Andean thrusts would lie beneath the Frontal Cordillera.

Summary of Early and Middle Paleozoic Tectonic Evolution

The Cambrian and Lower Ordovician strata of the Precordillera terrane represent a continental margin with the ocean to the west of the Precordillera and land to the east (in present coordinates), which Bond et al. [1984] interpret as a thermally subsiding passive continental margin. During the inferred passive margin development there was at least some coeval magmatism in the Pampeanas terrane, indicating that the two terranes may not have been immediately adjacent at that time. Intense deformation along the western edge of the Precordillera terrane predates the Carboniferous. We relate this deformation to subduction and formation of an accretionary prism along the margin of the terrane; evidence for the polarity of subduction is meager, but the dominant westward vergence of pre-Carboniferous structures of the western Precordillera is consistent with eastward subduction. Peak plutonism apparently occurred in the Pampeanas terrane during the Late Ordovician and it could have been related to subduction west of the Precordillera if the two terranes were adjacent at that time. However, the mélange at the eastern side of the Precordillera is post-early Silurian and pre-Carboniferous in age and may indicate that the two terranes were not joined until that time. The absence of volcanic detritus or volcanic tuffs in the Ordovician strata of the Precordillera is particularly problematic: either (1) the Pampeanas was not located adjacent to the Precordillera during the early Paleozoic, (2) wind-driven or fluvial systems distributed the volcanic debris away from the Precordillera, or (3) no volcanic edifices capped the plutons at this time. By the Devonian, the accretionary prism was significantly thickened and uplifted, ponding a forearc basin to its east behind a submarine ridge which eventually emerged as the Protoprecordillera. Magmatism waned during the Silurian and Devonian in the Pampeanas terrane, and volcaniclastic detritus is completely absent in the equivalent aged strata in the Precordillera.

Carboniferous strata show that the three terranes were "stitched" together by that time (Figure 9): They unconformably overlie (1) intensely deformed Devonian units in the Western Precordillera, (2) undeformed units in the Central Precordillera, (3) the mélange of the Eastern Precordillera, (4) plutons and metamorphics of the Pampeanas terrane, and (5) the Chilenia terrane. Based on the onlap of Carboniferous strata from the Precordillera onto the Chilenia basement to the west, we hypothesize that a collision between the outboard two terranes occurred during the Middle or Late Devonian (Chánic event of Figure 2) [Criado Roque et al., 1981] and that, subsequently, the plate boundary began migrating to the west toward its present position. Minor plutonic activity in the orogenic belt postdated the collision (Figure 11) and could be related to postcollision uplift, similar to Caledonian granitoids (I-Caledonian type of Pitcher [1982]); however, pertinent geochemical data do not exist.

Two major unknowns are present in this model: (1) the spatial relations of the Precordillera and Pampeanas terranes prior to the Carboniferous, and (2) the timing of initial deformation, and hence subduction, along the western margin of the Precordillera terrane. A conservative extreme is that the Pampeanas and Precordillera terranes have been contiguous since the Precambrian, with only strike-slip displacement (along the Valle Fértil lineament or the Villicum-Rinconada mélange) between them during the time considered here. In this case, we would relate subduction on the west side of the Precordillera from Ordovician onward to the magmatism in the Pampeanas terrane. The basalts of the western Precordillera would represent volcanism into an accretionary prism, a situation tectonically similar to that documented by Moore et al. [1983] for the Paleocene accretionary wedge of Kodiak Island. This alternative best explains the magmatic history of the Pampeanas terrane in relation to the Precordillera, but we are troubled by the lack of volcanic detritus in the strata of the Precordillera. It also implies that the eastern edge of Chilenia was a passive margin.

The alternative extreme is that the Precordillera and Pampeanas terranes were unrelated prior to the formation of the Silurian-Devonian(?) mélange of the eastern Precordillera. In this case, magmatism in the Pampeanas terrane was not a result of subduction beneath the Precordillera, and the passive margin of the Precordillera could have existed for a longer period of time. This alternative would allow convergence between Chilenia and the Precordillera due to westward subduction beneath Chilenia, accounting for the lack of volcanic detritus in the Precordillera. However, there is no record in the meager exposures of Chilenia for the hypothesized arc activity during the early and middle Paleozoic, and it contradicts the evidence for westward vergence of structures in the western Precordillera. Variations on these two extremes cover a broad spectrum and become very speculative due to lack of data.

CARBONIFEROUS TO TRIASSIC—THE GONDWANA TECTONIC CYCLE

Keidel [1925] first recognized a series of important Permian diastrophic episodes, which resulted in the formation of the Gondwanide orogenic belt. Windhausen [1931] suggested that this folded belt bordered the periphery of the continent of Gondwana and continued toward the east from South America into South Africa (the Cape fold belt). Three major provinces of this orogenic belt are evident in a transect across the region between 30° and 33°S (Figure 12): (1) a back-arc province located in the Sierras Pampeanas, Precordillera, and eastern part of the Frontal Cordillera, in which shallow marine and terrestrial sediments accumulated in several basins during the Upper Devonian to Permian; (2) a magmatic arc that was centered in the Frontal Cordillera north of 32°S but extending along the eastern slopes of the Coastal Cordillera south of 32°S; and (3) a forearc province, including a large upper Paleozoic accretionary prism constructed during the subduction of oceanic crust beneath the newly accreted Chilenia. Various aspects of this tectonic cycle have been discussed by Hervé et al. [1981], Forsythe [1982], and Dalziel and Elliot [1982].

Late Paleozoic Back-Arc Basin Development

The Devonian deformation culminated with the thrusting and emergence of the Protoprecordillera as a subaerial high, which subsequently separated two different Carboniferous basins [Rolleri and Baldis, 1969; Baldis and Chebli, 1969; Baldis et al., 1982]. Although some authors infer that the Protoprecordillera did not have great continuity along strike [e.g., Vasquez et al., 1981], at a minimum it extended from about 30° to 33°S, and, given the lack of field data to the north and south, it may have had a much greater extent. Carboniferous to Early Permian intermontane basins on the east side of this positive area were filled with glacio-fluvial deposits that change eastward to the alluvial fan and local tidal deposits of the Paganzo basin, while on the west side a westward thickening wedge of deltaic and marine strata was deposited (Figure 12).

Carboniferous sedimentary facies suggest that the fluvial systems of the back-arc region prograded from east to west [Vasquez et al., 1981; Criado Roque et al., 1981]. The eastern deposits are continental red beds of the Paganzo Group which contain typical Gondwana floras and range in thickness from 100-500 m. To the west near the Calingasta Valley and the eastern Frontal Cordillera, black shales, probably representing prodeltaic deposits, alternate with marine turbidites; the entire sequence may be as much as 7000(?) m thick [Polanski, 1958; Amos and Rolleri, 1965; Caminos, 1965, 1979b]. The western limit of documented deltaic facies, located in the eastern part of the Frontal Cordillera, could represent either the continental edge [Rolleri and Baldis, 1969] or simply the border of the deltaic platform, an interpretation which would not require the presence of an ocean basin immediately to the west. Intense deformation and low-grade regional metamorphism of the westernmost Carboniferous units obscures evidence of the original bathymetry. In the most western sector of the Carboniferous back-arc basin (located in Chile), lacustrine or shallow marine facies of volcanic provenance locally underlie a volcanic arc sequence (see below) (Sierra del Hielo at 28°S, Río Valeriano at 29°S, and Río Hurtado [Cornejo et al., 1984]).

The Gondwana Magmatic Arc

Gondwana magmatism, represented by a complex sequence of diverse plutonic and volcanic events, peaked during the Carboniferous and Permian and continued into the Early Triassic [Ramos and Ramos, 1979; Forsythe, 1982]. Sparse geochemical analyses suggest normal calcalkaline magmatism, typical of a Pacific-type suite [Coira and Koukharsky, 1976; Caminos, 1979b].

A 600-km-long batholith crops out in the Coastal Cordillera south of 32°S (Figures 2 and 12). The batholith, composed of calcalkaline tonalite, granodiorite, and minor gabbro and diorite intruded the eastern metamorphic belt of the Upper Paleozoic accretionary wedge (described below). The age of the main intrusion is considered to be Permo-Carboniferous on the basis of Rb/Sr isochrons and K/Ar ages [e.g., Shibata et al., 1984; Hervé et al.,1985]. The intrusives appear to be I-type granitoids with $^{87}Sr/^{86}Sr$ initial ratios ranging between 0.706 and 0.707, indicating significant crustal contamination [Hervé et al., 1985]. Magmatism (mostly epizonal stocks) continued in the Coastal Cordillera until the Triassic.

North of 32°S the Late Paleozoic-Triassic magmatic activity was centered along the Cordillera Frontal where large batholiths were emplaced togther with a coeval volcanic cover (Choiyoi Group) [Caminos, 1979b; Parada, 1984; Mpodozis et al., 1985]. In Chile, plutonism seems to have started during the Carboniferous along the western edge of the Frontal Cordillera, where large bodies of calcalkaline, hornblende-biotite tonalites, and granodiorites intruded across subduction complexes or forearc assemblages (e.g., El Tránsito area, 29°S (L. C. Ribba et al., personal communication, 1985)). Contamination with the host rocks resulted in the formation of muscovite granodiorites [Mpodozis et al., 1985]. During the Permian the locus of magmatic activity shifted slightly eastward, and the nature of the plutons changed to much more evolved, high silica, epizonal "pink" granites and porphyries

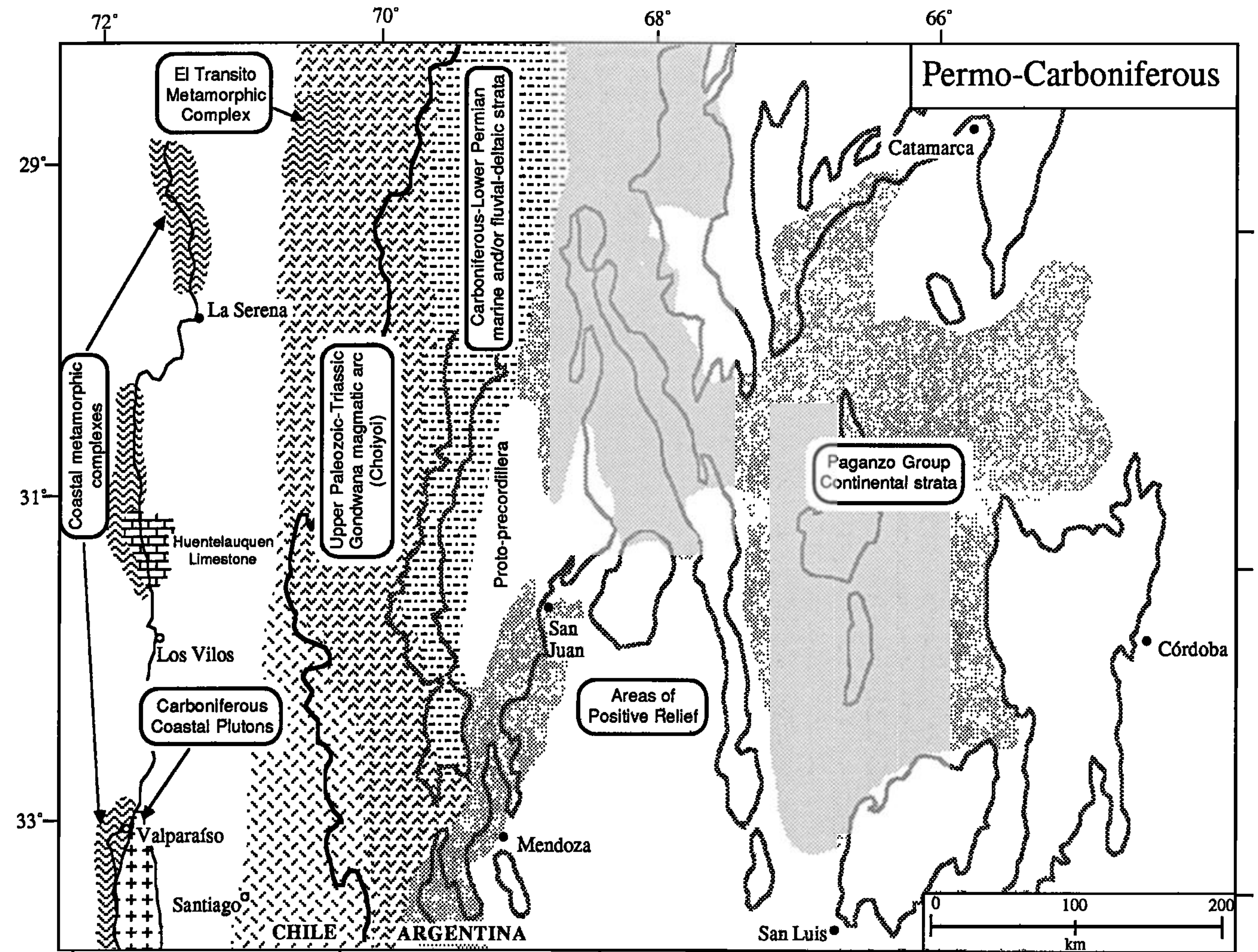

Fig. 12. Permo-Carboniferous paleogeography: non-palinspastic, outline base from Figure 3. There is a smooth gradation from Paganzo Group continental strata to the Carboniferous-Lower Permian marine and/or fluvial deltaic strata of the Frontal Cordillera.

[Caminos, 1979b; Parada, 1984; Mpodozis et al., 1985]. These compositional changes may represent a major shift from a mantle-dominated source in the western Carboniferous belt to a crustal-dominated source for the eastern belt in the Permian to the Triassic.

The "crustal" signature of the younger plutons may be derived not from the accreted Late Paleozoic wedge or the Carboniferous plutons but from much older continental sources [Mpodozis et al., 1985]. La Pampa Gneisses (Figure 2) and similar rocks which may be the remnants of the continental basement of the Chilenia terrane are candidates for those older sources. In summary, although most of the plutons of the Gondwana magmatic arc in the Coastal and Frontal Cordilleras were probably subduction-related, the nature of the Permian to Triassic plutons seems to reflect a strong interaction between the rising magmas and some kind of continental crust. This occurred on such a large scale that most of ancient Chilenia could have either melted or mixed to produce the Permian and Triassic intrusives.

On the Argentine side of the Frontal Cordillera and locally in Chile, the plutons are related to extensive andesitic and rhyolitic volcanism (the hundreds of meters of thick Choiyoi Group, Figure 12) and late hypabyssal facies of more acidic character [Mpodozis et al., 1976; Coira and Koukharsky, 1976; Caminos, 1979b; Parada, 1984]. In the western part of the region the basal sequences are composed of hornblendiferous andesites and dacites in lava, breccia, and pyroclastic facies [González Díaz, 1958; Caminos, 1965], while in the eastern part a rhyolitic facies, for the most part ignimbrites, dominates throughout the whole sequence. Although most authors [Caminos, 1979b; Coira et al., 1982] consider the Choiyoi to be Permian to early Triassic, growing evidence from the Chilean part of the Frontal Cordillera between 29° and 33°S indicates that acidic volcanism had begun no later than the Late Carboniferous.

In general, there is an eastward migration in the age of volcanism: In the western part of the Argentine Cordillera Frontal it is Late Carboniferous(?) to perhaps basal Triassic [Polanski, 1958; Caminos, 1979b], but farther east only localized Triassic occurs (e.g., the Sierras Pampeanas of San Luis [Criado Roque et al., 1981] and perhaps the Huaco region of the San Juan Precordillera [Furque, 1979]). In the eastern Sierras Pampeanas some minor granitoid stocks yield an early Carboniferous age (F. Hervé et al., unpublished manuscript, 1986). The $^{87}Sr/^{86}Sr$ ratios of these granitoids are considerably higher than those of the older granitoids in the region, suggesting considerable crustal contamination and possible thickening of the crust since emplacement of the Devonian plutons.

The Forearc Region

Between 28° and 36°S, the Coastal Cordillera of Chile exhibits large and discontinuous outcrops of metamorphic and sedimentary rocks interpreted as accretionary wedges or forearc basin strata accumulated during the Gondwana orogeny [Hervé et al., 1981; Forsythe, 1982]. Between Isla Chañaral (29°15'S) to Bahía El Teniente (31°S) (Figure 12) there are sporadic outcrops of strongly deformed metasediments interleaved with metacherts and metabasites with relict pillow structures that have oceanic tholeiite affinities [Godoy, 1979]. A similar group of rocks, including marbles and garnet-bearing mica schists, crops out in the Frontal Cordillera 150 km to the east (El Tránsito Metamorphic Complex) where a metamorphic event of Carboniferous age (Figure 2) has recently been detected (L. C. Ribba et al., personal communication, 1985). On the coast at Los Vilos (29°40'S, Figures 2, 3 and 12), metamorphosed accretionary prism rocks (the Choapa Metamorphic Complex) also occur together with a nonmetamorphosed turbidite sequence of Upper Devonian-Lower Carboniferous(?) age (Arrayan Formation [Sepulveda, 1984]). The relations between the Choapa Complex and the Arrayan Formation (Figure 2) remain a topic of debate: Does the Arrayan postdate the metamorphism and deformation of the Choapa, or was it simply sufficiently far removed from the site of subsequent metamorphism? The former would suggest that subduction beneath Chilenia began before it was attached to South America. The controversy must await further geochronologic studies. Upper Carboniferous-Lower Permian platform carbonates and conglomerates (the Huentelauquen Formation) unconformably overlie both the Arrayan and Choapa units (Figures 2 and 12).

Recent paleomagnetic work [Forsythe et al., 1986] seems to indicate that the whole coastal block between 31° and 32°S could have suffered important horizontal displacement during the Late Triassic-Early Jurassic. Until those movements are better understood, the Gondwana cycle history of the forearc region will remain uncertain.

South of Santiago, Chile, the forearc province is represented by the Coastal Cordillera "paired metamorphic belt." The western belt includes strongly deformed mica schists and metabasites of tholeiitic affinities, affected by a high P-low T metamorphism (glaucophane-bearing schists); the eastern belt has less deformed pelitic schists metamorphosed under a low P/T regime [Hervé et al., 1981]. New Rb/Sr isochrons suggest that both the Western belt (Pichilemu Schist, 311±2 Ma) and the Eastern belt (Tanume metamorphics, 347±2 Ma) were metamorphosed and deformed during the Carboniferous [Hervé et al., 1984].

In summary, the Early Carboniferous appears to be the major period of accretionary prism formation and metamorphism in the forearc province between 29° and 34°S. This suggests a very short time span between the "docking" of Chilenia with South America (in the Late Devonian) and the development of eastward subduction and a substantial accretionary wedge on the west side of Chilenia by the Early Carboniferous. Either subduction along the western margin of Chilenia began before the docking was complete or perhaps Chilenia arrived with a sedimentary fringe on a western passive margin that was subsequently deformed by the younger subduction.

DISCUSSION

In 1931, Windhausen explicitly postulated the existence of a Pacific continent, presently represented by the Coastal Cordillera of Chile. Although our synthesis supports his notion of the growth of the Gondwana/South American continent by accretion of terranes, the evidence now available implies that the major terranes were accreted during the early and middle Paleozoic and are located farther inboard than he had postulated. Other authors have proposed the existence of terranes in the Andes that might have been similar to the island arcs and microcontinents in the present day southeast Pacific [Martínez, 1980; Dalmayrac et al., 1980]. The most notable of these is the Arequipa terrane of southern Perú and other fragments of ancient basement such as at Belén [Pacci et al., 1979] and Sierra Moreno [Breitkreuz and Zeil, 1984] in Chile, and Antofalla in northern Argentina [Allmendinger et al., 1982] (Figure 1). These terranes were considered as part of a single allochthonous block by Coira et al. [1982], Allmendinger et al. [1982], and Mpodozis et al. [1983] that was accreted during the Early Paleozoic perhaps during the Late Ordovician Oclóyic event (Figure 2), but they may in fact represent several separate accreted blocks. The relations of Chilenia to the Arequipa terrrane are difficult to assess because nowhere are the basements of each in contact. Syntheses of the sparse available data suggest that they were accreted at different times and that they have different geological evolutions during the Paleozoic [Hervé et al., 1981].

The degree of allochthoneity of the Arequipa terrane and Chilenia is unknown. Based on the northward extension of the Ordovician basin of northern Argentina and Chile into the ensialic, intracratonic lower Paleozoic basin of Perú and Bolivia [Dalmayrac et al., 1980; Carlier et al., 1982], Dalziel and Forsythe [1985] suggest that the Arequipa terrane was only a paraautochthonous "finger" of South America and that in northern Argentina this finger was separated from the main South American continent by a short-lived ocean basin. Coira et al. [1982] interpreted the closing of an ocean basin during the Late Ordovician Oclóyic deformation creating an orogenic belt that divided a western marine basin from the eastern marine facies during the Devonian [Isaacson, 1975; Davidson et al., 1981]. Chilenia appears to have accreted after the Arequipa terrane, and few data exist on how far it had traveled. The chemical signature of the Precordillera mafic and ultramafic rocks is compatible with near margin or back-arc basin oceanic crust [Kay et al., 1984; Haller and Ramos, 1984]; if so, then Chilenia need not have come from great distances.

Although the eastern limit of Chilenia is defined by a suture that is partly represented by the belt of mafic volcanics already described, its transverse borders remain enigmatic. Evidence derived from the Late Cenozoic volcanic arc along the Chile-Argentina frontier indicates that a Precambrian lower crust ends south of 37°S [López-Escobar, 1984]. South of that latitude, the Devonian to Jurassic accretionary prisms stretch across the entire width of the Andean Cordillera from the Chilean coast [Forsythe, 1982].

Likewise, the present northern extent of the Precordillera terrane and its allochthoneity with respect to South America are poorly defined. The key stratigraphic signature of the Precordillera, the lower Paleozoic carbonate platform, does not extend north of 29°S. Furthermore, the Ordovician facies belts of northern Argentina and Bolivia (north of 24°S) are significantly different than those of the Precordillera, although climatic variations cannot be ruled out as a cause of this variation. Many of the key relations bearing on this problem probably exist in the relatively poorly known and inaccessible part of the Argentine Andes between 29° and 26°S. B. Baldis (personal communication, 1985) has argued on the basis of satellite lineament continuity that the Precordillera must have been part of South America since the Late Precambrian. However, it seems unlikely that a passive margin sequence and carbonate shelf that completely lack volcanic detritus could have evolved next to a terrane characterized by plutonism and metamorphism during the Cambrian and Early Ordovician. That observation, plus the Silurian-Devonian(?) mélange on the eastern boundary of the Precordillera and the fact that Carboniferous rocks are the oldest that stratigraphically link the two terranes, all suggest that the Precordillera was not in its present position with respect to Pampeanas terrane during the early Paleozoic. Thus the relations between the magmatism in the Sierras Pampeanas and the accretion of Chilenia are not clear either.

To answer this and other questions, it is vitally important to increase the existing amount of paleomagnetic data, especially in the Lower Paleozoic sequences. At present, the scarce available data for Chilenia have been obtained from Upper Paleozoic rocks [Vilas and Valencio, 1982]. These authors found indications that rocks of that age in the Frontal Cordillera have been displaced, although given the structural complexity of the region, the paleomagnetic data are difficult to interpret. The available paleomagnetic data for the Mesozoic in Chile indicate that Chilenia was already part of the South American continent by the Cretaceous [Palmer et al., 1980; Turner et al., 1984; May and Butler, 1985].

Below, we present one possible model for the tectonic evolution of the region based on the geologic characteristics described here (illustrated in Figure 13). Given the unknowns stated throughout the paper, this model is extremely speculative, and there is disagreement even among the present authors about individual aspects of it.

1. At the start of the Famatina cycle, a prism of miogeoclinal strata were deposited along the length of the Precordillera. These carbonate platform strata, which interfingered westward with the deeper water clastic strata, covered an old continental margin which thinned westward toward an oceanic basin. The Lower Paleozoic granitoids of the western margin of the Sierras Pampeanas indicate the initiation of subduction beneath the Pampeanas terrane during the Cambrian and beneath the Precordillera as early as the Late Cambrian or Ordovician. An oceanic basin separated the Precordillera miogeocline from Chilenia, which was probably at least partly ensialic.

2. During the Middle and Late Ordovician, the possible subduction of an oceanic ridge or some other source of near-margin mafic magmatism produced the interfingering of mafic lavas and intrusions with the sediments derived from the continental margin. A stage of deformation related to this subduction could have controlled the formation of ridges and the deposition of conglomerates on the older carbonate sequences on the east side of the Precordillera.

3. During the Silurian and Early Devonian, subduction continued along the western margin of the Precordillera, producing an outer arc high that ponded the Punta Negra submarine fan in a forearc basin. The Villicúm-Rinconada mélange represents uplift, gravity sliding, and tectonic deformation in the Eastern Precordillera, perhaps due to strike-slip motion between the Pampeanas and Precordillera terranes.

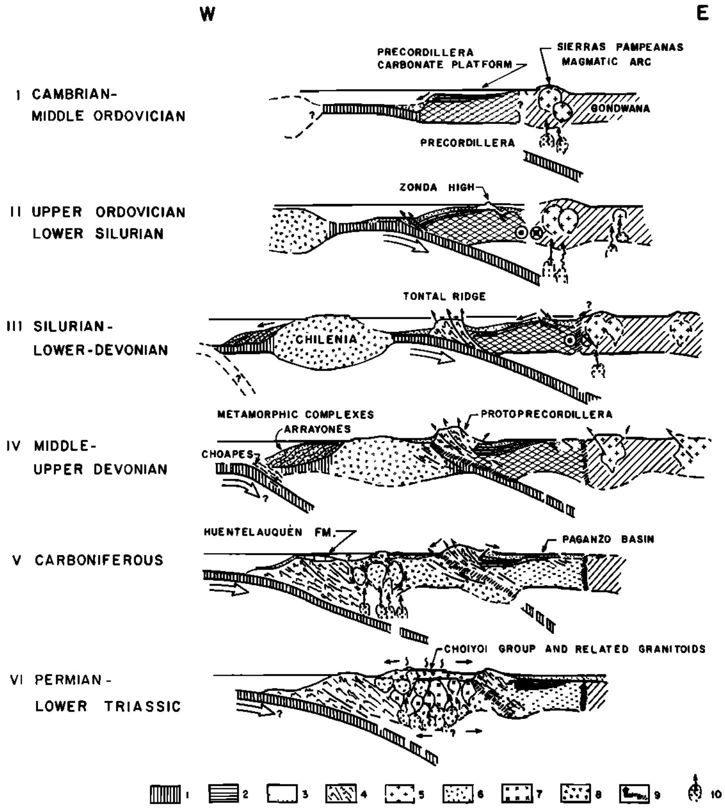

Fig. 13. Schematic tectonic cross sections of western South America during the Paleozoic based on one of the models described in the text. Sections drawn at ~31°S latitude. Key to symbols used: (1) oceanic crust, (2) lime-stone, (3) terrigenous sediments, (4) accretionary prisms or subduction complexes, (5) early Paleozoic granitoids of the Pampeanas terrane, (6) Carboniferous granitoids, (7) Permian and early Triassic granitoids, (8) rhyolitic and andesitic lavas, (9) suture zones, and (10) zone of partial melting.

4. During the Middle and Late Devonian Chánic deformation, Chilenia, which was attached to a subducting oceanic plate, collided with the Precordilleran continental margin. This produced an intense deformation in the western Precordillera, forming the Protoprecordillera. Shortening may also have occurred along some of the major lineaments to the east. In the Sierras Pampeanas, important uplift and coeval erosion was related to the end of subduction and of the magmatic arc. Carboniferous marine deposits translap the suture between Chilenia and the Precordillera and grade into continental deposits in the Central Precordillera and Pampeanas to the east.

5. During the Carboniferous and Permo-Triassic, eastward subduction was again established along the new Pacific margin of South America, west of what had been Chilenia. Melting of the old continental crust of Chilenia, producing the extensive Permo-Triassic highly silicic granites and ignimbrites, was a major phenomenon during this period and because of that only small remnants of the original Chilenia crust are preserved in the Cordillera Frontal. The strata previously deposited on the western edge of Chilenia were strongly deformed, creating the Late Paleozoic accretionary wedge of the Coastal Cordillera.

CONCLUSIONS

Despite the unknowns about many aspects of the Paleozoic tectonic evolution of western South America, four important points can be stated with certainty:

1. During the Cambrian and Ordovician, at least, an ocean basin lay to the west of the Argentine Precordillera. The ~300-km-wide belt of rocks presently lying between the Precordillera and the Chile trench have all been added to the South American continent since that time.

2. The Pampeanas terrane experienced sporadic magmatism and metamorphism throughout the lower and middle Paleozoic, suggesting the existence of an active plate boundary along the margin of what is now South America.

3. The distribution of upper Paleozoic strata ties both Chilenia and the Precordillera to the Pampeanas terrane and South America by the Carboniferous. Prior to that time, the positions of both terranes with respect to the continent are uncertain.

4. Late Paleozoic terranes identified to date have minor areal significance, although the studies that will clarify their existence and size are in progress. The margin of South America by the end of the Paleozoic appears to have been

located close to the present continental margin (± 100 km?). Transcurrent faulting or continental erosion [Rutland, 1971] may have largely destroyed possible terranes that might have been subsequently accreted.

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