Late Paleozoic Subduction and Accretion in Southern Chile

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by Francisco Hervé

The Coast Ranges of southern Chile are underlain for the most part by a variably metamorphosed subduction complex of late Paleozoic age. In a contribution to IGCP 279, "Terranes in Latin America," the author reviews the depositional and metamorphic development of this huge accretionary unit developed in the Gondwana continental margin. South to north transport of the accreted material parallel to the continental margin may prove to have been an important tectonic process in the region. (Ed.)

Introduction

A main portion of the Coast Ranges of Chile, south of 34°S , is underlain by igneous and metamorphic complexes. The metamorphic rocks have been considered to be Precambrian (Ruiz, 1965) and were represented as such in the 1:5,000,000 geological map of South America (Harrington, 1962). However, during the late 1960s and early 1970s, these complexes were shown to have conspicuous metamorphic and structural zoning (González-Bonorino, 1971; González-Bonorino and Aguirre, 1970), as in the paired metamorphic belts of Miyashiro (1961). At the same time, radiometric dating of the complexes failed to yield ages older than Carboniferous (Munizaga, 1967; Munizaga et al., 1973; Hervé et al., 1974). Even though the meaning in terms of the geological events they represented was not absolutely clear, both Rb-Sr whole rock isochrons and K-Ar dating on amphiboles were interpreted as ages of metamorphism, and little could then be said about the age of the protolith.

The associated granitoids were indicated as Cretaceous in the 1:1,000,000 geological map of Chile (Anon, 1960), but radiometric dating (Muñoz-Cristi, 1964; Hervé et al., 1976a) provided convincing evidence that the granitoids were also emplaced during the Carboniferous. These findings led to the conviction that very important tectonic and petrogenetic processes had taken place during the late Paleozoic in this continental margin of Gondwana.

This paper presents a synthesis of lithologic, structural, mineralogic and chronological data on the metamorphic complexes and interprets their mode of origin and emplacement within the conceptual framework of plate tectonics. For descriptive purposes the area will be divided from north to south into the Pichilemu area, the Nahuelbuta mountains, the Temuco-Chiloé area, the Chonos Archipelago, the Madre de Dios Archipelago and Cordillera Darwin (Fig. 1).

Lithology

The metamorphic rocks of southern Chile are dominantly turbidite sequences and their metamorphic equivalents (phyllite and mica schist), which constitute vast areas in the westernmost outcrops, and have a characteristic spotted appearance, black albite porphyroblasts being very abundant in them. Some mica schists are rich in graphitic material, and are spatially related to gold-bearing bodies within the schists (Zuccone, personal communication, 1988). Primary sedimentary structures are well preserved in the more easterly portions of the complex, in particular in the Nahuelbuta Mountains and the Chonos Archipelago. The turbidite sequences in the latter display prominent graded bedding, sedimentary lamination, and occasional grooved base structures (Fig. 2). Thick sandy units exist at Patranca and neighbouring islands.

The Chonos Archipelago is also characterized by the presence of widespread mélanges. Turbidite sequences are disrupted tectonically (Fig. 3) and contain a few exotic clasts of meta-igneous origin up to several metres long (Garrido, 1987). Mélanges are well recognized only in the eastern low-grade areas. However, because schists formed with mélanges as a protolith are indistinguishable from other schists, mélanges may have been originally more abundant than presently recognized.

Meta-basalts are widespread, mostly as greenschist, but also greenstones with pillow structures are present (Figs. 1 and 4). Geochemical studies of these meta-basites (Hervé, 1977; Hervé et al., 1976b; Godoy, 1979, 1980, 1986) indicate that they have geochemical characteristics similar to those of modern ocean floor basalts.

Meta-cherts are also common, many being iron rich, with Fe grades up to 40% at the Mahuilque deposits (38°S), containing several million tons of ore. A possible environment for the deposition of meta-chert is indicated by the Madre de Dios outcrops, where metalliferous red cherts directly overlie pillow basalts and are overlain in turn by radiolarian rich green cherts (Forsythe and Mpodozis, 1979). Geochemistry of the latter and of those ribbon cherts interbedded with the turbidite sequences at the Chonos Archipelago (Fig. 5) are not incompatible with deposition in a region affected by ocean ridge hydrothermal processes.

Limestone and its metamorphic equivalents are very rare in the complex, with the main outcrops at the northwestern shore of Lago General Carrera, and at the Madre de Dios Archipelago. Forsythe and Mpodozis (1983) concluded that the latter were deposited in an oceanic island free from detrital continental influence. Probably the same environment produced the Lago General Carrera marbles, presently the site of important Pb, Zn, Cu and Ag mineralization related to the intrusion of Late Cretaceous plutons into the metamorphic complex.

Serpentinite bodies metres to several kilometres in length are common in parts of the complex, in particular between 38 and 41°S. They seem to have been tectonically emplaced into the surrounding schists during an early stage of metamorphism. They contain no relic silicate minerals, but in some of them podiform lenses and veinlets of chromite or chromite + pyrrotite + pentlandite are found. The ultramafic igneous rock parentage is also clearly indicated by bastite structure of the antigorite. Some have breccia structures that can be interpreted as mélanges (Gana and Hervé, 1983).

Limited major element chemistry data (Ojeda, 1976) indicate Al contamination by the host rocks. Nb-Sm studies on the Quitratue serpentinite indicate values characteristic of depleted harzburgitic rocks, which are comparable to mantle beneath active mid-ocean ridges. Sulphide pods and layers, usually hosted by greenschist, constitute volumetrically minor but well-distributed component of the metamorphic complex. They are composed of pyrite-pyrrhotite-sphalerite-chalcopyrite aggregates (Collao et al., 1986) with minor mackonawite, galena and bornite.

The meta-basites may have been derived from the ocean floor, at spreading ridges (Hervé et al., 1976b, Godoy, 1986), from intraoceanic volcanic arc material, or from isolated oceanic islands or guyots (Forsythe and Mpodozis, 1979). Metalliferous sediments as well as massive sulphides deposited over basaltic material is a characteristic of near-ridge environments. The extremely long extension of the complex along the present coast of South America (2500 km, see Fig. 1 of Ramos, this issue) allows enough space for all of these different tectonic settings.

Metamorphism

Metamorphic grade varies from east to west across the belt but has some remarkably constant features along it. A

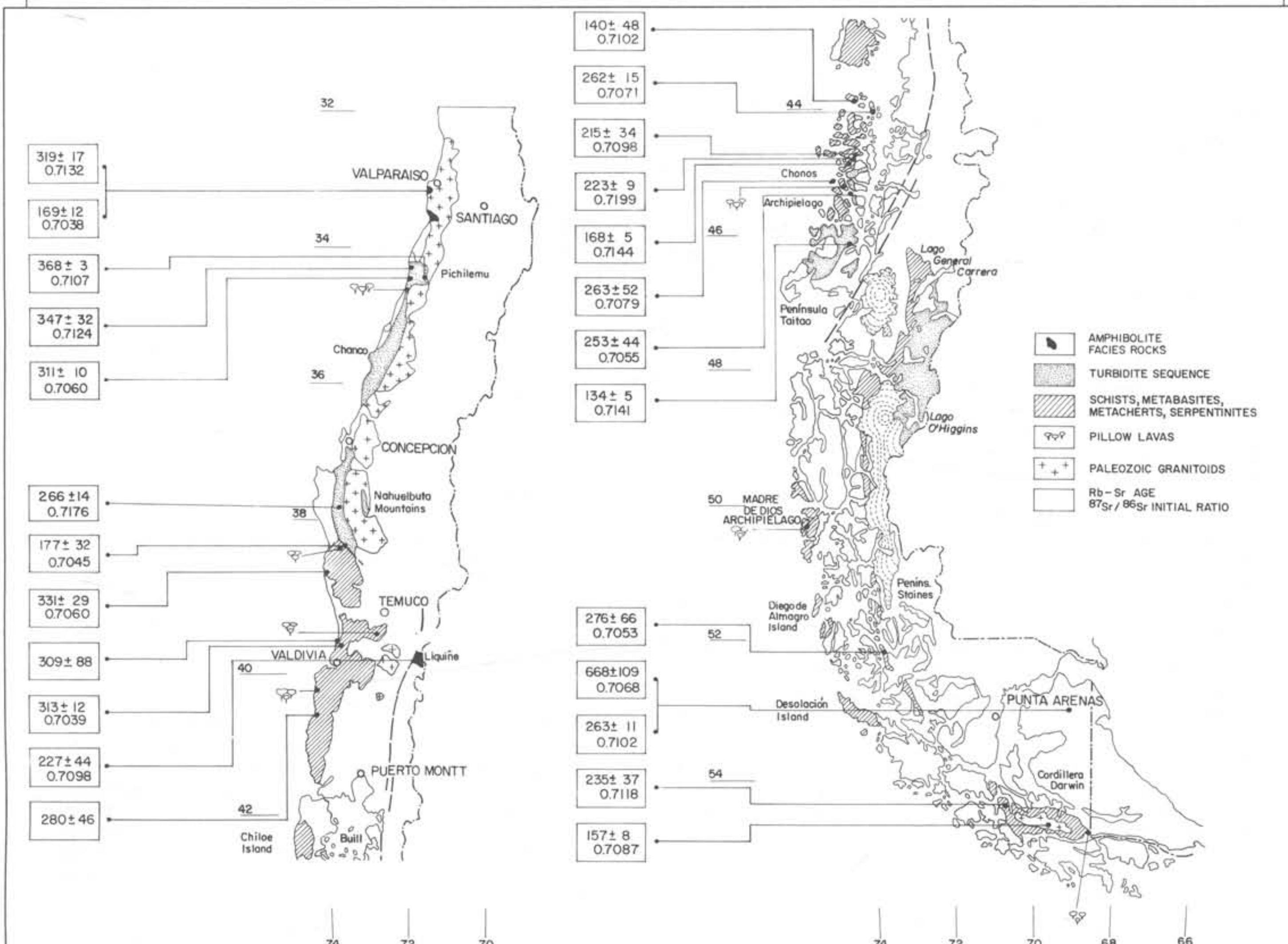

Figure 1: The metamorphic and plutonic complexes of the Andes south of 34°S, showing Rb-Sr whole rock isochron dates.

The lithology of the metamorphic complex indicates that its protolith was generated in an oceanic environment. The mainly turbiditic composition of the easternmost outcrop areas, suggests that their source was a continental margin that provided abundant detrital material to the continental shelf, and perhaps beyond. A deep-sea fan environment was envisaged by Godoy and others (1984) for the turbiditic sequence of the Chonos Archipelago, in view of its sedimentary facies and the interbedded pelagic radiolarian cherts, which would have been generated in fan lobes during inactive periods.

Carboniferous granitoid belt is the eastern limit north of 38°S, with a strong metamorphic gradient increasing towards it, moving from low-grade biotite-bearing greenschist facies in the west, through continuous andalusite and discontinuous staurolite zones, to high-grade sillimanite-cordierite-garnet gneisses. These metamorphic zones are developed in the turbidite sequence rocks, and are devoid of meta-basites across the 20 km outcrop width.

South of 38°S, the late Paleozoic granitoids are absent, except for a small massif in the Panguipulli-Riñihue area (east of Valdivia), and the metamorphic complex is intruded by the North Patagonian batholith of Jurassic to Cenozoic age, with only very narrow (500 m or less) hornfelsic contact aureoles. Biotite and occasional andalusite are char-

Figure 2: Very low-grade meta-turbidites showing well-preserved bedding, Chonos Archipelago.

acteristic, and staurolite and sillimanite occur sporadically. At Cordillera Darwin, a staurolite-kyanite zone is developed near the contact with a Jurassic pluton.

A regional metamorphic gradient increasing westwards is well developed away from the influence of the granitoids, both in the northern and southern sections. At the Chonos Archipelago there is a continuous increase in the crystallinity of illite from CR (relative crystallinity) 227, indicating very low-grade metamorphic conditions (Garrido, 1987), to CR 118, implying low-grade metamorphism. Deduced temperatures vary from a miniumum of 200°C to a maximum of 400°C. The westernmost areas are typical greenschist facies rocks with the following mineral associations:

- meta-basites: albite-epidote-chlorite-actinolite sphene (± Na amphiboles),
- mica schists: quartz-albite-chlorite-muscovite tourmaline,
- meta-cherts: quartz-stilpnomelane-magnetite (± Na-amphibole).

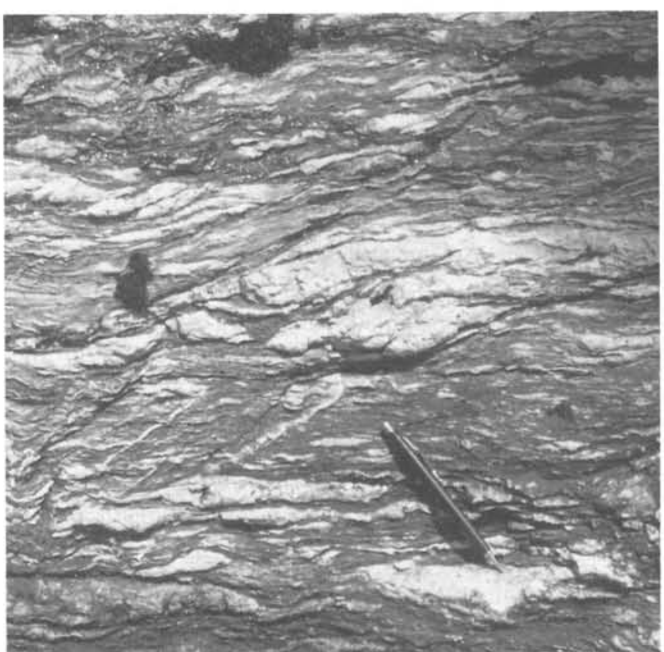

Figure 3: Mélange at Teresa Island in the Chonos Archipelago.

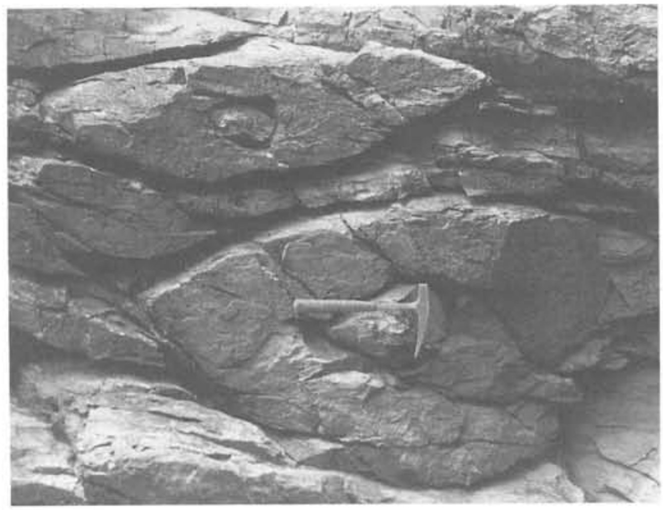

Figure 4: Greenstone with well-preserved pillow structure and geochemically similar to present day ocean floor basalts. Punta de Lobos, 5 km south of Pichilemu.

Similar mineral assemblages occur in the northern section where sporadic abundant Na-amphibole occurs, as in Pichilemu. Lawsonite has only been recorded from Chiloé Island (Saliot, 1968), where it is accompanied not by glaucophane but by chlorite and albite. South of the Taitao Peninsula, Na-amphibole has been recorded in otherwise typical greenschist facies assemblages (Forsythe and Mpodozis, 1979). Higher grade rocks containing omphacite are found exclusively as loose boulders in spatial association with a serpentinite body at Los Pabilos (40°S, Kato, 1985), probably having been tectonically brought to higher levels along with the ultramafic body.

Thus, the rocks of the western parts of the metamorphic complex contain greenschist facies assemblages with some indications of higher pressure minerals. Kato (ibid) has presented evidence that a former high greenschist-lower amphibolite assemblage was present in these rocks near Valdivia. The sphalerite-chalcopyrite geothermometer suggests pressures of 6.5 ± 2.5 Kb for the metamorphism of massive sulphides in greenschists near Concepción (Collao et al., 1986).

Structure

The structure of the complex is well displayed in the Nahuelbuta Mountains and the Chonos Archipelago (Fig. 6). In the former area, the eastern part of the section has the

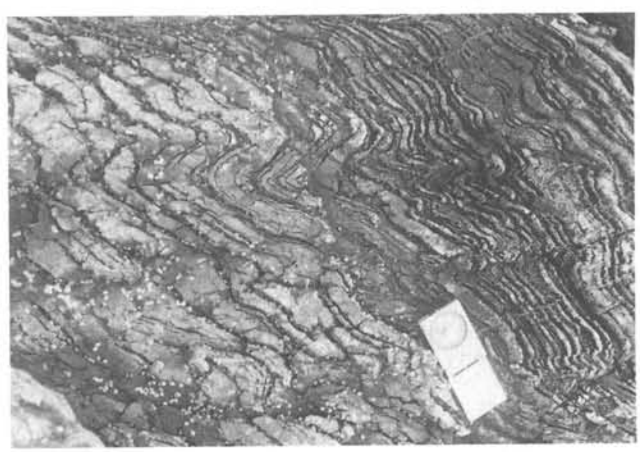

Figure 5: Radiolaria-bearing ribbon cherts at Chalacayec Island, Chonos Archipelago, have geochemical characteristics similar to metalliferous siliceous sediments near modern mid-ocean ridges.

general shape of a synform with granitoids located in its centre. Primary structures are preserved in the lower grade parts of the series, which are particularly well exposed in the Laraquete area.

The strata are folded into complicated interference patterns. An early S_1 foliation associated with upright folds and a later S_2 foliation dipping moderately eastwards are recognized. The granitoids intruded during S_2 time. This foliation develops progressively towards the west, making it difficult to recognize S_0, and leaving S_1 as rootless isoclinal minor folds in the microlithons bounded by S_2. This is the typical structure of the characteristic spotted mica schist all along the Coast Ranges.

At the Chonos Archipelago, the structure of the complex is surprisingly similar in its overall pattern. The easternmost portion is characterized by upright tight folds with a well developed S_1 axial-plane cleavage, and mélange areas. A low-dipping S_2 crenulation cleavage (Fig. 7) is progressively developed towards the west, where it becomes the predominant structural feature. A big difference between the two areas, however, is that the batholith to the east is here Mesozoic-Cenozoic.

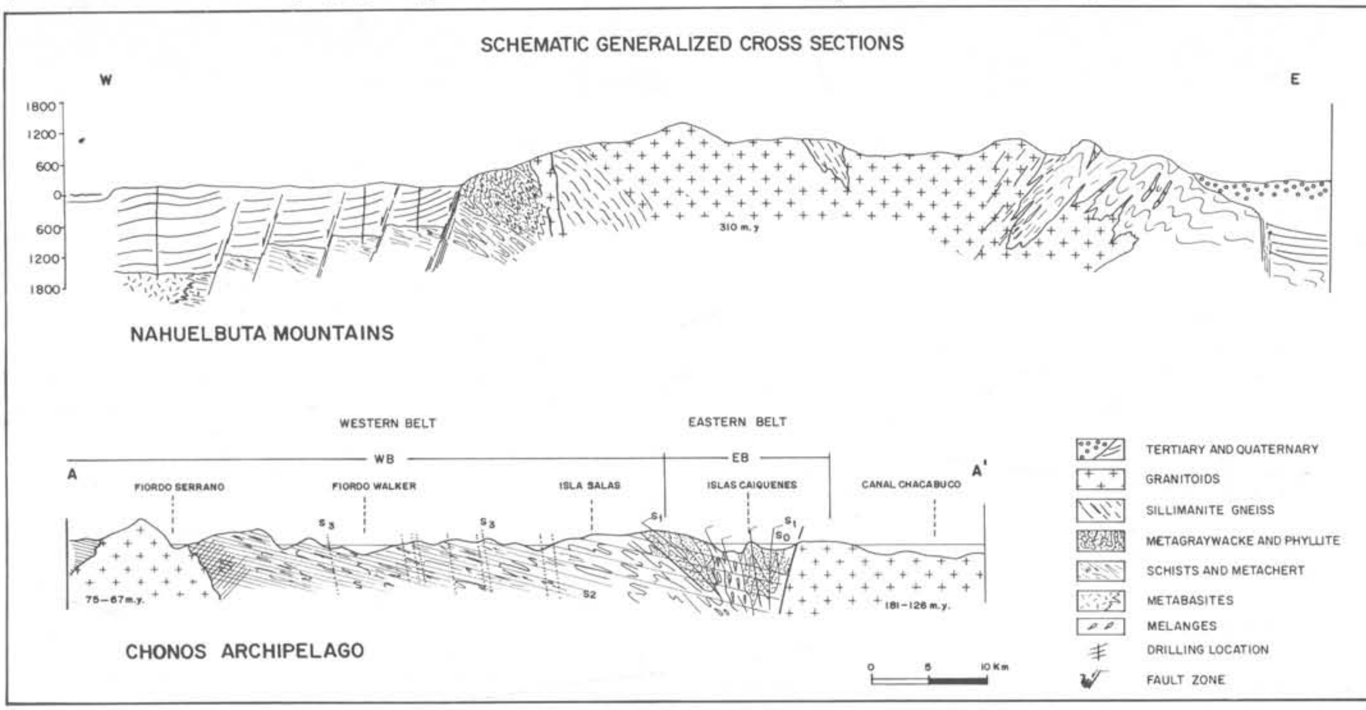

Figure 6: Sections across the metamorphic complexes at Nahuelbuta Mountains (38°S) and Chonos Archipelago (44°S).

Geochronology

There are a few indications of the age of deposition of the protolith to the metamorphic complex. At Lumaco, Tavera (1983) described the presence of worm tubes of Gordia? sp and Crossopodia nahuelbutanus sp. nov., which he interpreted as indicating Silurian deposition. Miller and Sprechmann (1978) described Devonian brachiopods from coarse sandstones at Isla Patranca. Apparently these were transported by turbidity currents to the deep ocean during the Early Devonian or Late Silurian. At Punta Buill (Chiloé), Levi and others (1966) recorded from rocks not in place trilobites, crinoids, tetracorals and nautiloids, which would indicate a Devonian age.

From Madre de Dios, Douglass and Nestell (1976) described a fusulinid assemblage in massive limestones, indicative of deposition in warm waters during the Permian. Radiolarian cherts have yielded Late Carboniferous to Permian ages (Ling and Forsythe, 1987) at Madre de Dios and Early Permian ages at Regalada island (54°S), supporting the idea of a younging of the deposits from north to south.

As regards radiometric dating of the metamorphic complex, Munizaga and others (1972) interpreted the 270-342 Ma "limiting reference isochrons" as the probable age of metamorphism between 34° and 38°S. Further dating of these rocks has produced the 26 Rb-Sr isochrons (error-chrons) shown in Figure 1, as well as numerous K-Ar mineral ages. All the isochrons yield ages between 368 and 140 Ma for the metamorphic complex of the Coast Range south of 34°S.

The age pattern emerging from these data indicates older ages for the easternmost rocks in any particular east-west profile south of 34°S. East of Pichilemu, the higher grade sillimanite gneisses are 368 Ma old, the andalusite-staurolite rocks west of them have a concordant 347 ± 32 Ma metamorphic age and the blueschists at Pichilemu 310 ± 11 Ma. Between Concepción and Valdivia, isochrons range between 290 and 330 Ma for rocks near the coast. The younger Carboniferous ages are thought to represent the age when S_2 was generated in the rocks, and phase of increased convergence rate or of sedimentary input into the trench.

At the Chonos Archipelago, older ages also tend to be encountered in the easternmost rocks, in which S_1 is the predominant structure. Younger ages of 140 ± 40 Ma and 168 ± 5 Ma are obtained in more western rocks where S_2 is the predominant structure. A complete resetting of the Rb-Sr systems during the development of S_2 appears to have taken place, and this age pattern is supported by a few K-Ar whole rock age determinations.

South of the Taitao Peninsula, the few determinations include Late Jurassic K-Ar ages on glaucophane schists near Madre de Dios. Cretaceous mineral ages and Triassic (235 ± 37 Ma) Rb-Sr isochrons at Cordillera Darwin (Hervé et al., 1981) tend to support the southward-younging pattern deduced from the few paleontological sites. Thus, the metamorphic complex varies both in the depositional age of the protolith and in its metamorphic age. The former is probably Devonian or Silurian (or earlier?) from the Chonos Archipelago to the north, and Late Carboniferous and Permian south of the Taitao Peninsula. The apparent east to west younging of the metamorphism along the belt is in accordance with successive accretion from the west, with upheaval of the rocks after metamorphism.

The $^{87}Sr/^{86}Sr$ initial ratios of the rocks in the Pichilemu area indicate higher values (0.712) in the eastern metamorphosed turbidite sequence, in agreement with the idea that the clastic material comes from a continental source in the South American craton. Westerly rocks, including the pillow basalts and meta-cherts, have lower values (0.706), indicating the greater influence of oceanic materials. Still lower values (0.704-0.705) are obtained from the meta-basites and meta-pelites associated with the massive sulphides in the Temuco-Valdivia area. Assuming no metasomatic processes during their metamorphism, and a $^{87}Sr/^{86}Sr$ value of 0.7025 for the upper mantle from which these rocks were derived, a maximum age for the basaltic protolith would be around 400 Ma, that is Silurian.

Geological Evolution

The metamorphic complex of the Coast Ranges of central and southern Chile records geological processes along the south and southwestern margin of Gondwana during the late Paleozoic. Thick turbidite sequences accumulated on the ocean floor adjacent to the continent, probably from as early as the Silurian but mainly, it seems, during the Devonian. These thick sedimentary detrital sequences of continental origin indicate the presence of an emerging continent with active erosional and sediment transport processes towards the fringing ocean. The absence of Silurian or Devonian granitoid belts suggests that subduction processes were not very active during these periods: a passive type of continental margin may have existed here.

The pelagic sequence was accreted to the continent before the Early Carboniferous in the north and after the Early Permian in the south, during a constructive phase of the accretionary prism (Davidson et al., 1987). Mélanges developed between tectonic wedges of turbidite material. During this phase, oceanic rocks were incorporated into the accretionary prism from the west, representing either material generated at oceanic ridges or island arcs, or tectonic slices of the ocean floor supporting the turbidite sequence. These oceanic rocks were metamorphosed in the accretionary prism, and low initial Sr ratios indicate that the time of the extrusion of pillow basalts was not much earlier than their metamorphism. The easternmost and probably thickest part of the accretionary sequence was affected by a long low-PT metamorphism, beginning in the north.

In the Late Carboniferous, the tectonic regime changed dramatically in the north, giving rise to the development of higher PT metamorphism and high strain during the generation of S_2. This "destructive phase" on the accretionary prism may correspond to an increase in shear strain along the base of the accretionary prism, a phenomenon that could have been enhanced by a faster convergence rate, a reduced sedimentary input or a decrease in pore pressure that resulted in a strong mechanical coupling between the oceanic plate and the accretionary wedge. At this stage, the tectonic conditions led to burial of the rocks deep in the lithosphere, giving rise to processes culminating in the generation of the huge late Paleozoic magmatic belt. This belt turns westward around 38°S, trending southeastwards along northern Patagonia, tracing out the old continental margin.

The same process was active in the southern part on the complex after the Permian, as indicated by the involvement of rocks of that age in the accretionary wedge, and perhaps into the Jurassic, as indicated by the Rb-Sr isochrons at the Chonos Archipelago. A special tectonic situation existed in Cordillera Darwin with the generation of an aborted ocean-floored marginal basin, which allowed Cretaceous metamorphism to take place affecting previously metamorphosed rocks of the subduction complex.

The constructive phase of the subduction complex involved the generation of a wide area of accreted material, including island arcs and sedimentary deposits of intervening basins. This is a situation similar to the present day Western Pacific margin, where complicated patterns of island arcs and ocean ridges contrast with the simple linear volcanic belt of South America. The characteristics of the late Paleozoic environment in Chile could be described as those of a Mariana-type continental margin during the "constructive" phase of an accretionary prism. The change of regime to a destructive phase of the accretionary prism, marked by the generation of the S_2 foliation and the intrusion of the granitoids, might be the record of the initiation of a Chilean-type regime for the continental margin in the classification of Uyeda (1982).

After the diachronous high-PT metamorphism, the metamorphic complex was rapidly uplifted and eroded to levels similar to the present exposures by Late Triassic times in the north and probably by the Early Cretaceous in the south. K-Ar mineral ages are only a little younger than the Rb-Sr isochron ages, probably indicating rapid uplift just after the generation of S_2. The accretion was displaced westwards so that along the present coastline no outcrops of a Cenozoic accretionary complex exist. If present, they are offshore, in contrast to the situation in Barbados and some island arcs of the west Pacific where late Cenozoic accretionary prisms outcrop. Munizaga and others (in press) suggest that tectonic erosion of the continental margin in the northern part of the complex took place from the Mesozoic to the Cenozoic.

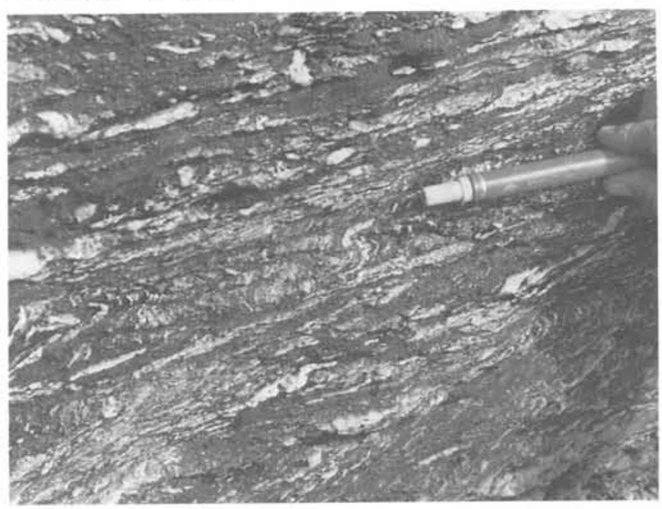

Figure 7: Crenulation cleavage (S_2) in banded phyllite at Teresa Island, Chonos Archipelago.

The metamorphic complex of the Coast Ranges of south-central Chile probably originated by subduction and accretion from west to east, related to the consumption of a proto-Pacific Oceanic plate. However, little is known about the later history of displacement of the subduction complex once it was incorporated to the continental overriding plate. Recent paleomagnetic studies around the Liquiñe-Ofqui megafault (García, 1987), which extends to the east of the Coast Range between 39 and 45°S have shown that 400 to 500 km of dextral strike-slip movement might have occurred along it, displacing the coastal metamorphic complex northward.

It is interesting to point out that at this latitude, rocks similar to those outcropping in the coastal areas appear at Lago General Carrera (Fig. 1), in an anomalous position to the general organization of the complex. This might, perhaps, be the result of doubling the complex by oblique slicing and northwards transport of the western slice along the continental margin. However, this is one problem to be resolved before confident paleogeographic reconstructions for the late Paleozoic for the area can be produced.

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