Taitao ophiolite: a ridge collision ophiolite in the forearc of southern Chile (46° S)

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ABSTRACT

The Taitao ophiolite, exposed at 46°S on the Pacific coast of Chile, consists of ultramafic rocks, gabbro, sheeted dikes, and volcanic and clastic sedimentary rocks. In June-July 1990 the Taitao ophiolite and surrounding rock units were studied using helicopter and zodiac support from the R/V Polar Duke. Stratigraphy and structure of the ophiolite and structural relations with surrounding geologic units were refined from previous scant reconnaissance. In coastal exposures of the volcanic-sedimentary unit of the ophiolite the Bahía San Andrés Formation is defined as a 2,000-3,000 m thick sequence of volcanic, volcaniclastic, and sedimentary strata that records the initial rifting and volcanism and progressive deepening of the basin. Two sheeted dike units are distinguished with perpendicular dike trends. The main, NW-trending steeply-dipping unit is *ca.* 6 km thick (normal to dikes) and contains basaltic and andesitic dikes; the northern, NE-trending steeply-dipping unit is basaltic and directly underlies and intrudes the Bahía San Andrés Formation. The strongly layered, but generally unfoliated gabbro unit is *ca.* 4 km thick (normal to vertical layers). It is interpreted to have formed in a short-lived magma chamber in an active rifting environment. The thin (<1 km) ultramafic tectonite unit contains high-temperature flow fabrics overprinted by brittle shear fabrics and is faulted against the 4 Ma old Cabo Raper tonalite pluton. Andesitic and rhyolitic volcanic rocks are present in fault blocks and may represent evolution of the ophiolite magmatic system, or younger syn- or post-obduction magmatism unconformable on the ophiolite. If the sedimentary/volcanic cover is not unconformable on the igneous portions of the ophiolite, comparison with other ophiolites and the progressively deepening nature of the sedimentary sequence suggest that the ophiolite formed in a forearc rift above the subducting spreading ridge, rather than on the ridge prior to ridge collision.

Key words : Taitao ophiolite, Pliocene, Tres Montes Peninsula, Triple Junction, Southern Chile.

RESUMEN

Ofiolita Taitao: ofiolita de dorsal de colisión en el antearco del sur de Chile (46°S). La ofiolita Taitao, expuesta en la costa pacífica de Chile a los 46°S, está formada por rocas ultramáficas, gabros, enjambres de diques, rocas volcánicas y clásticas sedimentarias. En Junio-Julio de 1990, la ofiolita y unidades geológicas circundantes fueron estudiadas utilizando helicóptero y botes inflables a partir del R/V Polar Duke. Estos trabajos permitieron precisar su estratigrafía interna y relaciones estructurales con unidades circundantes. La sección volcanosedimentaria superior (Formación Bahía San Andrés) incluye 2.000-3.000 m de niveles volcánicos, volcanoclásticos y sedimentarios que registran el volcanismo y 'rifting' inicial y una progresiva profundización de la cuenca donde se generó la ofiolita. La unidad de enjambres de diques comprende dos familias perpendiculares de diques subverticales: la principal, andesítica y basáltica, orientada en dirección noroeste alcanza hasta 6 km de potencia normal a los diques, mientras que la secundaria, orientada en dirección noreste, es basáltica e infrayace directamente o intruye a la Formación Bahía San Andrés. La unidad de gabros, bandeada, y, en general, no foliada, alcanza hasta 4 km de espesor, medido perpendicularmente al bandeamiento subhorizontal y parece haberse formado en una efímera cámara magmática asociada a un ambiente de 'rifting' activo. El delgado (<1 km) nivel de tectonitas ultramáficas aflora en contacto por falla con las tonalitas de 4 Ma del plutón Cabo Raper y presenta fábricas de flujo de alta temperatura a las que se superponen fábricas de cizalla frágil. Lavas andesíticas y riolíticas aparecen en bloques limitados por fallas, pudiendo representar productos evolucionados del sistema magmático ofiolítico, o bien, un magmatismo tardío, sin o postobducción. Si los niveles volcánicos y sedimentarios superiores de la ofiolita (Formación Bahía San Andrés) son concordantes con el resto del complejo, la profundización progresiva registrada en la sedimentación más la comparación con otros complejos ofiolíticos, sugiere que la ofiolita Taitao se formó, no en una dorsal en ambiente oceánico franco, sino en el borde continental, en un 'rift' de antearco sobre una dorsal en proceso de ser subductada.

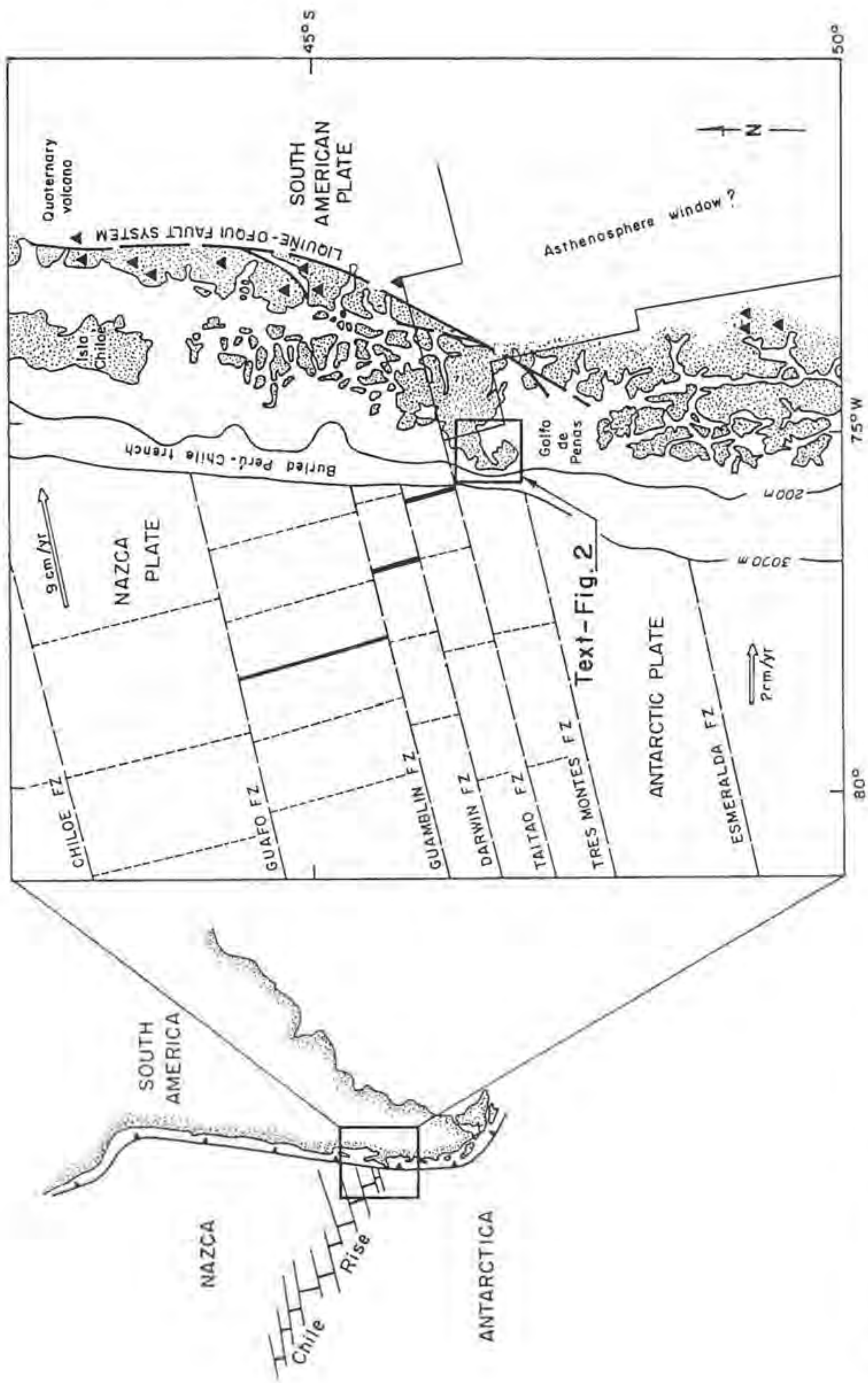
Palabras claves: Ofiolita Taitao, Plioceno, Península Tres Montes, Punto triple, Sur de Chile.

INTRODUCTION

Since mid-Tertiary the Pacific coast of southernmost Chile has been the site of convergence and collision of an actively spreading oceanic ridge (Chile Rise) with the continental margin of the South American plate. The present point of ridge collision (46.5°S) forms the triple junction between the Nazca, Antarctic, and South American plates, and lies only a few kilometers from the Península de Taitao (text-Fig. 1). A number of late Cenozoic features on this peninsula are related to ridge collision over approximately the last 5 million years (see Forsythe *et al.*, 1986; Nelson and Forsythe, 1989): a- generally silicic, epizonal ntrusions, some dated as Pliocene (Forsythe and Nelson, 1985; Mpodozis *et al.*, 1985); b- marine strata containing Oligocene and Miocene fossils exposed along the inner shores of the Península de Taitao and Península Tres Montes, and more clearly exposed along the shores of the islands in the Golfo de Tres Montes (DeVries and Stott, 1984; Forsythe *et al.*, 1985; Stott and Webb, 1989); and c- the Taitao ophiolite, including serpentinized ultramafic rocks, gabbro, diabase dikes, pillow lavas, volcanic breccias, and clastic strata, exposed in the interior of the Península de Taitao and along the outer coast (text-Fig. 2; Forsythe *et al.*, 1986).

The primary objective of this paper is to present the results of significant additional field work on the Taitao ophiolite. These findings help to clarify its relation to surrounding units, the history of ridge collision, and its mode of origin and emplacement. Previous studies have led to several views regarding the modes of igneous origin and structural emplacement of the ophiolite. One model suggests that the Taitao ophiolite formed offshore, on a late Miocene segment of the Chile Rise and was subsequently obducted during ridge collision. A second model suggests that the ophiolite formed in a forearc rift from magmas rising from the spreading ridge, as it began to subduct below the leading edge of the continent.

The Taitao peninsula is very isolated and access is inhibited by dense vegetation and high wave energy along a rugged, cliffy coast. Thus, the peninsula remains largely unexplored. Previous work focussed on the inner coast of the peninsula, where the ophiolite is poorly exposed and outcrops are fractured or sheared along a fault zone; only about 10 field sites had been visited in the well-exposed portions of the ophiolite. Thus, little was known about the types and distribution of rock units. The 1990 expedition used helicopter and zodiac support from the R/V Polar Duke, and studies focussed on the outer coasts in Bahía San Andrés and Estero Cono, and on the mountainous interior; over 80 new sites were studied. Of these sites, 10 were in the ultramafic unit, 21 in the gabbro unit (and its transition zone with the ultramafic unit), 20 in the sheeted dikes, and over 30 in the upper volcanic-sedimentary member. Despite these and other new observations pertaining to the non-ophiolitic plutonic rocks and overall structural relationships, many details of unit distribution and contact relationships remain obscure due to vegetation cover and to the paucity of field sites, given the area covered by the ophiolite and related rocks (*ca.* 125 km^2). On a geologic map of the ophiolite (text-Fig. 2) most contacts are approximately located or inferred. The proportion of inland exposure is best in the ultramafic and gabbro unit (nearly 90% exposed), less in the transitional zone and sheeted dike unit (roughly 10-25% exposed), and low in the volcanic and sedimentary unit (<1% exposed). The proportion



Text-FIG. 1. Location map and plate relations.

of coastal exposure is generally high, especially along the southern shore of Bahía San Andrés where the volcanic and sedimentary unit is over 90% exposed.

ULTRAMAFIC ROCKS

Four modes of occurrence of ultramafic rocks are recognized in the Taitao ophiolite: **a-** ultramafic and mafic tectonites are well exposed in lenticular bodies (1/2-1 km long and 200-300 m wide; Plate 1, Fig. 1) along the southwestern margin of the ophiolite; the strongly foliated and transposed tectonites include harzburgite and gabbroic rocks; the ultramafic rocks are partially to totally serpentinized and commonly display mesh structure; some contain large (1-2 cm long) porphyroclasts of pyroxene, and some contain a relatively high proportion of magnetite; the gabbroic rocks locally have been rodingitized and contain magnetite and hydrogrossular; these ultramafic bodies are locally intruded by thin (<10 cm) diabase dikes; **b-** unfoliated, layered, cumulate ultramafic rocks are present between the tectonite ultramafic rocks and the gabbro unit (Plate 1, Fig. 2); these rocks include lherzolite and rare dunite(?); **c-** generally equidimensional blocks (up to 300 m in diameter) of massive ultramafic rock are present within the gabbro unit, and are cut by a stockwork of gabbro dikes (text-Fig. 2; Plate 1, Fig. 3); **d-** unfoliated, layered, cumulate ultramafic rocks are enclosed as layers within the lower portion of the gabbro unit; these rocks are predominantly lherzolite, although one clinopyroxinite (websterite) layer (3 cm thick) was observed.

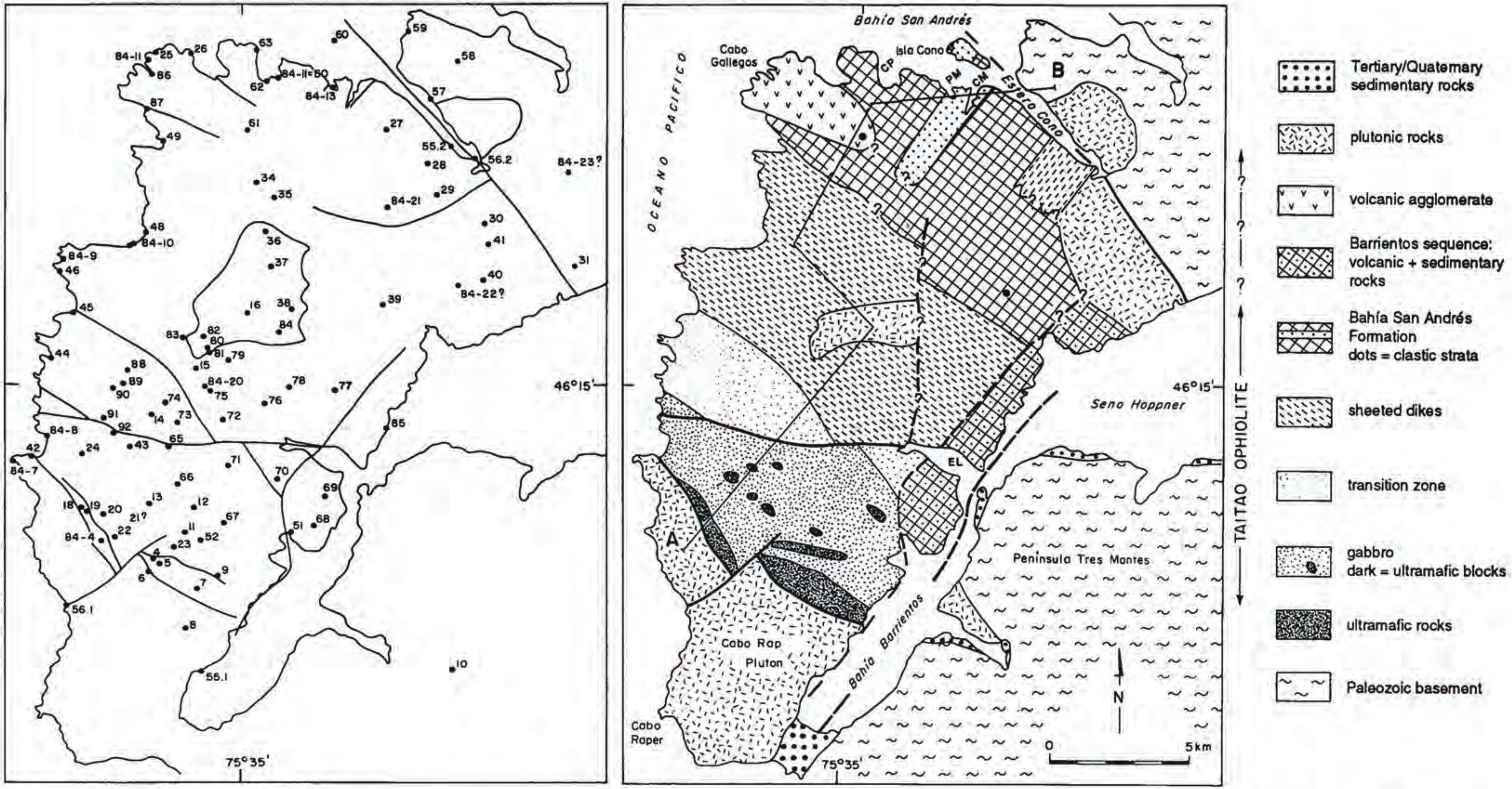
GABBRO UNIT

The base (not necessarily paleohorizontal) of the gabbro unit is fairly sharp where observed, although dikes of very coarse-grained gabbro intrude the adjacent cumulate ultramafic rocks. The approximate thickness (measured normal to subvertical compositional layering) of the gabbro unit is 4-5 km. Near the base of the unit, the gabbro contains at least one major layer of ultramafic rock (type 4 above) as large as 3 km long and 100 m thick.

Gabbroic rocks include olivine gabbro, troctolite, norite, gabbronorite, olivine gabbronorite, and minor anorthosite. Gabbros exhibit cumulate layering (Plate 2, Fig. 1) in the lower and middle portions of the unit and generally become more massive upward (here 'upward' is toward the sheeted dike unit and normal to layering). Layering in the gabbros exhibits a number of features including isomodal layering, modally graded layering, undulatory or cuspate (Plate 2, Fig. 2) layering and angular unconformities (truncated layering; Plate 1, Fig. 5). Grading is both modal (compositional) and textural in layers tens of cm thick; coarse to very coarse grain size and high pyroxene/olivine ratios at the 'base' grade upward to finer grain size and lower pyroxene/olivine ratios and a sharp contact at the 'top' (Plate 1, Fig. 6). Although the unconformities clearly indicate current flow or syndepositional slumping within the magma chamber, it is unclear if the graded layers were formed by a sedimentary or crystallization process. The gabbro unit is intruded locally by diabase dikes

TRANSITION ZONE

The zone between the gabbro and sheeted dike units is transitional and contains a number of features distinct from either unit (text-Fig. 2). The map width of this zone, up to 3 km, may not be representative of initial thickness because of the likelihood of faulting in this interval (see Structure section). The transition zone contains a mixture of gabbro, diabase, basaltic rock, and serpentinite. Gabbro in this zone is coarse- to very coarse-grained, commonly altered to a greenschist mineral assemblage, and is weakly foliated locally. Diabase is present in two modes: **a-** it forms thin (<15 cm thick), irregular dikes that are usually



Text-FIG. 2. Geologic map of the Peninsula de Taitao. Note: all contacts are approximately located or inferred. EL=Estero Lobos; CP=Caleta Pascuas; CM=Caleta Monona; PM=Punta Monona. A-B is cross section line for figure 8. Sites 61 and 39, shown by black dots, are approximately 5 km SE of Cabo Gallegos and 6 km NE of Estero Lobos, respectively. Map on left shows field sites from 1990 season and 1984 season 84-' prefix).

relatively low dipping (28-44°), as well as thicker, steeply-dipping tabular dikes; **b**- it is present in irregular bodies at outcrop scale with non-planar, diffuse contacts; these textures are interpreted to have formed during magma mingling. Rare outcrops of serpentinite were observed, but their relationship with surrounding gabbro and diabase is unknown. The transition zone also contains thin (cm's wide) shear zones which contain either serpentine and/or fragments of the surrounding gabbroic or diabasic material.

SHEETED DIKE UNIT

Sheeted dikes are exposed in two regions: a main body well exposed along the Pacific coast and on ridges in the interior of the peninsula northeast of the transition zone, and a northern body poorly exposed along the inner, southern shore of Estero Cono (text-Fig. 2). The main body is approximately 6 km 'thick' (measured approximately perpendicular to the dikes). Individual dikes range in thickness from less than 1 m to over 4 m, and strike, consistently, northwest. Although the majority of dikes are basaltic in composition, with both diabasic and porphyritic textures, some are andesitic or even more silicic.

Dikes in the northern body strike NNE and dip moderately to the southeast, include light green to grey aphanitic rocks, feldspar and/or pyroxene porphyries, and are more highly metamorphosed than the majority of dikes in the main body. In the southeasternmost outcrop of Estero Cono dikes have unusual screens of foliated and disharmonically folded felsic metamorphic and plutonic rocks, which are either xenoliths of the Paleozoic basement and/or felsic intrusions.

VOLCANIC-SEDIMENTARY UNIT

Interbedded sedimentary and volcanic rocks are exposed in two areas on the Península de Taitao: **a**- along the NW coast of Bahía Barrientos, and **b**- along the SW coast of Bahía San Andrés (text-Fig. 2). The northwestern shore of Bahía Barrientos north of 46°45'S exhibits a narrow (<1/2 km wide) topographic platform 150-200 m above sea level. Boulders of gabbro found on this platform are interpreted as glacial drift, as no gabbro was found in outcrop. Rare outcrops of pillow lavas and pillow breccias were found on the platform, and outcrops of volcanic and sedimentary rocks are present along the shore. The volcanic-sedimentary sequence in Bahía Barrientos (here informally termed the Barrientos sequence) is poorly exposed, locally strongly sheared, and in most localities does not appear to extend inland more than a few 100 m. It consists of basaltic, andesitic and rhyolitic pillow lavas, pillow breccias, banded flows, and sills interbedded with shale (locally black), siltstone, sandstone and conglomerate. Bedding orientations are variable, but in general are not parallel to those in Bahía San Andrés (text-Figs. 7d, 7e). Because of fundamental differences with the Bahía San Andrés Formation (described below), the Barrientos sequence and the Bahía San Andrés Formation are not considered to be correlative. The Barrientos sequence, described in Mpodozis *et al.* (1985), was not studied in detail during the 1990 expedition.

The Bahía San Andrés sequence consists of about 3,000 m of volcanic and sedimentary rocks well exposed in seacliffs along the southern shores of Bahía San Andrés to Caleta Pascuas (point A-G, text-Fig. 3). A 4-5 km-long semicontinuous coastal profile (text-Fig. 4) was constructed from observations made from zodiac and helicopter at a distance of approximately 100 m, and on landings in selected areas which permitted more detailed observations. The Bahía San Andrés sequence, because of its relationship (discussed below) to sheeted dikes in the northern dike body, is interpreted as being the stratigraphic cover of the ophiolite. This section is the best and most complete exposure of this part of the ophiolite, and is described here as the type section of the Bahía San Andrés Formation. The base is placed in a poorly-exposed transition zone between the northern sheeted dike complex and the dominantly volcanic and volcaniclastic breccia units containing dikes approximately 1 km from the southeastern end of Estero Cono (point A, text-Fig. 3). We estimate that as much as 1-2 km of dikes and volcanic breccia lie

Text-FIG. 3. Aerial photomosaic of the southern shore of Bahía San Andrés. Profile line A-G shows portion of shore represented by profiles in figure 4. Localities 1-4 show location for logs 1-4 shown in text-figure 6: 1 is the eastern headland of Caleta Monona; 2 is the western tip of Isla Cono; 3 is Punta Monona; 4 is the western shore of the unnamed bay *ca.* 1 km west of Punta Monona.

beneath the eastern end of the profile in text-Fig. 4.

The Bahía San Andrés Formation is divided into three members, described below: A lower, dominantly volcanic member; a middle, dominantly sedimentary member; and an upper, mixed volcanic and sedimentary member. The middle, sedimentary member was accessible in Caleta Monona, on Isla Cono, and at the unnamed bay 1 km to the west of Punta Monona, and therefore, was studied in greater detail than the generally inaccessible lower and upper members.

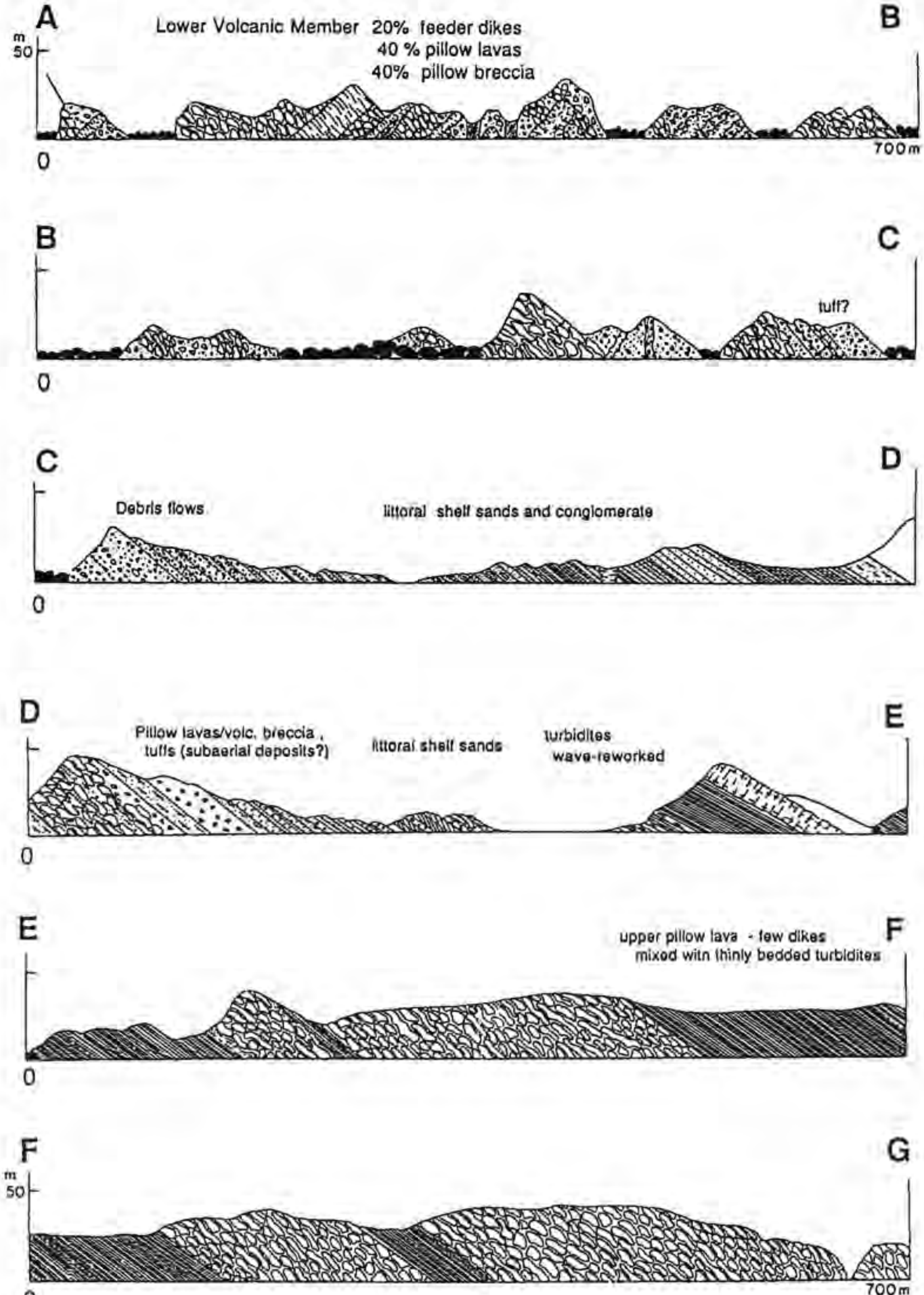
LOWER VOLCANIC MEMBER

The lower volcanic member, exposed from point A to the west approximately 1.5 km, is *ca.* 1,000 m thick. Dikes and beds have fairly consistent orientations throughout the exposures (text-Fig. 7e). This member is composed of a mixture of coarse volcanic agglomerate, vesicular and/or amygdaloidal pillow lava, and columnar to radially-jointed dikes (or irregular small intrusions). Pillows range in vertical dimension from 10-15 cm to over 2-3 m. Two unpillowed flows that may represent subaerial eruptions are present near the top of the section. The breccias are matrix-supported, poorly-sorted, generally unstratified, and contain angular clasts of pillows up to a meter in diameter. No well-stratified sedimentary deposits were observed in the lower member. Whereas dikes that intrude the lowermost lavas tend to have planar margins, dikes that intrude the middle and upper volcanic and agglomerate beds have very irregular, bulbous margins. This suggests that the upper dikes intruded into unconsolidated deposits and were probably feeders to that particular stratigraphic level.

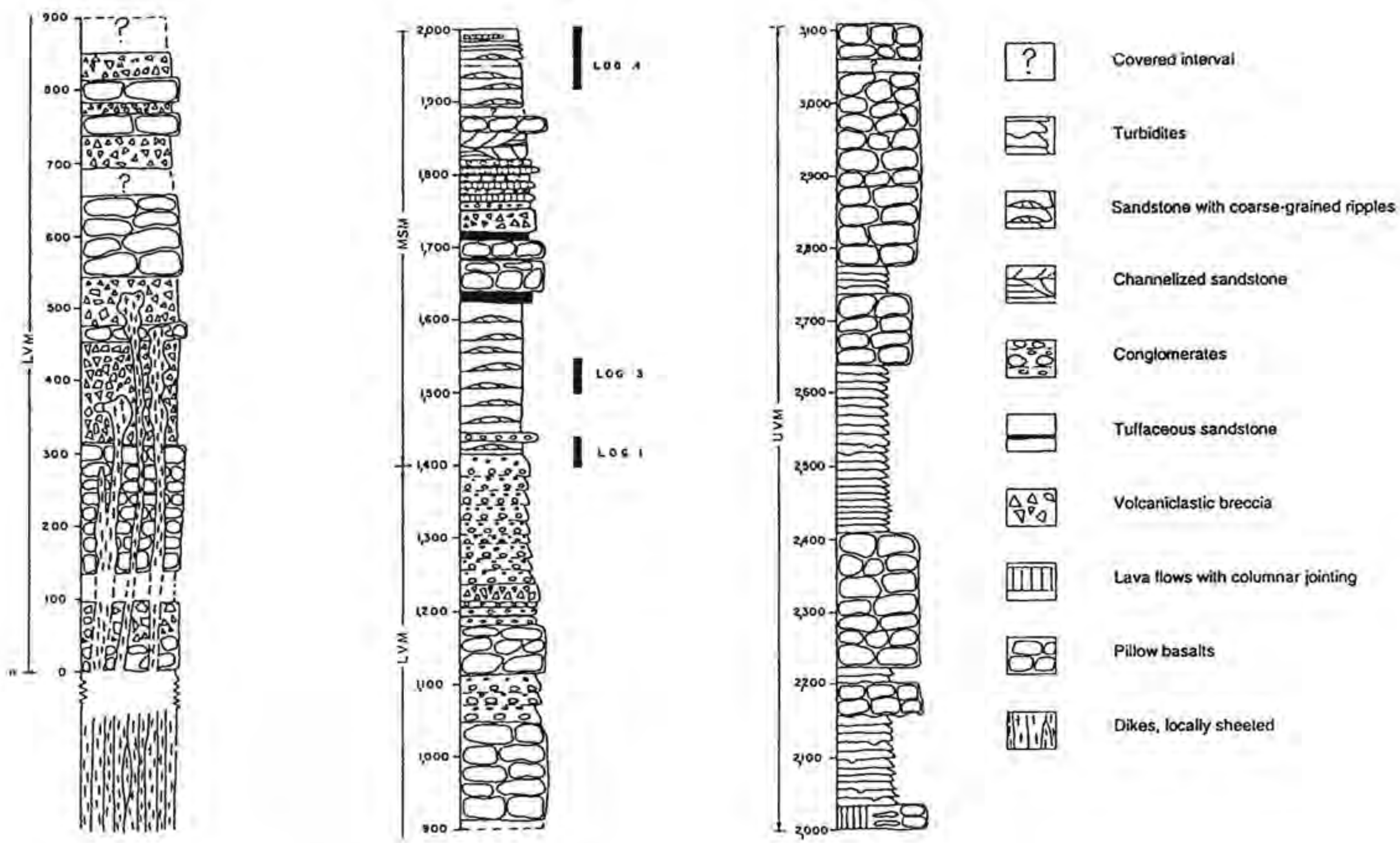
A tabular breccia, observed 1,200 m along the profile, does not offset the stratigraphic section, and is thus interpreted as a clastic dike rather than a tectonic breccia. The dike is vertical in orientation, and is therefore discordant to, and younger than, the suite of dikes in the lower section, which are normal to bedding.

DEPOSITIONAL ENVIRONMENT

The preponderance of pillow lava in the lower member indicates that the volcanic environment was dominantly submarine. The two blocky, unpillowed flows seen near the top of this member may indicate



Text-FIG. 4. Geologic profiles constructed by zodiac reconnaissance from point A-G shown in text-figure 3. Topography of the coast is diagrammatic. Black areas indicate talus cover; cross-hatched areas indicate sea caves.



Text-FIG. 5. Generalized stratigraphic section of the Bahía San Andrés Formation divided into the three members: **LVM**= lower volcanic member; **MSM**= middle sedimentary member; **UVM**= upper volcanic and sedimentary member. The section was constructed using the profiles of text-figure 4. The positions of logs 1, 3, and 4 are indicated. Note: thicknesses are approximate and may be up to 15% too thick.

that conditions became subaerial. It is likely that the lavas were fed locally by the dikes observed in this part of the section. The lower breccia deposits are interpreted to have formed by explosive submarine volcanism. This interpretation is consistent with the presence of vesicular pillow lava. The lack of stratified sedimentary rocks suggests that, either the submarine environment was isolated from detrital sources or, that volcanism was semicontinuous during this phase.

MIDDLE SEDIMENTARY MEMBER

The middle sedimentary member is dominated by sedimentary strata with subordinate pillow lavas and intrusive rocks (text-Fig. 5). This member is approximately 1,000 m thick, extending upward from the first occurrence of crudely stratified volcaniclastic breccias and conglomerates to the base of a 30 m thick, tabular, mafic flow with columnar jointing (text-Fig. 5).

FACIES ASSOCIATIONS

Four facies associations were recognized in the middle sedimentary member. Facies association 1 (fa1) is composed dominantly of 1-5 m thick, massive to crudely-bedded, matrix-supported breccias and conglomerates with sand to boulder size volcaniclastic material. Crudely-bedded framework-supported conglomerates are present locally. Fa1 is common in the lower part of the middle sedimentary member (0-2 m level, text-Fig. 6a), especially down-section of locality 1 (text-Fig. 3).

Facies association 2 (fa2), well exposed at localities 1 and 2 (text-Fig. 3), is composed of interbedded conglomerates, sandstones, and mudstones. The conglomerates are matrix and framework supported, decimeters to meters thick and composed predominantly of volcaniclastic, sand to boulder size, material. Intraformational sandstone cobbles and boulders, and basement cobbles are locally present. Although most conglomerates are tabular, some are channelized with decimeters of relief on the basal erosional surfaces (17 m level of log 1, text-Fig. 6a). Fine- to very fine-grained sandstones are typically erosively based, decimeters thick, and grade up to 1-5 cm-thick bioturbated mudstones. The sandstones are burrowed, typically massive to horizontally-stratified, and rarely cross-laminated with both unidirectional and wave ripple cross-lamination.

In two 9 m-thick, coarsening-upward sequences of fa2 (0-9 and 9-18 m levels of log 2, Fig. 6a) conglomerate increase in abundance and thickness upsection (Plate 3, Fig. 1; text-Fig. 6a). The capping conglomerate (up to 2 m thick) is matrix-supported in the lower sequence (7-9 m level of log 2, text-Fig. 6a) and cross-stratified and framework-supported in the upper sequence (16-18 m level of log 2, text-Fig. 6a).

Facies association 3 (fa3), well exposed at locality 3 and the lower part of locality 4 (text-Fig. 3), is composed of interbedded conglomerates, sandstones, and mudstones. It differs from fa1 and fa2 in that the conglomerates are typically finer-grained (pebble- to cobble size) and framework-supported, and channelized conglomerates are rarely present. Conglomerates of fa3 are typically decimeters thick, erosively-based and have either planar or undulating tops (Plate 3, Fig. 2). Those with undulating tops pinch and swell laterally for meters to tens of meters. In cross-section the conglomerates exhibit hummocks and swales similar to hummocky cross-stratified sandstones, although the gravel hummocks locally display trough cross-stratification with the cross-beds dipping dominantly to the northwest. Some of the gravel hummocks are overlain by sandstones with the low angle cross-stratification and internal truncation surfaces, characteristic of hummocky cross-stratified sandstones.

The sandstones of fa3 are typically centimeters to decimeters thick, erosively-based, massive or horizontally-stratified and grade upward from fine to very fine sand. Less commonly, they are hummocky cross-stratified or cross-laminated with wave ripple forms on their top surfaces. Bioturbation and soft-sediment deformation features are common. The sandstones are typically draped by heavily bioturbated, 1-5 cm thick mudstones. Common trace fossils are *Planolites*, *Chondrites*, and *Rhizocorallium* (Plate 3, Fig. 3).

Facies association 4 (fa4) is composed of interbedded sandstones and mudstones and rare, decimeter-thick conglomerates (upper part of log 4, text-Fig. 6c). The conglomerates are dominantly massive, matrix-supported and gravel size, and, in contrast to fa3, channelized. Sandstone beds in fa4 are fine- to very fine-grained, centimeters to a decimeter thick, and erosively based (Plate 3, Figs. 4, 5). Characteristic sedimentary structures are horizontal stratification grading upward to cross-lamination, climbing ripple cross-lamination and asymmetrical ripple forms. Paleoflow indicators are dominantly to the northwest (text-Fig. 7f). The upper parts of the sandstones and the 1-5 cm-thick mudstones are commonly bioturbated. Angular dropstones or volcanic bombs were observed in one sandstone unit (Plate 3, Fig. 4).

Facies association 4 is well-represented in the upper part of log 4 where it overlies a section of fa3 (text-Fig. 6c). The transition between the two facies associations (30-35 m level of log 4, text-Fig. 6c) includes elements of both; there are hummocky gravel horizons interbedded with sandstones containing climbing ripple cross-lamination and asymmetrical ripple forms. The tops of some of the sandstones in the transition zone have been reworked, so that wave ripple forms and wave ripple cross-lamination replace the current ripples and cross-lamination.

DEPOSITIONAL ENVIRONMENT

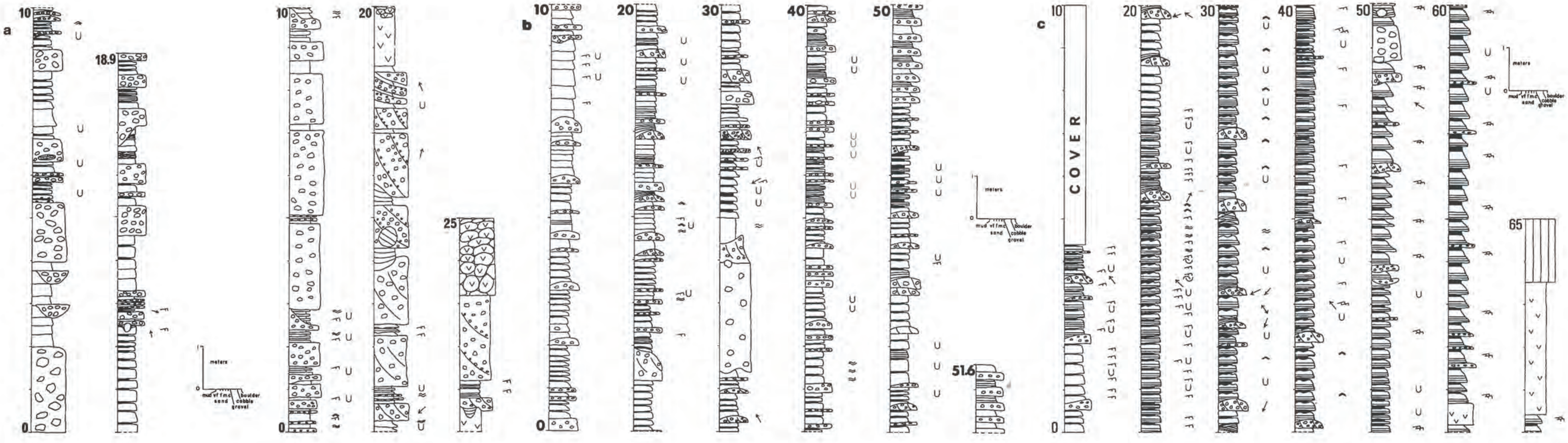
The four facies associations are interpreted as the products of a variety of submarine depositional environments. Facies association 1 contains debris and grain flow deposits composed dominantly of reworked volcaniclastic material. A submarine setting is inferred for fa1, on the basis of the close association with pillow basalts and the other facies associations which contain fossils, trace fossils, and sedimentary structures characteristic of marine settings. The matrix-supported conglomerates and breccias are similar to facies A2 of Nelson and Nilsen (1984). The framework-supported conglomerates are similar to facies A1 of Nelson and Nilsen (1984). A possible depositional setting for fa1 is a proximal debris apron adjacent to a submarine high or emergent coastline.

Facies association 2 is interpreted as submarine sediment gravity flow deposits. The conglomerates are composed of both grain and debris flow deposits. The source terrane was composed of basaltic volcanic rocks and basement metasedimentary rocks. The sandstones are composed of debris flow deposits (massive beds) and turbidites (graded beds). Paleoflow indicators (text-Fig. 7f) suggest, that the sediment gravity flows travelled dominantly northwestward (assuming that no vertical-axis rotations have affected the exposed block). Wave ripples (*e.g.*, 1 m level of log 2, text-Fig. 6a) suggest depths, at least, above storm wave base. The 9 m thick coarsening upward sequences are interpreted as prograding submarine fan deposits capped by channel deposits.

Facies association 3 is interpreted as wave-dominated deposits formed in a shallow marine setting. The hummocky cross-stratified sandstones formed in water depths between storm and fairweather wave base (*e.g.*, Allen, 1985; Dott and Bourgeois, 1982; Duke, 1985; Duke and Leckie, 1986; Harms *et al.*, 1982; Hunter and Clifton, 1982; Nottvedt and Kreisa, 1987; Southard *et al.*, 1990; Swift and Nummedal, 1987). The gravel hummocks also formed by wave deposition between fairweather and storm wave base, and are similar to the coarse-grained ripples discussed by Leckie (1988). Such coarse-grained ripples form in conditions similar to hummocky cross-stratification, but in locations where sand is unavailable (Bourgeois and Leithold, 1984; Cotter, 1985; DeCelles, 1987; Leckie, 1988; Leckie and Walker, 1982; Wright and Walker, 1981). The source for the sand and gravel may have been sediment gravity flows generated by storm waves in shallower water upslope from the site of deposition.

Facies association 4 is turbidites deposited on distal portions of a submarine fan at water depths in excess of storm wave base (Mutti, 1979; Nelson and Nilsen, 1984; Walker, 1978). The sandstones comprising fa4 are similar to Facies D1 of Mutti (1979) and Nelson and Nilsen (1984), and the mudstones are comparable to Facies G of Nelson and Nilsen (1984). The transition zone between fa3 and fa4 contains features of both and is interpreted as being a distal submarine fan deposit, where the fan surface was close to storm wave base.

The middle sedimentary member, therefore, records deepening of the depositional basin through time. The coarse-grained deposits of fa1 and fa2 were probably deposited rapidly by sediment gravity flows in a proximal setting. The evidence for wave reworking in the finer-grained portions of fa2, suggests water depths above storm wave base. As basin evolution proceeded the grain size diminished, reflecting an increase in distance to the sediment source areas. These finer-grained sediments were reworked by wave action into hummocky cross-stratified sandstones with coarse-grained ripples, as seen in fa3, suggesting water depths above storm wave base. With further deepening of the basin, the distal turbidites of fa4 accumulated below storm wave base, probably, on the distal margins of a submarine fan.



Text-FIG. 6. Sedimentologic logs of four outcrops in the middle sedimentary member. See text-figure 3 for locations and text-figure 5 for stratigraphic positions of the logged sections: a- Log 1 (18.9 m thick) on left; Log 2 (25 m thick) on right. The lowest 2 m of log 1 are fa1, otherwise all the strata in logs 1 and 2 consist of fa2; b- Log 3 (51.6 m thick). All of log 3 is composed of fa3; c- Log 4 (65 m thick). Log 4 is composed of fa3 up to the 30 m level. Above the 35 m level, log 4 is composed of fa4. The interval between 30 and 35 m is a transition zone (see text).

UPPER VOLCANIC AND SEDIMENTARY MEMBER

The remaining 1,000 m of the Bahía San Andrés Formation to the west of site 4 were observed at a distance, from zodiac and helicopters. This upper member is composed of, at least, four cycles of interbedded pillow lavas and gray to grayish-green graded beds less than 30 cm thick. The graded beds are laterally persistent for meters to tens of meters. The colors, erosional contacts, and thicknesses of these sedimentary beds appear very similar to the fa4 deposits of the uppermost middle sedimentary member.

Volcanic rocks in the upper member appear to be composed of pillow lavas and few dikes; no volcanic breccia was observed. Pillow forms are well exhumed, suggesting less metamorphism than that observed in the lower pillow sections, where pillows are commonly weathered along fractures rather than bedding surfaces. In Caleta Pascuas, thin (<0.3 m) volcaniclastic sandstones were observed in the pillow lava sequence.

DEPOSITIONAL ENVIRONMENT

The upper volcanic and sedimentary member is a marine unit. Few dikes and no evidence of explosive volcanism were observed, suggesting off-axis volcanism. The sedimentary strata are interpreted as distal turbidites. Therefore, the upper volcanic and sedimentary member formed in a deepening basinal environment, more distal from detrital sources than the middle sedimentary member.

PLUTONIC AND OTHER ROCK UNITS

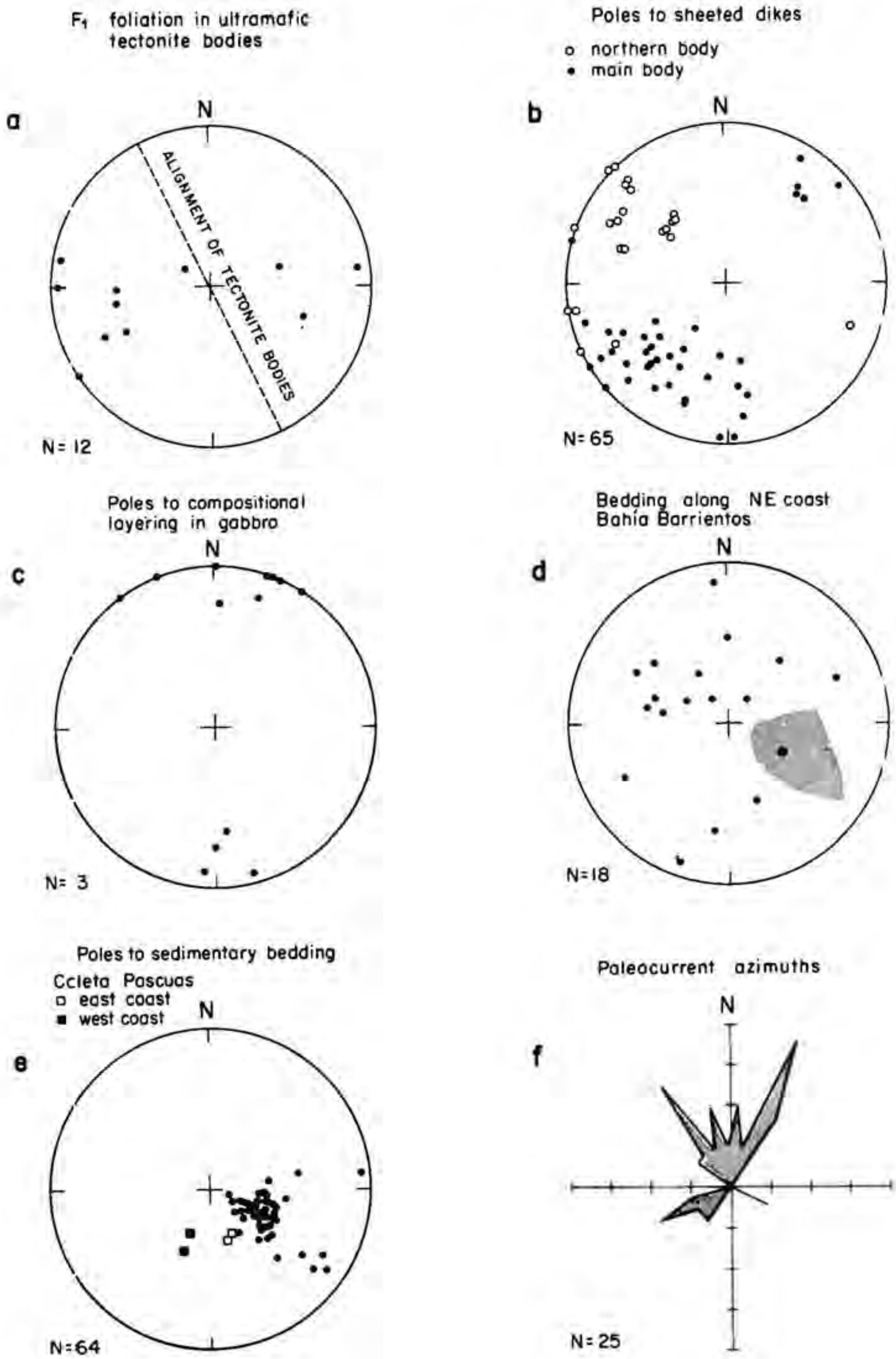
A number of plutonic bodies has been mapped in the region of the Península Taitao and Golfo Tres Montes (see Forsythe and Nelson, 1985; Mpodozis *et al.*, 1985; Forsythe *et al.*, 1986). In addition, at least two other plutons were mapped or sampled during the 1990 expedition. Along the north shore of Estero Cono psammitic and pelitic metasedimentary rocks, correlated with the late Paleozoic basement of the Archipiélago de los Chonos (Chonos Archipelago) to the north (Davidson *et al.*, 1987), are intruded by tonalite (here termed the Cono intrusion) with equigranular to porphyritic textures and sulfide mineralization. A second pluton, informally termed the Central pluton, was mapped near the center of the main sheeted dike unit (text-Fig. 2). This felsic, tonalitic pluton is porphyritic, contains large xenoliths or roof pendants of diabase, exhibits an irregularly-developed flow foliation near the margin, and contains a propylitic alteration. The contact along the southern and southwestern margin was accurately mapped, but the extension of the body to the north and east is poorly constrained due to lack of outcrop and few helicopter landings.

Andesitic agglomerates and andesitic porphyry are exposed in the area of Cabo Gallegos and in two isolated outcrops (sites 39 and 61, text-Fig. 2). These rocks (here informally termed the Cabo Gallegos andesite), contain orthopyroxene and minor hornblende phenocrysts and rare xenocrysts of olivine. Just south of the peninsula, this sequence is probably faulted against diabase and altered, vesicular, pillow basalt, interpreted to be near the top of the main sheeted dike unit. The relationships of the Cabo Gallegos andesite to the Bahía San Andrés Formation and the Barrientos sequence are unknown. The andesitic rocks (and rhyolitic rocks in the Barrientos sequence) may represent a progressive change upward from more basaltic volcanism in the Bahía San Andrés Formation, or they may rest unconformably on the Bahía San Andrés Formation.

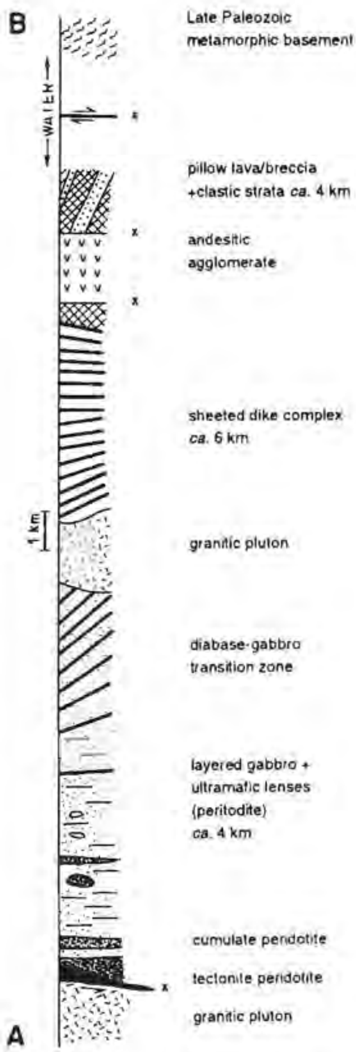
STRUCTURE

The Taitao ophiolite has been tilted and faulted against the surrounding basement rocks (text-Fig. 8). If the dip of layering in cumulate ultramafic and gabbroic rocks was formed in a horizontal orientation, then these portions of the ophiolite have been tilted approximately 90°. Evidence also exists for faulting and disruption between some of the units within the ophiolite.

Ductile structural fabrics in the ultramafic tectonites include strong penetrative foliation and lineation (some rocks are nearly L-tectonites) and isoclinal, asymmetric, mesoscopic folds (Plate 1, Fig. 4). These fabrics are overprinted by brittle faulting and fracturing. The poorly exposed 'base' of the ophiolite is in fault contact with the Cabo Raper pluton, and possibly



Text-FIG. 7. a-e: Equal area, lower hemisphere, stereographic plots of orientation data; a- ultramafic tectonite unit. Dashed line shows orientation of lens-shaped bodies of ultramafic tectonite along the base of the ophiolite; b- poles to dikes in the main and northern sheeted dike unit; c- poles to compositional layering in the gabbro unit; d- poles to bedding along the NE coast of Bahía Barrientos. Shaded area shows distribution of poles from San Andrés Formation (this figure e); e- poles to bedding from the Bahía San Andrés Formation (dots from Estero Cono; squares from Caleta Pascuas); f- histogram (10 degree intervals) of directional paleocurrent data in the middle sedimentary member of the Bahía San Andrés Formation.



Text-FIG. 8. Cross section of the Taitao ophiolite; x= fault. See text-figure 2 for location of section line.

other lithologies. Within about 10 m of the basal contact, the tectonites are completely serpentinized and locally contain a phyllitic, anastomosing cleavage typical of sheared serpentinite. Strongly-foliated, lenticular blocks (*ca.* 3 x 5 m in map dimension) of the Cabo Raper granodiorite are enclosed within serpentinite within this basal shear zone, and foliation and elongation of the bodies are parallel to the contact. The basal contact trends approximately 334°, whereas the dominant strike of ductile foliation and compositional layering in the ultramafic bodies is about NS (text-Fig. 7a), a relationship suggesting a component of left lateral shear during or after obduction emplacement of the ophiolite. Also, although a few steep (>70°) lineations were measured, most lineations in these ultramafic rocks plunge between 5-30°, suggesting a component of horizontal ductile flow.

The orientation of compositional layering and gabbro dikes within the gabbro unit is very consistent; strikes range from 055-125° and average *ca.* 095°, and dips are steep (>50°) to vertical (text-Fig. 7c). Thus, the strike of gabbro layering is essentially perpendicular to that of foliation in the ultramafic rocks. Gabbros in the transition zone locally contain a foliation and thin (<20 cm thick), serpentinized ductile and brittle-ductile shear zones which dip 30-60° east to southeast when the main sheeted dike unit is rotated to vertical. Thus, these foliations and shear zones strike perpendicular to dikes in the main sheeted dike unit. Assuming the dikes formed parallel to a paleo-spreading ridge, these relatively low-dipping shear features may have formed along a transform fault, possibly by transtensional or transpressional deformation.

The orientation of sheeted dikes within the main body is very consistent; strikes range from 80-155° and average *ca.* 126°, and most dips are steeply northeast to vertical (text-Fig. 7b). However, dikes within the pillow lavas in Caleta Pascuas dip to the southwest between 60-80°. This reversal of dip could have been caused by rotation of normal fault blocks at the spreading ridge environment, or by faulting or folding during obduction emplacement.

The orientation of sheeted dikes within the northern body is perpendicular to those in the main body, with strikes averaging about 040°, and dips averaging 70°, mostly to the southeast (text-Fig. 7c). The orientation of bedding in the Bahía San Andrés Formation is very regular along the southwest coast of Bahía San Andrés from Estero Cono to the eastern shore of Caleta Pascuas, averaging 25-26°NW (text-Fig. 7e). However, on the western shore of Caleta Pascuas the orientation of bedding is roughly perpendicular and dips are to the NE (text-Fig. 7e). The divergence of these latter bedding orientations (only two were obtained) may be related to fault block rotation or to folding, although the strike of dikes does not change significantly. The internal structure of the narrow fault block along the NE coast of Bahía Barrientos is unknown, but is probably complex, as rocks are commonly sheared or fractured, and bedding attitudes are highly irregular and discordant to those in the Bahía San Andrés Formation (text-Fig. 7d).

At least, four megascopic faults were mapped or inferred in the Taitao region (text-Fig. 2). Along the base of the ophiolite, as described above, shear fabrics and blocks of foliated granodiorite in the basal serpentinite indicate the presence of a shear zone, here termed the basal fault. Along with clasts of the granodiorite, clasts of slate were observed in float near this contact. However, due to heavy vegetation covering the actual fault contact was not observed. Sense of shear and amount of displacement along the basal fault are unknown, but are probably large, as this fault represents the surface along which the ophiolite was obducted, and/or later displaced.

The northeastern margin of the ophiolite is presumed bounded by a fault (here termed the Cono fault), which is hidden below Estero Cono and the low valley to the southeast. Basement rocks and a granitic pluton, exposed on the northeast shore of the fjord, are both hydrothermally altered and contain sulfide mineralization, suggesting hydrothermal circulation along the fault. No evidence was observed to indicate sense or amount of displacement along the Cono fault.

The southeastern margin of the ophiolite is also bounded by a fault or series of faults (here termed the Barrientos fault system) inferred by a number of lines of evidence. Along the northwestern shore of Bahía Barrientos south of Estero Lobos, pillow lavas are exposed on a topographic bench southeast of the gabbro and main sheeted dike units. The shores of Bahía Barrientos are composed of linear segments, and expose many highly fractured outcrops. Also, two hot springs were located along this shore. The fault zone also contains an isolated block of Eocene marine siltstone (Forsythe *et al.*, 1985). The juxtaposition of pillow lavas against the gabbro and main sheeted dike units suggests components of right slip and/or down to the south slip if the Bahía Barrientos sequence is, in part, correlative with the Bahía San Andrés Formation. However, Kaeding *et al.* (1990) proposed a left lateral offset on the basis of geochemical correlation between the Cabo Raper pluton and the pluton exposed on the south shore of Bahía Barrientos (text-Fig. 2).

A fault, here termed the Yunques fault, was mapped along an EW topographic lineament between Estero Lobos and the Pacific coast. Other evidence for this fault, includes the concentration of hydrothermal alteration in the transition zone, and the presence of slates of unknown affinity (probably basement) along the north side of the lineament. The sense and amount of displacement along this fault are unknown; the position near the transition zone suggests that the fault origin may be related to detachment at this level of the ophiolite during ocean ridge evolution, although the presence of the slate suggests later movement.

DISCUSSION

OPHIOLITE'S TECTONIC AFFINITY

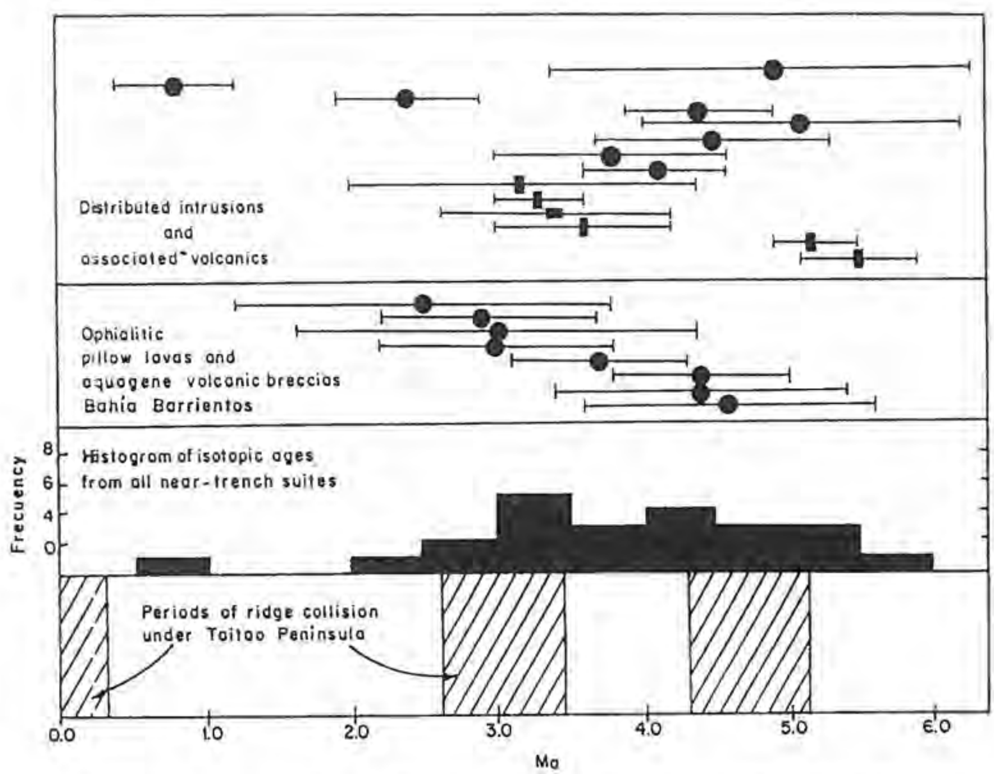
Although field work during the 1990 expedition added a large number of field sites to existing knowledge of the Taitao ophiolite and associated rocks, many details concerning the nature and relationships of the various units remain unclear. High-temperature deformation fabrics in the thin (<1 km) ultramafic tectonite unit formed during aesthenospheric flow, possibly prior to formation of the magmatic portion of the ophiolite. The generally low-angle ductile lineations may have formed by channelling of mantle flow along the ridge axis (Nicolas, 1989, p. 77). These fabrics are overprinted by brittle shear fabrics formed during obduction emplacement and/or subsequent faulting. The strongly layered, but generally unfoliated gabbro unit probably formed in a short-lived magma chamber in an active rifting environment. This contrasts with ophiolites, such as the Oman ophiolite, in which nearly all of the layered gabbros are foliated by magmatic flow in continuously replenished magma chambers (Nicolas, 1989). Although two sheeted dike units were recognized, their trends are mutually perpendicular. Exposure is insufficient in the interior of the peninsula to determine if the two dike units are correlative, but have been rotated by faulting or folding, or if they evolved separately. In the latter case, one of the dike units may have formed parallel to the paleo-ridge axis, whereas the other, may have formed in a transform fault environment. Alternatively, the axis of spreading could have rotated in time.

The clastic nature of the Bahía San Andrés Formation clearly indicates that the ophiolite formed in proximity to a continental source. The basin initially filled rapidly with on-axis submarine volcanic flows and breccias and built up to, and possibly above, sea level. Subsequently, the basin subsided progressively while clastic, wave-dominated shelf and then submarine fan strata were deposited during lulls in volcanic activity. The basin widened and deepened and deposits became increasingly finer, more distal and further removed from the effects of wave action. Whereas, the volcanic deposits in the lower parts of the Bahía San Andrés Formation are cut by extensive swarms of dikes and, apparently, represent on-axis volcanism, the uppermost volcanic flows have few dikes and are likely products of off-axis volcanism.

Nicolas (1989) discusses two fundamental ophiolite types: harzburgite ophiolite types (HOT) and lherzolite ophiolite types (LOT). HOT's tend to form in well-developed, rapid (>2cm/yr) spreading systems whereas LOT's tend to form in incipient rifts or transtensional settings. The Taitao ophiolite seems to have affinities to both types, although more so to LOT's. Typical LOT features include: a clastic sedimentary cover, contact with metamorphic continental crust, lack of chromite pods in the ultramafic section, and rodingized gabbro dikes in the ultramafic section. A typical feature of HOT's is a thick, well-developed, but undeformed gabbro unit. On the basis of these comparisons, and on the basis of the present state of knowledge of field relations in the Taitao region, the Taitao ophiolite is interpreted to have formed in a rift basin within the forearc, above the magmatic system of the subducting spreading ridge (suprasubduction setting).

OPHIOLITE FORMATION AND EVOLUTION OF THE CHILE MARGIN TRIPLE JUNCTION

All K/Ar age dates (Mpodozis *et al.*, 1985) for the igneous units of the Taitao and Tres Montes Peninsular regions (text-Fig. 9) were obtained from felsic intrusions and volcanic units collected from the shores of Bahía Barrientos and Golfo de Tres Montes. No



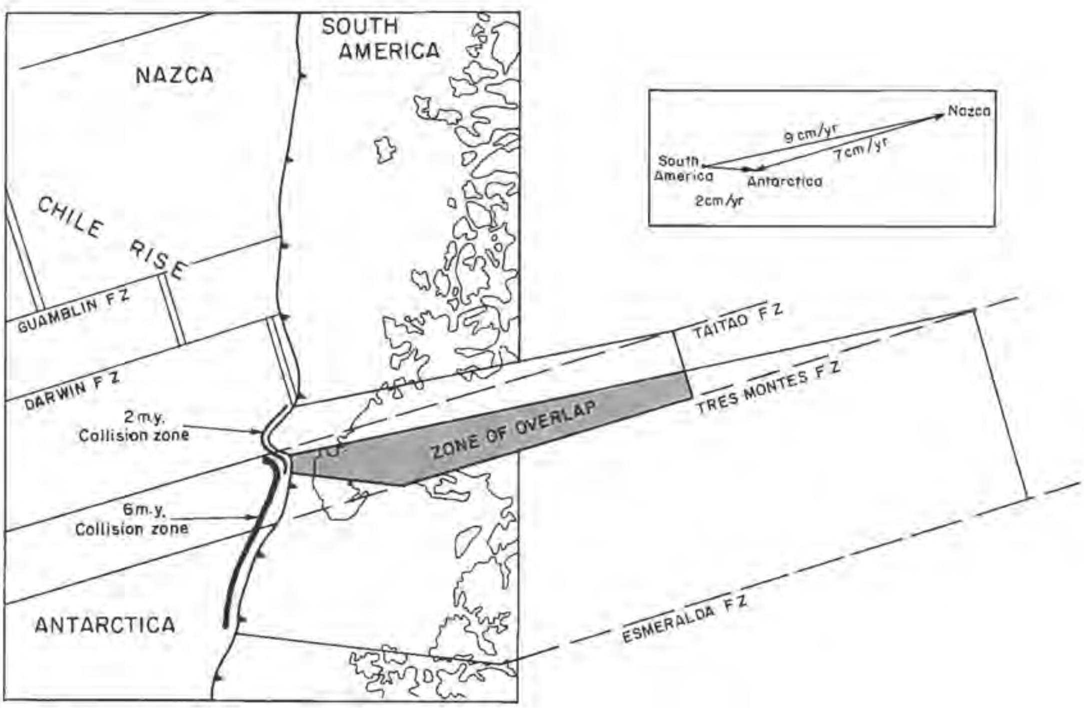
Text-FIG. 9. Radiometric ages of near-trench magmatism and periods of ridge collision under the Peninsula de Taitao region. Ages are from Mpodozis *et al.* (1985). Periods of ridge collision are estimated from the plate kinematics shown in text-figure 10. Circle = whole rock; vertical bar = biotite; horizontal bar = hornblende.

age dates have been obtained from the lower plutonic sections of the ophiolite or from the two more recently identified plutons (Cono and central pluton). In addition, the Bahía San Andrés sections have not been dated, although foraminifera of Plio-Pleistocene age have been reported from the middle sedimentary member (Forsythe *et al.*, 1985).

These K/Ar ages demonstrate that the volcanic units have ranges in ages similar to the felsic intrusions. If the volcanic rocks dated from Bahía Barrientos represent the upper strataform part of the ophiolite, then the ophiolite has a prolonged history extending from 6-3 Ma. This minimum of 3 million years of volcanism can be understood most easily in terms of the kinematics of ridge collision.

As pointed out by Cande and Leslie (1986) and Cande *et al.* (1987), the relative motion of the Nazca, Antarctic and South American plates is such that the transforms (or fracture zones) are riding obliquely into the continental margin (text-Fig. 10). Segments of the Chile Rise between the Esmeralda and Tres Montes, and Tres Montes and Taitao Fracture Zones collided with the margin at 6 Ma and 3 Ma, respectively. For each colliding ridge segment asthenospheric windows opened, as these segments were consumed under the South American plate. Due to the oblique angle of transform convergence the tracks of the successively colliding ridge segments (and their respective asthenospheric windows) have small regions of overlap. The Taitao peninsula is situated in a region which had an asthenspheric window pass underneath at 6 Ma and at 3 Ma. Thus, the range of ages for the intrusive units from 3-6 Ma is consistent with the plate kinematic data.

Regarding the formation of the ophiolite, the situation is slightly more problematic. If the ophiolite was created between 3 and 6 Ma, by typical spreading processes at rates comparable to the offshore Chile Rise spreading center, at least 300 km of crust would have formed in a 3 m.y. interval. Given the small size of the Taitao ophiolite (sheeted dike complex is *ca.* 6 km wide), the ophiolite would have formed due to a



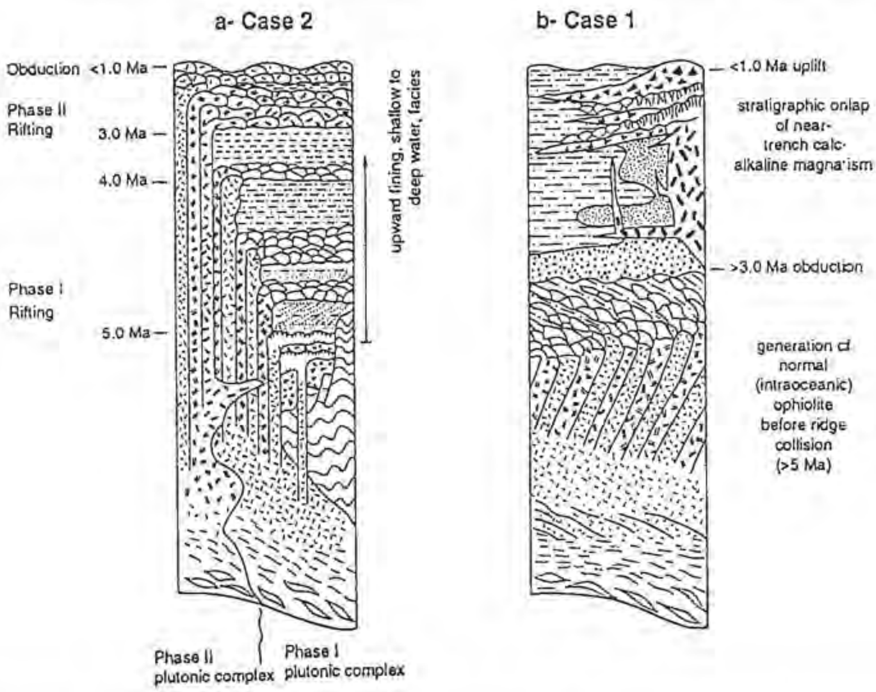
Text-FIG. 10. The shaded area represents the region which has been underridden by the two Chile Rise spreading segments that were situated between the Taitao, Tres Montes, and Esmeralda Fracture Zones. An area under the Peninsula de Taitao was underridden by both ridge segments, at roughly 5-4 Ma, and 3.5-2.5 Ma, due to the slight obliquity of the Nazca-South American and Antarctica-South American plate motions.

few 100,000 years of magmatic activity. Thus, an atypical model must be evoked to explain the ages. Two models are under present consideration, given the available age and regional tectonic and stratigraphic data (text-Fig. 11). The two cases are presented below, along with arguments to support each case.

Case 1 (text-Fig. 11b). Only the lower plutonic portions of the complex are truly part of an ophiolitic complex. The volcanic units were brought up through fissures within the ophiolite post-obduction or were extruded by nearby volcanic centers at a later time. In this scenario, the plutonic units could be greater than 6 Ma in age, and not likely formed during the Chile Rise collision. Strataform units of the ophiolite formed prior to ridge collision would have been deposited in deep water, and then unconformably overlain by volcanic deposits and shallow water sediments during and post-obduction. The section may have been intruded by felsic intrusion and unconformably overlain by felsic volcanic flows interbedded with shallow water to subaerial sediments.

Case 2 (text-Fig. 11a). The ophiolite includes the volcanic rocks of Bahía Barrientos and Bahía San Andrés sequences. The ages of volcanic units reflect the duration of 'spreading'. However, the environment for spreading is that of a forearc rift that evolves in two stages. The first stage is during the collision at 6 Ma, and the second during the collision at 3 Ma. The first phase would have had more continenta contamination, and magmas potentially would have evolved within subaerial to submarine environments during the early collapse and rifting of the continental margin. The second phase, potentially, could have involved more extensive differentiation as well as remelting of previously formed ophiolitic units. During this phase, the rift was reactivated during the second interval of ridge collision, and magmas worked their way through previously formed units. The sediments interbedded with the volcanic units would have evolved from shallow to deep and proximal to distal facies.

Of these two scenarios, which are diagramatically



Text-FIG. 11. Diagrammatic sections for two models of ophiolite formation and basin sedimentation; a- (on left) is the preferred model for ophiolite generation. Here, within an incipient fore arc rift that initially opens up over the 5-4 Ma collision zone, magmas ascend into, and are contaminated by, fore arc crust. In a subsequent second 2-3 Ma phase, the rift is reactivated. The basin preserves an upward fining sequence, and is uplifted during the Pleistocene; the second model, b- (on the right), has only one oceanic phase of magmatism, which was produced >4-5 Ma offshore, on the segment of the Chile Rise that was situated between the Tres Montes and Esmeralda Fracture Zones. After obduction, a second phase of volcanism would be created during the 2-3 Ma collisional period, but in this model this is near-trench 'blow torch' magmatism.

portrayed in text-figure 11, the first fits some of the observations and the second, others. Cross-cutting or multiple intrusive relationships are observed within the lower gabbros. The gabbros and sheeted dikes are themselves cut by a late-stage felsic pluton. The ophiolite, as mentioned earlier, is most similar to the 'LOT' types, which are believed to typify ophiolites of continental rift environments. The northern dike complex contains screens of hornfels that were originally metamorphic basement or preexisting plutonic rocks. The lower sedimentary units within the strataform parts of the ophiolite contain shallow to subaerial facies, and include debris flows with abundant clasts of basement material mixed with volcanic clasts. The Bahía San Andrés Formation includes a lower and upper volcanic-dominated member separated by a central sediment-dominated member. The lower volcanic member has abundant screens of feeder dikes, while the upper member appears to have volcanic flows fed by a lateral source out of the plane of the exposed section. Overall, the sedimentary facies described earlier in this paper can be viewed as an upward fining section from shallow to deep water facies. There have been no unconformities described within the Bahía San Andrés section, which includes in its lower parts abundant screens of subparallel dikes. The volcanic units along Bahía Barrientos could, however, conceivably rest unconformably on the lower units of the ophiolite, but such an unconformity has not been identified todate. These observations are best interpreted in light of the second case for a reactivated (or two phase) forearc rift structure floored by the Taitao ophiolite. The extension and magmatism within this rift persisted for *ca.* 3 m.y. during two ridge collision events.

Uplift of the ophiolite may only have been initiated in the Pleistocene, as the continental margin just north of the Taitao ophiolite was subject to the collision of the segment of the Chile Rise, north of the Taitao Fracture Zone.

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PLATE 1

Features of mafic and ultramafic rocks in the Taitao ophiolite; p. 140

Figures

1	Aerial view of lens-shaped bodies of ultramafic tectonite along the base of the ophiolite. The Cabo Raper pluton underlies the hills to the left.
2	Compositional layering in unfoliated ultramafic rocks.
3	Ultramafic block within gabbro unit cut by stockwork of gabbro dikes.
4	Ductile mesoscopic folds in ultramafic tectonite unit.
5	Angular unconformity or channel in compositional layering of gabbro unit. Note, layering is nearly vertical in this outcrop.
6	Graded compositional layering in gabbro unit. Note, up (toward the dike unit) is to left.

PLATE 1

1

2

3

4

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6

PLATE 2

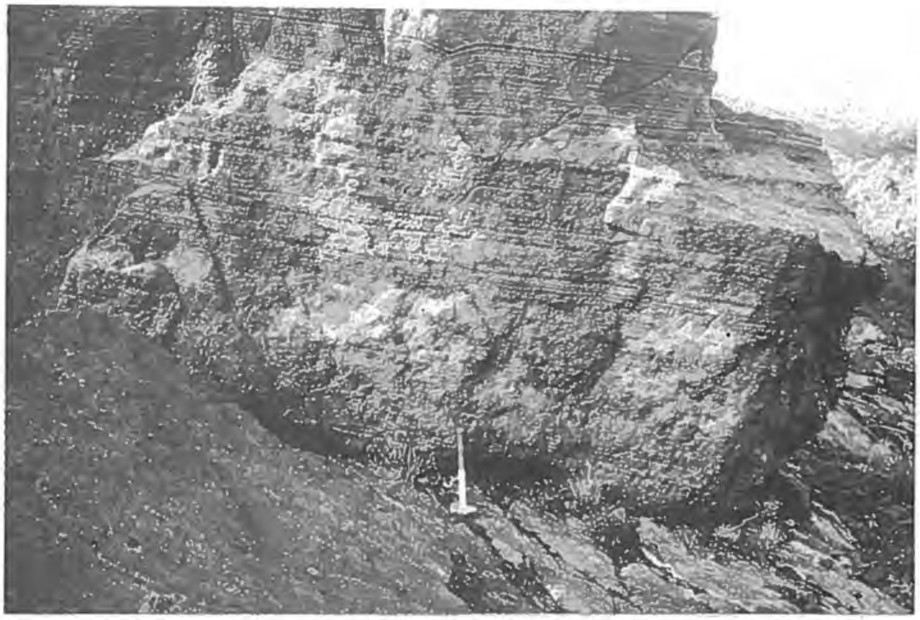
Features of gabbroic rocks in the Taitao ophiolite; p. 140

Figures

1 Fine compositional layering in a boulder of gabbro (in outcrop, layering is consistently steeply-dipping).

2 Undulatory compositional layering in gabbro unit.

PLATE 2



1

2

PLATE 3

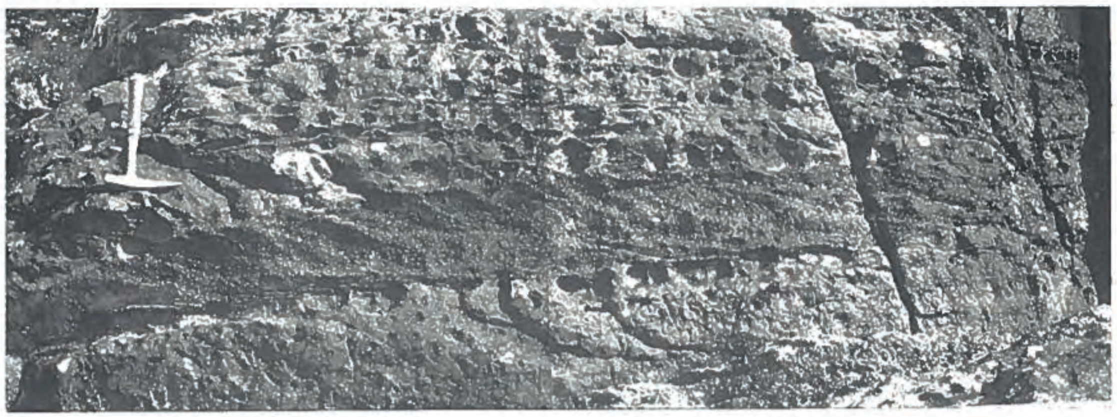
Features of volcanic-sedimentary unit in the Taitao ophiolite; p. 147, 148

Figures

1	Photomosaic of two 9 meter-thick coarsening-upward sequences in facies association 2 of middle sedimentary member at locality 2 (text-Fig. 3). The upper sequence has large-scale cross bedding and is capped by pillow basalt. Note person for scale and helicopter tail at left.
2	Photomosaic of a cross-stratified gravel unit with a horizontal base and a convex upward top in facies association 3 (log 3, 17 m level, text-Fig. 6b). The cross bedding dips to the right (NW). The gravel bed is similar to the coarse-grained ripples of Leckie (1988).
3	Bedding plane view of *Rhizocorallium* in facies association 3 (log 3, 28 m level, text-Fig. 6b).
4	Cross section view of four graded beds (log 4, 45 m level, text-Fig. 6c). The third graded bed is the thickest and is composed of 2 to 3 cm of fine sandstone grading up to 15 to 20 cm of horizontally-stratified sandstone which in turn grades up to 5 cm of cross-laminated sandstone.
5	Cross section view of erosively-based sandstone grading up into climbing ripple cross lamination just above the scale (log 4, 47 m level, text-Fig. 6c).
6	Horizontally-and cross-laminated sandstone in facies association 4 with an angular volcanic bomb (log 4, 50 m level, text-Fig. 6c).

PLATE 3

1



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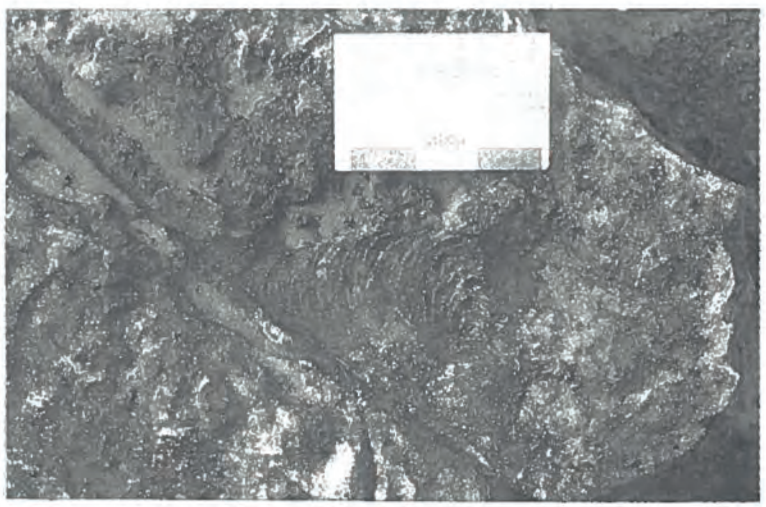

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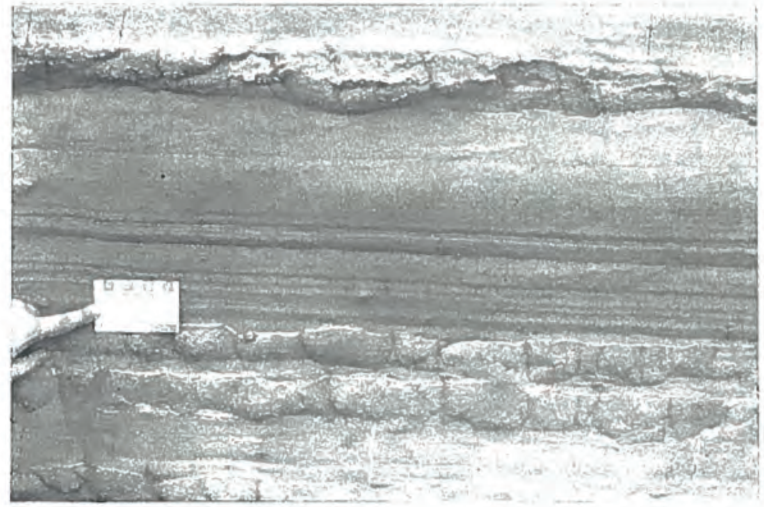

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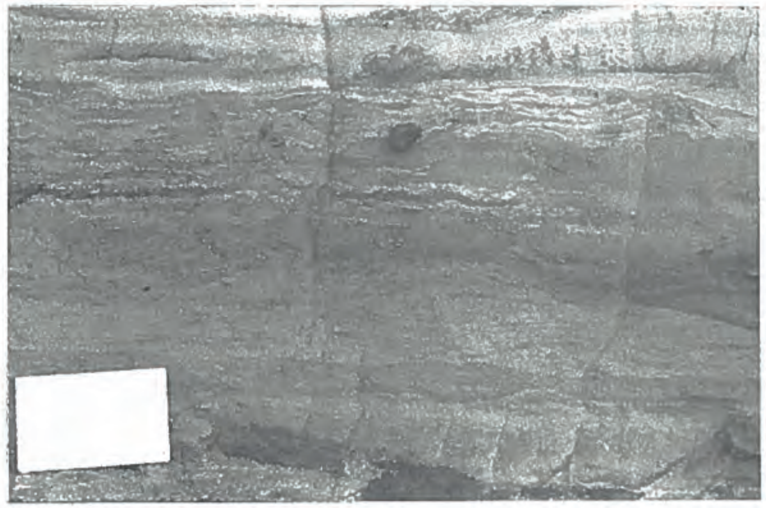

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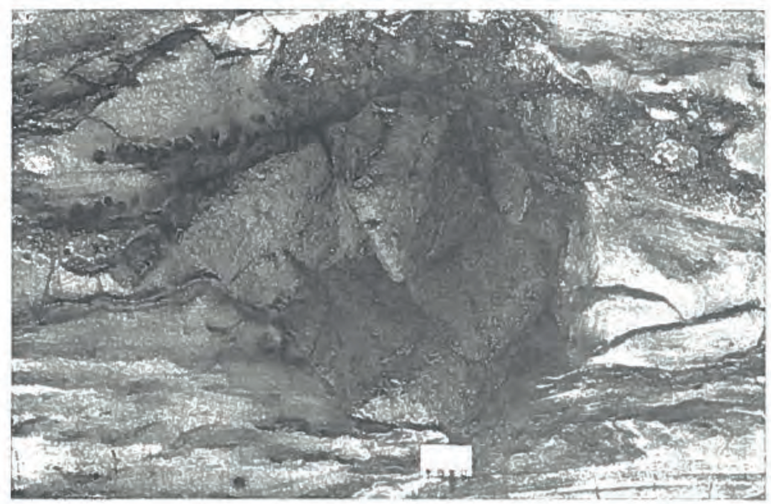

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