The Lower Cretaceous Apeleg Formation of the Aisén basin, Southern Chile. Tidal sandbar deposits of an epicontinental sea

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ABSTRACT

The Apeleg Formation is a Lower Cretaceous marine succession of the Aisén Basin of southern Chile. Clastic sediments were deposited in a shallow epicontinental sea in a north-south elongated retroarc basin. This sedimentary basin developed as a thermal sag to the east of a subduction-related magmatic arc on the South American continental margin. A sequence of up to 1,200 m of well-sorted sandstones and mudstones are characterised by mud-draped ripples and a well-preserved and varied trace fossil assemblage. The sediments were deposited as offshore tidal sandbars or sand ridges on a shallow marine shelf.

Key words: Retroarc Sedimentary basin, Tidal, Lower Cretaceous, Aisén.

RESUMEN

La Formación Apeleg del Cretácico Inferior de la Cuenca de Aisén, sur de Chile: depósitos mareales de bancos de arena de un mar epicontinental. La Formación Apeleg es una sucesión marina del Cretácico Inferior, depositada en la Cuenca de Aisén, en el sur de Chile. Los sedimentos clásticos fueron depositados en un mar epicontinental somero en una cuenca de retroarco, elongada en dirección norte-sur y que se desarrolló por subsidencia térmica al margen continental de America del Sur. Esta formación comprende hasta 1.200 m de areniscas bien seleccionadas y lutitas, caracterizadas por ondulitas cubiertas de lodo, y una asociación variada y bien preservada de trazas fósiles. Los sedimentos fueron depositados como bancos de arena mareales o bancos de arena en una plataforma marina somera.

Palabras claves: Cuenca sedimentaria retroarco, Mareal, Cretácico Inferior, Aisén, Chile.

INTRODUCTION

The Apeleg Formation is a clastic marine sequence which forms part of the sedimentary infilling of the Lower Cretaceous Aisén Basin (M. Suárez and R. De la Cruz, 1994)[1]. The Aisén Basin, also known as the Río Mayo Embayment, forms a northernly extension of the Austral Basin of southern

[1] 1994. Estratigrafía del Jurásico-Cretácico Inferior de la Cordillera Patagónica Oriental (45°-46° Latitud Sur), Chile: facies, paleografía. Unpublished. *Gobierno Regional, XI Región-Servicio Nacional de Geología y Minería*, 82 p.

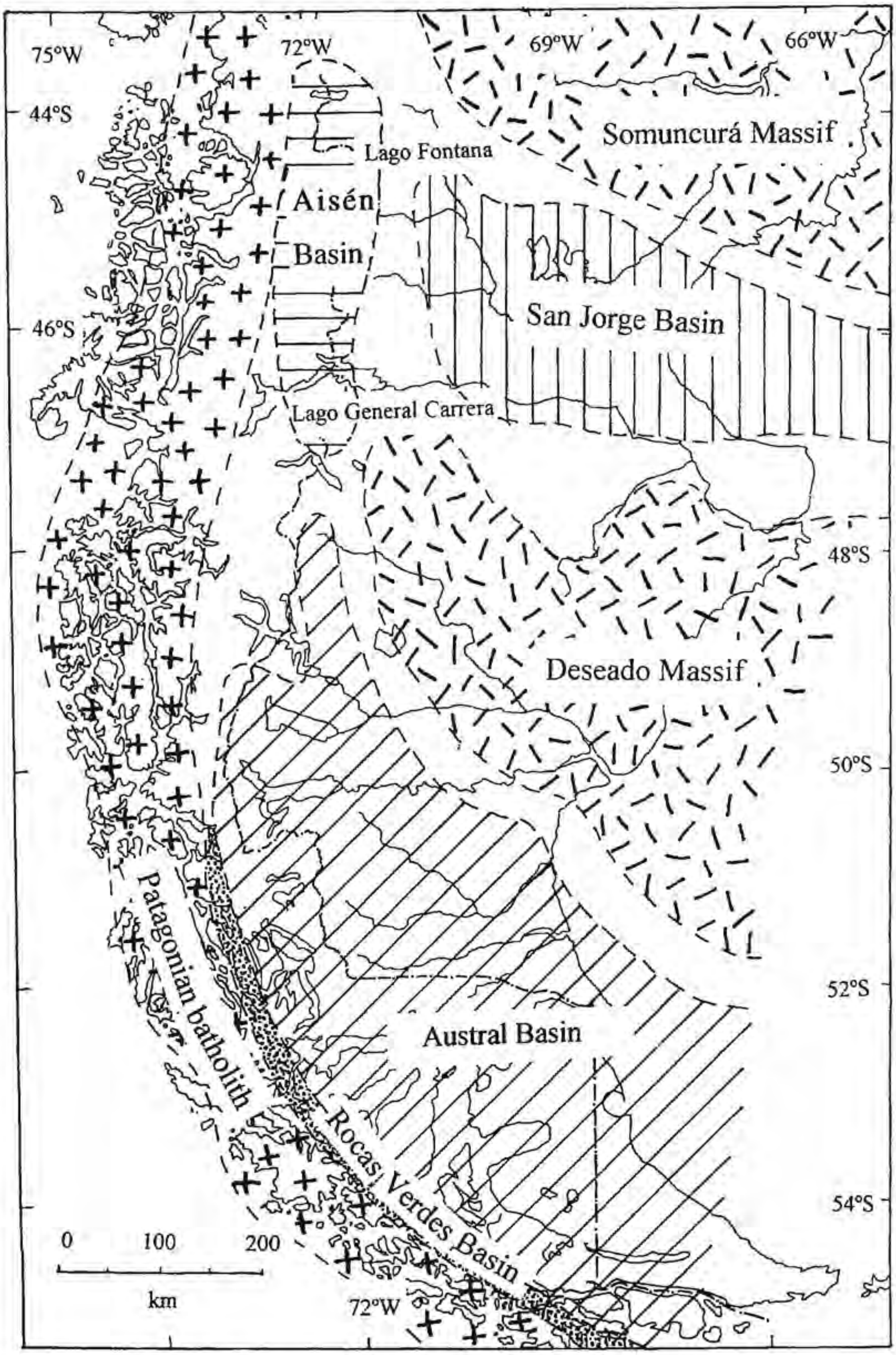


FIG. 1. The geographical and geological setting of the Aisén Basin.

Chile and Argentina (Fig. 1) (Biddle *et al.*, 1986; Ramos and Aguirre-Urreta, 1994; Riccardi, 1988; Wilson, 1991). The sediments were deposited in a retroarc basin on continental crust to the east of a magmatic arc. This arc, which is now represented by parts of the Patagonian batholith, was formed by the subduction of an oceanic plate beneath the South American continental margin (Niemeyer *et al.*, 1984).

The formation was defined between 44°30' and 45°S in Argentina by Ploszkiewicz and Ramos (1977). Its extension into the region of the present study, and as far as 47°S, was recognised by Suárez and De la Cruz (1994). In this southern region a sedimentary succession, which includes the Apeleg Formation, was initially named the Coihaique Formation (A. Lahsen[2]; Skarmeta (1976, 1978); Niemeyer *et al.* (1984)), but was re-named as the Coihaique Group by M. Suárez and R. De la Cruz (1994)[1].

The Apeleg is the youngest of the three formations which comprise the Coihaique Group (Table 1). At the base is the Toqui Formation, also known as the Cotidiano or the Tres Lagunas Formation, which was the product of a marine transgression over subaerial volcanic rocks of the Upper Jurassic to Lower Cretaceous Ibáñez Group (Suárez and De la Cruz, 1994). The Toqui Formation consists of calcareous and clastic sediments deposited on the high-energy shorelines of active andesitic volcanoes. This formation is conformably overlain by thick black shales of the Katterfeld Formation, which were deposited in the still-water anoxic conditions of a sheltered and partly enclosed marine embayment during Valanginian to early Hauterivian times. In the middle to late Hauterivian this embayment changed to an open marine shelf on which the sandstones and mudstones of the Apeleg Formation were deposited (Suárez and De la Cruz, 1994). Sediment accumulation was terminated by Aptian deformation, uplift and erosion. This tectonic episode was followed, in the late Aptian, by a major andesitic to dacitic volcanic event which produced the unconformably overlying Divisadero Group.

Most outcrops of the Apeleg Formation comprise small cliffs of pale green or brown sandstone, interbedded with poorly exposed mudstones. The formation comprises approximately equal proportions of mudstone and well-sorted medium to fine-grained sandstone. The sediments are characterised by the mud-draped ripples and small-scale cross bedding of the heterolithic facies. Trace fossils and bioturbation are common, but body fossils are rare.

TABLE 1. STRATIGRAPHY OF THE COIHAIQUE GROUP.

Group	Formation	Lithology	Geological setting	Age
Divisadero		Andesitic and dacitic volcanics	Subaerial calc-alkaline volcanic arc	Upper Aptian - Albian
			Marine regression and uplift. Local unconformity	Aptian
Coihaique	**Apeleg**	**Sandstones, mudstones and minor conglomerates**	Tidal sandbars and muddy flats of epicontinental shelf	Mid to Upper Hauterivian - Barremian (possibly Lower Aptian ?)
	Katterfeld	Black shales	Still-water, anoxic marine embayment	Valanginian - Lower Hauterivian
	Toqui (= Cotidiano =Tres Lagunas)	Calcareous and clastic/ volcaniclastic sediments	Shoreline of active andesitic volcanoes	Upper Tithonian to Berriasian
			Marine transgression	
Ibáñez		Subaerial silicic volcanics	Volcanic arc	Kimmeridgian - Tithonian

[2] 1966. Geología de la región continental de Aysén (Unpublished). *Instituto de Investigaciones de Recursos Naturales-Corporación de Fomento de la Producción, Chile,* No. 20, 25 p.

DISTRIBUTION OF THE APELEG FORMATION

Exposures of the Apeleg Formation studied during the present investigation extend over an area of approximately 250 km from north to south and 50 km from west to east (between 44°30' and 47°S and 71° and 73°W). Exposures are limited, as in most areas the sediments are covered by younger successions. The most extensive exposures are located southeast of Ñireguao, near Villa Ortega and northeast of Lago La Paloma (Fig. 2). Strata displaying similar sedimentary facies are known to extend from 43° 30' to 50° S (Suárez and De la Cruz, 1996; De la Cruz *et al.*, 1996), a distance of 500 km from north to south. The remarkable uniformity of the sedimentary facies across the whole region of the present investigation, with no recorded evidence of lateral interfingering with basin-margin facies, indicates that the present-day exposures probably represent the remnants of a significantly bigger depositional basin. The north-south elongation of present-day exposures probably reflects the shape of the depositional basin.

The northern boundary of the Aisén Basin was a westward extension of the Somuncurá Massif (Fig. 1). The western boundary of the basin is currently formed by the intrusive granitoid complex of the Patagonian batholith. No strata equivalent to those

FIG. 2. Locality map, showing observation locations and the distribution of sediments of the Apeleg Formation in the area between 45° and 46°S.

of the Aisén Basin have been recorded from within or to the west of this batholith. This suggests that a volcanic chain, the roots of which are represented by the batholith, formed the western boundary of the basin. The eastern boundary of the basin is not exposed, but it is reasonable to assume that the strata continue towards the east beneath the cover of younger rocks. They probably interfinger towards the east with contemporaneous terrestrial sediments of the San Jorge Basin. Rivers from this basin, together with the metamorphic basement rocks and an active volcanic belt of the Somuncurá Massif, and the active magmatic arc in the west, provided sediment input into the northern Aisén Basin.

THICKNESS

The Apeleg Formation has a thickness in excess of 200 m over the whole region of the present investigation. The original maximum thickness is not known, because no sequence with both top and bottom exposed has been identified. In the type locality of the Coihaique Group near Coihaique Alto (locality ACB 225) an incomplete section of about 10 m of the Apeleg Formation is exposed. The measured thickness of sections is about 200 m at Cerro Bayo (ACB 250; Fig. 3) (González-Bonorino and Suárez, 1995); 500 m east of Ñireguao (ACB 217 (Fig. 4a) and ACB 212); about 70 m north of Coihaique (ACB 239) and 200 m in the south of the region (ACB136 and ACB 110). The thickness at ACB 65 northwest of Villa Ortega is estimated to be in excess of 1,000 m. Ramos (1981) recorded between 700 and 1,200 m in the Lago Fontana area of Argentina (45°S). Niemeyer *et al.* (1984) reported between 130 and 720 m of sandstones equivalent to the Apeleg Formation near Lago General Carrera (46°30'S).

AGE

The Apeleg Formation was deposited during midearly Cretaceous times. The middle to late Hauterivian ammonite, *Favrella americana*, is found near the base of the formation. Aptian ammonites have been recorded south of Lago General Carrera at about 46°45'S (the late Covacevich and De la Cruz, verbal communication, 1995), indicating that the formation possibly extends up into the early Aptian. No stratigraphically diagnostic fossils were collected from the upper parts of the succession, and the precise upper age limit is, therefore, not known. The age of the basal strata of the unconformably overlying Divisadero Group is late Aptian to Albian (M. Suárez and R. De la Cruz[1]).

BASE OF THE APELEG FORMATION

In Argentina, east of latitude 71°W and north of 45°S, the Apeleg Formation overlies the calcareous and clastic sediments of the Tres Lagunas Formation (Ploszkiewicz, 1987). However, both north (De la Cruz *et al.*, 1996) and south of this latitude it conformably overlies the Katterfeld Formation. In the area of the present study the contact between the Apeleg and Katterfeld Formations is well exposed north of Villa Ortega (Fig. 2, ACB 79) and in the Valley of the Río Simpson west of Cerro la Virgen (ACB 156). At both localities the contact is distinct and conformable. The base of the Apeleg Formation is marked by the appearance of small ripples of very fine to fine sand in the black shales of the Katterfeld Formation. Sand becomes more abundant upwards over several metres, with rippled sand forming beds up to 2 cm thick within the shales. The overlying Apeleg Formation consists of rippled sandstones and grey-brown shales which are quite distinct from the fossiliferous black shales of the Katterfeld Formation. At these localities, there is no evidence of lateral or large-scale vertica interfingering between the two formations.

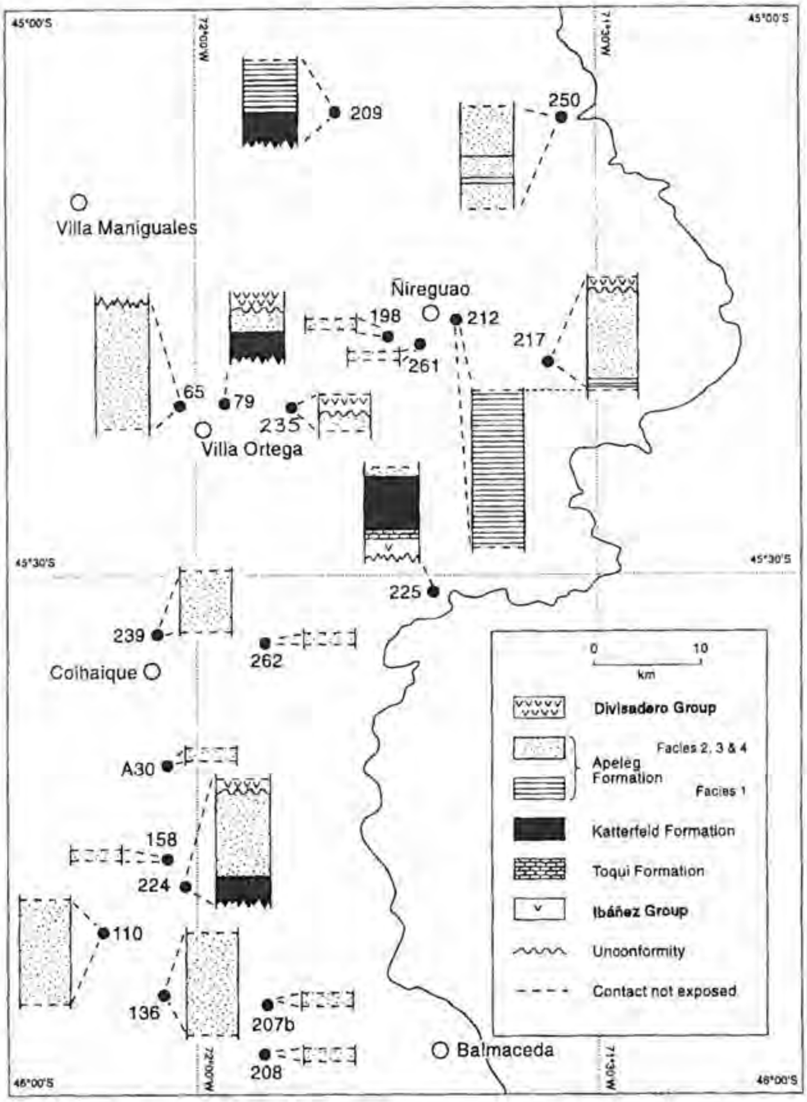


FIG. 3. Summary stratigraphic columns, showing the distribution of facies in the Apeleg Formation.

TOP OF THE APELEG FORMATION

The marine sediments of the Apeleg Formation are overlain by subaerial volcanic rocks and sediments of the Divisadero Group. Due to poor exposures there has been some controversy over the nature of this contact, in particular whether it represents an unconformity (M. Suárez and R. De la Cruz)[1]. In the northern part of the area of the present study, the contact is not exposed, and in places, rocks of the Divisadero Group appear to lie directly on the Katterfeld Formation. This implies that the Apeleg Formation was eroded prior to the deposition of the Divisadero Group. The strata of the Apeleg Formation exhibit steeper dips and more folding than those of the Divisadero Group, suggesting that an episode of deformation occurred between the deposition of the two successions.

An erosional contact between the Apeleg Formation and the Divisadero Group was observed at two localities. At ACB 79, 2 km north of Villa Ortega, an eroded surface of Apeleg sediments is overlain by 1 to 2 m of poorly-sorted, matrix-supported conglomerate, with clasts derived from the underlying succession. At ACB 306, approximately 10 km ENE of Villa Ortega, the unconformity is marked by 1 to 6 m of matrix-supported pebble conglomerate, tuffaceous sandstone and mudstone. Conglomerate clasts include angular to well-rounded fragments derived from the Apeleg Formation.

At ACB 155 (7 km NE of Lago La Paloma) and ACB 149 (west of Cerro La Virgen) the pale-green sandstones and mudstones of the Apeleg Formation are unconformably overlain by darker, red-coloured volcanogenic sediments of the Divisadero Group. Sediments of the Divisadero Group displaying erosion channels, cross-bedding, paleosols with rootlets and calcrete are interpreted as meandering river deposits. The change in sedimentary facies, from offshore tidal sediments of the Apeleg Formation to meandering river deposits of the Divisadero Group, indicates that this is a disconformable contact, equivalent to the unconformity observed farther north.

K-Ar biotite dates obtained from ignimbrites of the Divisadero Group exposed between latitudes 44° and 46°S, have given Upper Aptian and Albian dates (Harland *et al.* 1990 time scale). As Lower Aptian ammonites have been found in the Apeleg Formation at 46°45'S, it is possible that, locally, at least, the Divisadero Group and the Apeleg Formation were contemporaneous. The Divisadero Group volcanism possibly followed almost immediately after deposition of the Apeleg Formation, with no significant *hiatus* between the two units. Consequently the tectonic event that folded the Coihaique Group prior to accumulation of the Divisadero Group, was short-lived and local, and almost coeval with the initial stages of Divisadero volcanism.

FACIES AND FACIES DISTRIBUTION

FACIES F1: SHELLY MUDSTONE AND SANDSTONE

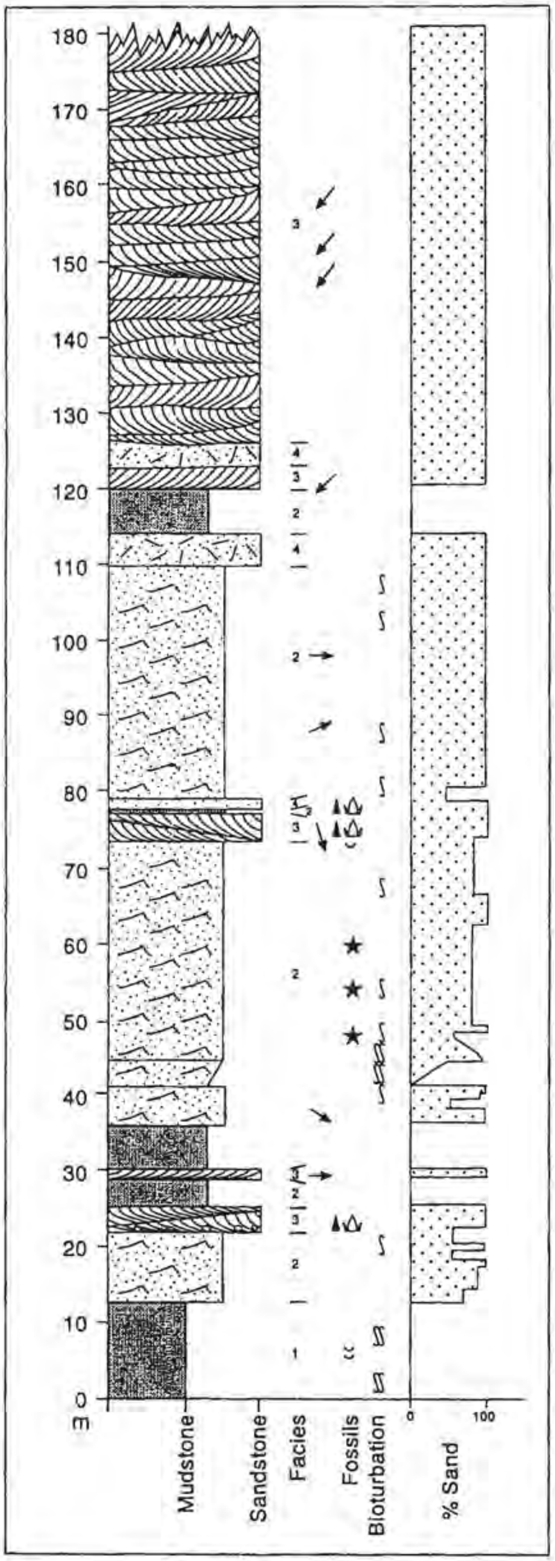
Shelly mudstones and sandstones of facies F1 comprise about 10% by thickness of the Apeleg Formation. Exposures are restricted to the northern part of the region, where the rocks form the base of the succession at Cerro Los Huemules (Figs. 2 and 3; ACB 209) and Ñireguao (Fig. 4; ACB 212 and ACB 217). East of Ñireguao (ACB 212), the facies possibly exceeds 300 m in thickness. Thin beds of shelly mudstone and sandstone also occur farther north within a predominantly sandy succession at Cerro Bayo (ACB 250; González-Bonorino and Suárez, 1995).

Facies F1 consists of mudstone with about 20% of very fine-grained glauconitic sandstone. The sediments are thinly and parallel bedded, with the sandstones showing small ripples and ripple cross-bedding. The sandstone is cemented with poikilotopic calcite and contains small septarian nodules (Table 2).

FACIES F2: HETEROLITHIC SANDSTONE AND MUDSTONE

About 80% of the sediment in the Apeleg Formation consists of the heterolithic facies F2 (Fig. 5). These sediments form uniform and monotonous successions of thinly-interbedded, rippled sandstone and mudstone (Figs. 5, 6, 7 and 8). Thin, parallel and laterally continuous layers up to several centimetres thick are amalgamated into homogeneous beds, varying from a few centimetres up to more than 20 m thick (Fig. 4). Some beds consist predominantly of sandstone, others of mudstone (Fig. 7). On average, the sediments comprise approximately equal proportions of sandstone and mudstone (Fig. 8). They range from parallel-bedded mudstones with thin elongated lenses of very fine sand, to well-sorted sandstones with very thin wisps of mud. Individual units, up to several metres thick, normally show a consistent sand to mud ratio (Figs. 4 and 7). Systematic vertical grain-size variations, or thickening or thinning sequences are very unusual. Figure 4 shows that there is no obvious cyclic sedimentation, or fining or coarsening sequences on a scale of metres or tens of metres. Most deposition occurred on flat surfaces and the contacts between beds are distinct and parallel (Fig. 9). There is little evidence of erosion or channeling.

The heterolithic sandstone and mudstone facies is characterised by mud-draped ripples. The most common structures are flaser and lenticular bedding (Reineck and Wunderlich, 1968). Ripples are very



a. ACB 217 East of Ñireguao

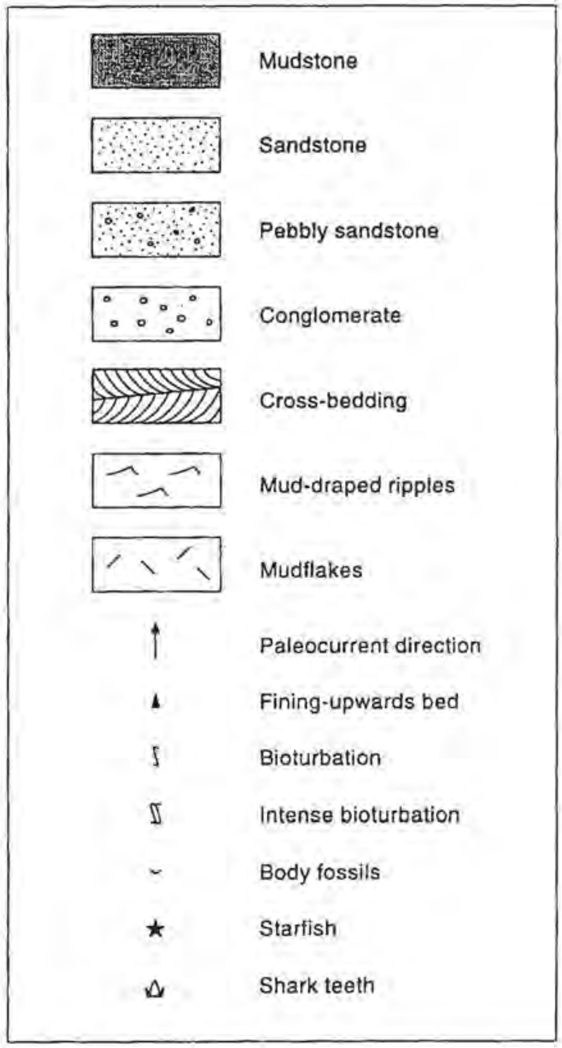
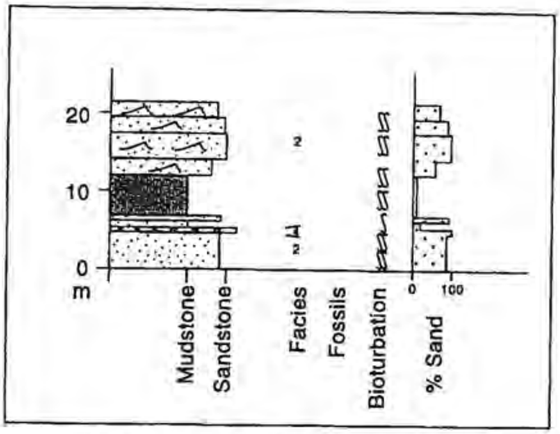
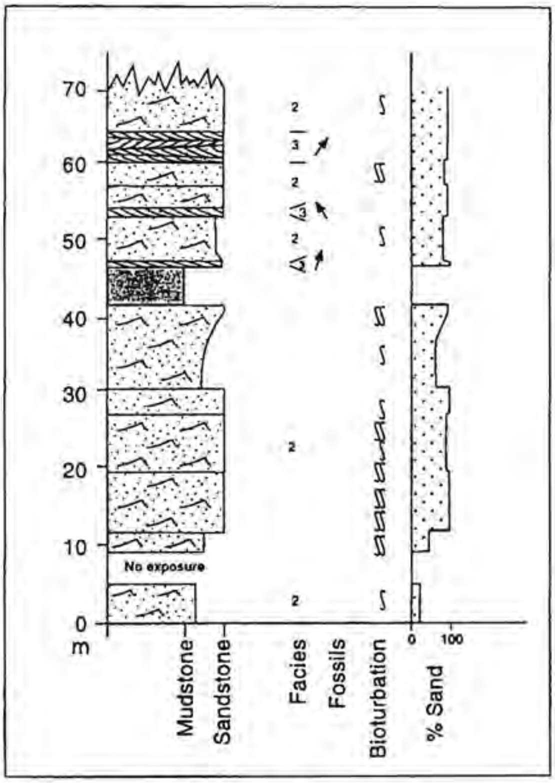


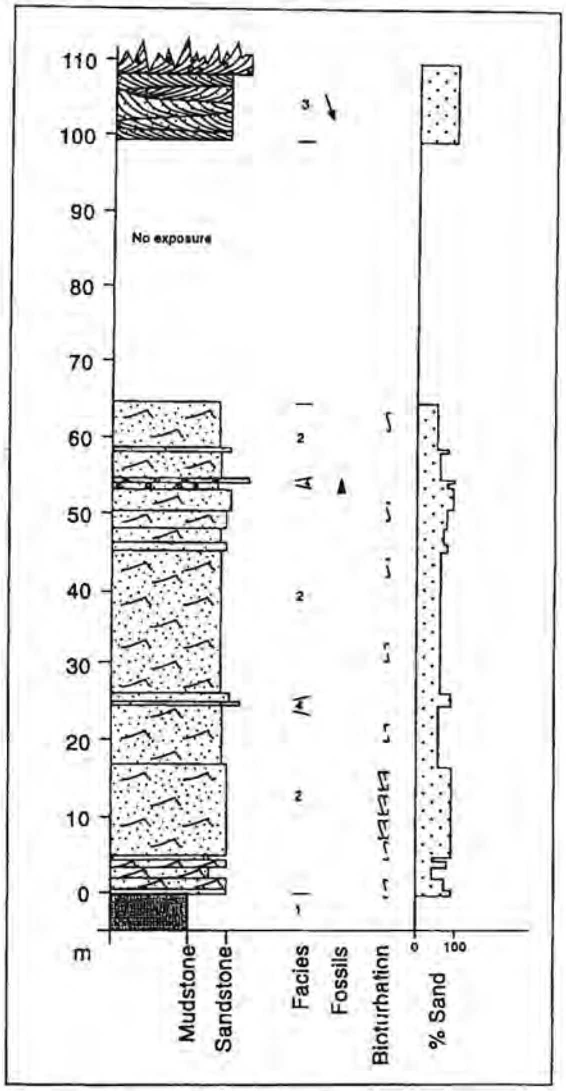
FIG 4. Detailed measured stratigraphic columns showing the distribution of facies at five localities.



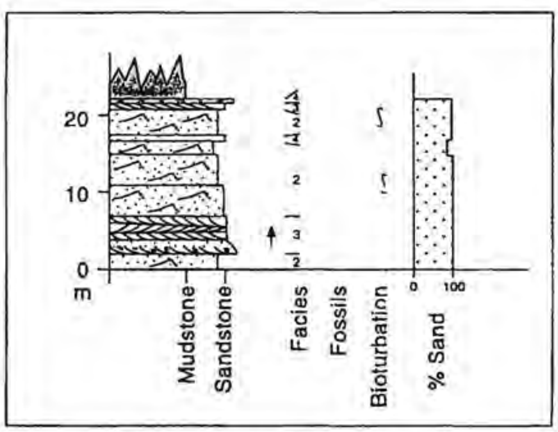
b. ACB 198 Southwest of Ñireguao



c. ACB 239 North of Colhaique



d. ACB 224 and 158 North of Lago La Paloma



e. ACB 207b West of Balmaceda

uniform in scale and appearance throughout the succession. In cross-section, they are gently undulating with a low height to wavelength ratio. Most are slightly asymmetrical with rounded crests and troughs. The height varies from 0.3 to 2 cm, with an average of 0.7 cm. Wave length ranges from 5 to 12 cm, with an average of 7 cm. Due to the uniformity of the sediment no distinct internal structures can be seen in most of the ripples. Ripple cross-laminations are very fine and low angled. Although the orientation of cross laminations can seldom be measured, some sets display a bi-modal pattern, possibly as a result of the reversal of current directions. In many places the ripples nest together into amalgamated sets up to several metres thick. In plan view, the ripple crests are discontinuous and irregularly curved to linguoid (Fig. 10). Straight or continuous crests are very rare. The troughs between ripples often show accumulations of mud, small mud flakes or small rounded fragments of carbonized plant debris.

Load casts and convolute laminations are rare. Thin and irregular mud cracks (Fig. 11) are common in thin mudstone beds and in the mud-drapes between ripples. They probably represent subaqueous synaeresis or diastasis rather than subaerial desiccation cracks (Astin and Rogers, 1991; Cowan and James, 1992). Rounded mudstone clasts or mudflakes (intraclasts or rip-up clasts), up to 10 centimetres long, are common.

FACIES F3: CROSS-BEDDED SANDSTONE

Cross-bedded sandstones of facies F3 form between 10 and 20% of the Apeleg Formation. The erosionally resistant sandstones form pale green-coloured cliffs about 5 to 10 m high. The well-sorted, fine to medium grained sandstones are lithologically identical to those in facies F2. There is a small proportion of mudstone and rare coarse sand and granules.

Cross-bed sets range from a few centimetres up to 90 cm in thickness, with an average of about 15 cm (Fig. 12). The contacts between sets are both curved and parallel, forming trough and tabular cross-sets. Some cross-beds form lens-shaped sets separated by scoured surfaces. Foreset laminations are generally at low angles, well below the angle of repose, and are either straight or gently asymptotic. In plan view, the dunes have irregular crests with a cuspate to lobate form. The wave length is between 1 and 2 m and the height between 0.1 and 0.5 m. Many dune foresets have superimposed ripples, separated by thin mudstone drapes and mud-draped foreset laminations. At some localities the intersecting, low-angle foresets resemble hummocky cross stratification, but no good examples of these structures were recorded. Thin erosional lags, consisting of well-rounded pebbles of mud, volcanic and metasedimentary rocks, together with small sharks teeth and bone fragments, form the base of some cross-bedded units (ACB 224, 55m in Fig. 4d; ACB 217, 75 m in Fig. 4a). Mudflakes orientated parallel to foreset laminations are concentrated near the base of the foresets. At locality ACB 158 a 0.5 metre deep channel with an irregularly eroded base forms a mud-filled lens within the cross-bedded sandstones.

FACIES F4: STRUCTURELESS SANDSTONE AND MUDFLAKE BRECCIA

Structureless sandstones and mudflake breccias of facies F4 form isolated beds, between 15 cm and 4 m thick, within facies F2 and F3. The sandstones display water-escape cusps and convolute laminations. The mudflake breccias consist of mudstone fragments up to 20 cm long in a structureless sandstone matrix.

FOSSILS

Abundant marine fossils are concentrated in beds of parallel-bedded sandstone a few centimetres thick in facies F1 east of Ñireguao. Most of the unbroken and articulated shells are scattered through the sandstone. The fauna, best preserved in nodules at locality ACB 212, includes gastropods (*Turritella* and *Natica*), bivalves (*Entolium argentinium, Pleuromya, Panopea, Protocardia?, Steinmanella, Pterotrigonia, Chlamys octoplicatus, Pinna patagoniensis*) and adult and juvenile forms of the ammonite *Favrella americana.* Shales at the base of the succession at ACB 217 contain bivalves

TABLE 2. FACIES IN THE APELEG FORMATION

Facies	Facies name	% of Formation	Lithology	Sedimentary structures	Fossils	Interpretation
F1	Shelly mudstone and sandstone	10-20%	Vary fine grained glauconitic sandstone and mudstone.	Septarian nodules. Thin parallel beds, asymmetrical ripples	Unbroken, articulated shell concentrations. Gastropods, bivalves ammonites. Plant fragments.	Marine, normal salinity, oxygenated, photic zone. Sediment transport by tidal currents. Deposition from traction and suspension. Prodelta flats, offshore shelf below storm wave base.
F2	Heterolithic sandstone and mudstone.	70-80%	Well-sorted, fine to medium-grained glauconitic lithic arenite and mudstone.	Thinly-interbedded rippled sandstone and mudstone in thick, parallel-bedded sequences. Muddraped ripples. Mud flakes.	Well-preserved trace fossil assemblage. Some intense bioturbation. Shark teeth. Very few calcareous shells. Plant debris.	Marine norma salinity, oxygenated. Ripples from low flow regime tidal currents alternating with settling from suspension. Flanks and inter-bar areas of offshore tidal sandbars. Below storm wave base.
F3	Cross-bedded sandstone	10-20%	Well-sorted fine to medium grained glauconitic lithic arenite. Some mud and coarse sand.	Small-scale trough and tabular cross bedding. Dunes have superimposed ripples and mud drapes.	Trace fossils including *Ophiomorpha*, *Thalassinoides* and *Rhizocorallium*. *Teredo* borings. No calcareous shells.	Marine, normal salinity, oxygenated. Migrating small-scale linguoid dunes on crests of offshore tidal sandbars. Below storm wave base.
F4	Structureless sandstone and mudflake breccia	-1%	Fine to medium-grained sandstone and mudflake breccia.	Isolated beds within F2 and F3. Water-escape cusps, convolute laminations. Mudflakes in structureless sandstone.	None recorded	Rare dilute mass-flow events resulting from storms or slumping.

(*Steinmanella herzogi, Trigonia, Protocardia, Entolium argentinum, Pecten* and oysters), ammonites (*Favrella americana*) and abundant gastropods (*Natica*). The fauna at Cerro Bayo (ACB 250) includes the ammonite *Favrella* and small, articulated and unbroken bivalves (*Lucina, Astarte, Pleuromya* and *Steinmanella*). Many shells are preserved as casts and impressions. Abundant plant debris includes elongated carbonized fragments and impressions up to 20 cm long. Plant fossils are also common as small rounded fragments in the troughs of ripples.

Trace fossils are a distinctive feature of the Apeleg Formation. Some beds are intensely bioturbated, but others are undisturbed (Fig. 15). Trace fossils in facies F1 include *Chondrites, Thalassanoides, Arenicolites, Gyrochorte, Skolithos?* and *Planolites?* The alternating thin beds of mudstone and sandstone of facies F2 and F3 display exceptionally well preserved trace fossils. The most distinctive and widely developed are the double tracks of *Gyrochorte comosa* (Fig. 10) and the bulbous *Lockeia* (also known as *Pelecypodichnus*, Figs. 11 and 16). The sand-filled burrows, lined with pellets of mud and plant debris, cf crustaceans (*Ophiomorpha irregulari* and *Ophiomorpha nodosa*) are common in facies F3. Other trace fossils include the beautifully-preserved resting traces of starfish (*Asteriacites lumbricatis*); the tracks, resting traces and burrows of ophiuroids; *Helminthoides; Thalassinoides; Rhizocorallium; Diplocraterion; Arenicolites; Ancornichnus; Scolicia?; Loevicycius; Skolithos; Planolites beverliensis* and *Planolites montanis; Phycoides palmatus?; Syringamorpha?; Uchirites?; Helminthopsis* and *Taenidium*.

Vertebrate fossils were recorded at three localities. A 20 cm long water-worn fragment of

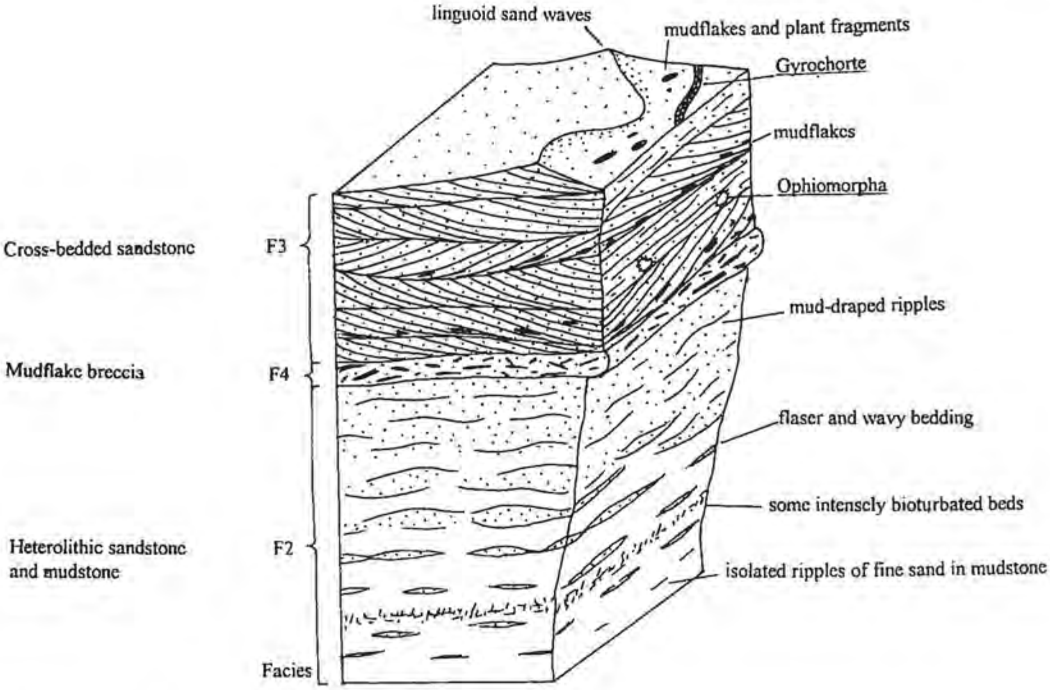


FIG. 5. Diagrammatic sketch of facies F2, F3 and F4.

FIG. 6. Parallel bedded sandstone and mudstone of the Apeleg Formation at ACB 239 (measured section Fig. 4c).

reptile bone was found at Cerro Bayo (ACB 250). Pebble lag deposits at locality ACB 217 contain fish scales, a tooth fragment probably from a marine reptile, a 3.5 cm long shark fin spine, and numerous small (less than 11 mm long) bladed and pointed shark teeth. The fin-spine has a highly fractured surface covered in unornamented enameloid. It can be assigned to either of the neoselachian groups (Squalidae or Heterodontidae). The teeth are tricuspid with flattened labial facies and rounded ligual faces. The smooth nature of the enameloid cap covering the denticles and the overall morphology indicates that they are from lamnid sharks (Sansom, personal communication, 1997). A pebble lag at ACB 224 contains small shark teeth and bone fragments.

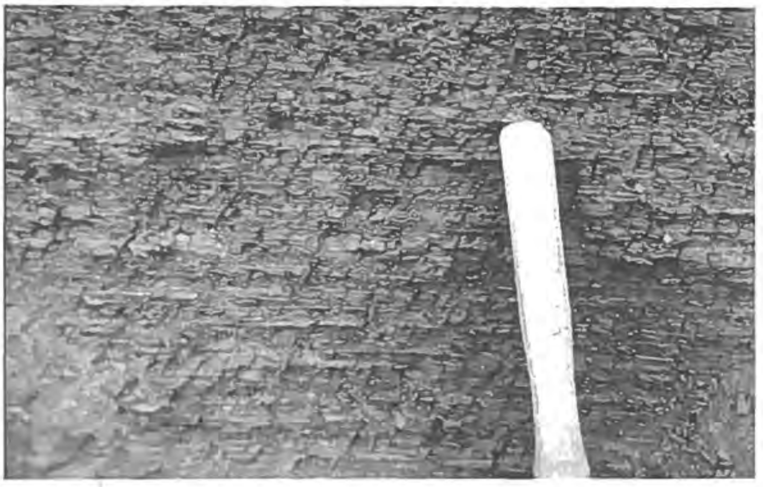


FIG. 7. Flaser-bedded mudstones and fine-grained sandstones of facies F2. Note the thick and uniform nature of the bedding (location at 10 m in Fig. 4c, ACB 239).

FIG. 8. Interbedded rippled sandstones and shales of facies F2 (location at 1.5 m in Fig. 4c, ACB 239).

FIG. 9. A typical sharp and straight contact between rippled sandstones and mudstones of facies F2 (location at 40 m in Fig. 4a, ACB 217).

Plant fossils, in the form of small flakes of carbon, and larger elongated, parallel-grooved fragments (preserved both as films of carbon and impressions) are very common throughout the succession. Ramos (1981) and Ploszkiewicz (1987) recorded silicified fragments of transported wood, carbonaceous shales and thin coal horizons in the Lago Fontana area. Most plants consist of rounded and water-worn fragments lying parallel to bedding planes. No distinctive leaf structures were recorded. One large wood fragment impression at Cerro Bayo displayed *Teredo* borings.

FIG. 10. Linguoid, asymmetrical ripples of facies F2 with a track of *Gyrochorte comosa* (location ACB 224).

FIG. 11. Thin and irregular sand-filled cracks produced by the subaqueous desiccation of a thin layer of mud. Blob-shaped structure is the trace fossil *Lockeia* (location ACB 224).

FIG. 12. Tabular cross-bedding in coarse-grained sandstone of facies F3 at location ACB 262.

SANDSTONE COMPOSITION

Twenty five specimens of sandstone from the Apeleg Formation were studied in thin section. The samples were selected to give a maximum spread of lithologies and a broad stratigraphic and geographical distribution. The rocks display a remarkable uniformity of texture and composition. All the sandstones are texturally mature, but compositionally immature lithic arenites. Most are fine to very fine-grained. A few specimens are medium to coarse grained and contain isolated granules and pebbles, together with mud flake intraclasts. The sandstones are moderately to very well sorted, with the grains in individual laminations all falling into one grain-size category. Matrix is very rare or absent. Most grains are subangular to subrounded.

Quartz comprises between 5 and 10%. About half the grains are single unstrained crystals derived from a volcanic source. The remainder are composite grains derived from mica schist, quartzite and vein quartz. Feldspar comprises between 20 and 40%; the majority is plagioclase together with a little microcline. Lithic clasts comprise between 30 and 80%, most are extensively altered fine-grained basic volcanic rocks with trachytic, porphyritic and vitric textures. About a quarter of the lithic grains consist of low to medium-grade metasediments. They include muscovite schist, quartz-muscovite schist, quartz-muscovite-garnet schist and quartzite, probably derived from the Paleozoic metamorphic basement rocks of the region. Plutonic and sedimentary clasts are very rare.

The sandstones contain between 5 and 10% of glauconite in the form of fine-grained, well-sorted grains with a rounded, globular shape and structureless texture. Accessory and heavy minerals are rare, forming less than 1%. Most specimens contain muscovite, zircon and opaque minerals together with some biotite and tourmaline. Many sandstones contain small carbon flakes, some exhibiting distinctive plant textures.

SANDSTONE DIAGENESIS

The Apeleg Formation sandstones display a complex diagenetic history. They are compacted and well-cemented with no obvious pore spaces. Most grains show three or four straight to concavo-convex contacts. Overgrowths on quartz and feldspar commonly mask the original grain shape. Some grains of mica, glauconite, mudstone and fine-grained volcanic material are distorted, but there is little other evidence of strain. Feldspar and basic volcanic clasts show extensive alteration to chlorite, clay and sericite. Many clasts have well-developed rims of radiating chlorite which developed after compaction. Abundant chlorite is also present as a replacement and cementing mineral, giving the sandstones their characteristic green colour. Development of chlorite rims was followed by cementation by quartz, chalcedony and calcite. Quartz normally forms optically continuous overgrowths, but in some specimens these overgrowths were inhibited by the chlorite rims. Calcite forms partial or complete grain replacement and pore infilling, in the form of irregular patches and poikilotopic crystals. A final stage of diagenesis is represented by iron oxide staining. In many places the oxidation of small pyrite crystals has produced iron staining adjacent to plant material.

The early authigenic suite of minerals, including chlorite, is characteristic of the diagenesis of marine sandstones (Tucker, 1991). The growth of chlorite rims, following adjustment of grain contacts by mechanical compaction, but prior to the beginning of quartz cementation, probably occurred during diagenesis within the first 2 km of burial (Ehrenberg, 1993). Quartz cementation followed burial to depths in excess of 2.5 to 3 km (Bjørlykke and Egeberg, 1993). The sequence of clay authigenesis associated with quartz overgrowths, and followed by carbonate precipitation, is typical of near-surface alteration (Burley *et al.*, 1985). The sediments show no secondary metamorphic or tectonic fabric, and mineral veins and breccias are uncommon. The diagenetic history of these rocks indicates that compaction, cementation and alteration was associated with marine formation waters and burial. There is little evidence of significant metamorphism, deformation or hydrothermal activity. The only exception to this is specimens from location ACB 225 which display extensive alteration, together with veins of epidote, quartz and calcite and a weak metamorphic fabric, probably related to a zone of faulting.

PALEOCURRENTS

Ninety eight dune foreset laminations, mostly recorded from facies F3, show an overall random pattern of paleocurrents (Fig. 13). Individual cosets show a unimodal pattern and in some cases a change in direction can be detected within a vertical succession (Fig. 4a). The currents show variations in orientation both over the whole area and within smaller sub-areas (for example east of Ñireguao). The data suggest a preferred direction of sediment transport towards the north and east at the base of the succession and towards the west near the top. This may indicate a change from a westerly to an easterly sediment source with time. González-Bonorino and Suárez (1995) recorded 100 foreset lamination orientations from the Cerro Bayo area. These showed a strong unimodal current direction towards the west.

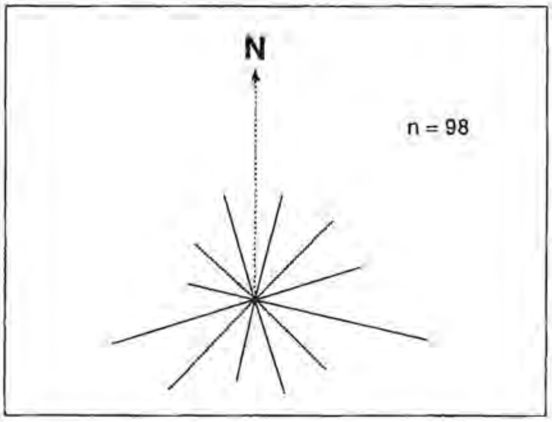


FIG. 13. Orientation of paleocurrents, indicated by the direction of maximum inclination of foreset laminations in sandstones. 98 observations showing no preferred orientation.

INTERPRETATION OF THE DEPOSITIONAL ENVIRONMENT

Mud-draped ripples and foreset laminations, together with the alternation of rippled sandstone and mudstone successions, indicate that most of the Apeleg Formation was deposited by tidal currents (Dalrymple, 1992). Currents, which were sufficiently strong to rip up mudflakes and form small migrating dunes, alternated with slack water. The heterolithic facies resulted from the deposition of sand ripples from low flow-regime tidal currents, alternating with the settling of mud from suspension during tidal slack water (Thomas *et al.*, 1987). The distinctive low amplitude liguoid ripples (Fig. 9), are the stable equilibrium structures developed by steady flow at low current velocities (Baas, 1994; Oost and Baas, 1994).

Cross-bedded sandstones were produced by the migration of small-scale linguoid dunes. Unimodal paleocurrents possibly reflect a dominance of either ebb or flood tides. Although tidal currents are usually bi-directional, they commonly produce deposits with a unimodal pattern (Dalrymple, 1992). The unimodal sets of paleocurrent data (Fig. 14) may represent the migration of individual sand bars. The regionally variable currents provide no evidence for the position or orientation of the shoreline, or for the overall direction of sediment transport.

The thick and uniform successions of sandstone and shale indicate that, with the exception of tidal variations, energy levels were constant over long periods of time. Currents were sufficiently strong to rip up and transport mudflakes, yet the preservation of mud-drapes, together with the ripple form, indicates that currents were generally of low strength. The combination of evidence for tidal deposition and the absence of hummocky cross bedding suggests that most deposition took place in relatively shallow water below storm wave base (between

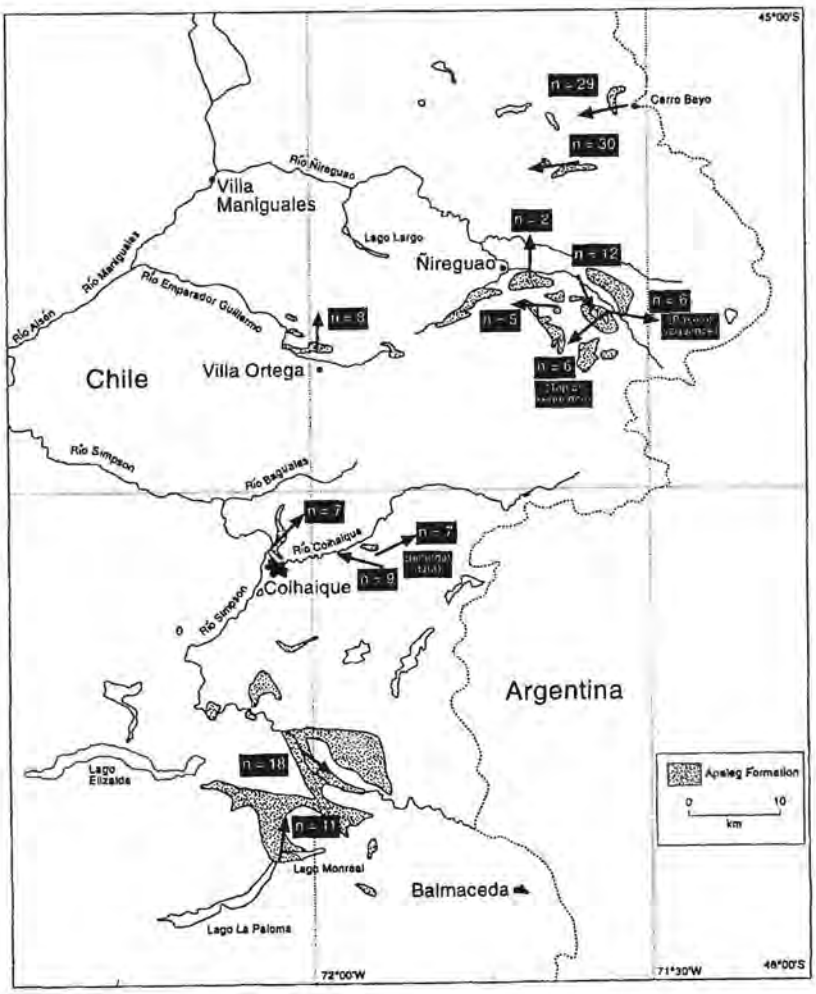


FIG. 14. Paleocurrents directions. Averages of data recorded mainly in facies F3. Individual locations and parts of sections show a preferred orientation, but the overall pattern is very variable. The two northern locations are from the work of González-Bonorino and Suárez (1995).

FIG. 15. Intensely bioturbated sandstone of facies F2 at location ACB 239.

FIG. 16. The trace fossil *Lockeia* (location ACB 224) .

about 30 and 100 m) and under calm meteorological conditions (Belderson *et al.*, 1982). Tidal currents sufficiently strong to produce ripples and dunes in water depths below storm wave base may represent the amplification of the tidal wave within a narrow gulf or strait (Bridges, 1982).

The structureless sandstone beds of facies F4 are interpreted as the products of dilute mass-flow events. Apart from these beds, there is no evidence of turbidity current or mass flow transport or deposition. A flat and tectonically stable depositional environment is also indicated by the virtual absence of soft-sediment deformation structures.

The sandstones were probably deposited on linear tidal sandbars or sand ridges similar to those described from the Cretaceous Sussex and Shannon sandstones of the western interior seaway of the USA (Bergman, 1994; Bergman and Walker, 1995; Berg, 1975; Swift and Rice, 1984; Shurr, 1984; Stride, 1982; Swift *et al.*, 1991), the Cretaceous Lower Greensand of Europe (Narayan, 1971) and the present-day North American Atlantic shelf (Davis *et al.*, 1993; Davis and Balson, 1992; Swift *et al.*, 1979; Swift and Field, 1981). The sandbars were probably kilometres in length and up to 20 m high, with very gentle gradients (Johnson and Baldwin, 1986;

Dalrymple, 1992). Rippled sediments of facies F2 were deposited on the flanks of the sandbars, with the cross-bedded sandstones of facies F3 produced by migration of megaripples along the bar crest (cf. Tillman and Martinsen, 1984). Between the bars, there were flat areas with finer-grained sediment and lower rates of sedimentation indicated by more intense bioturbation. Lag deposits resulting from winnowing at the bar crests form the base of overlying units of cross-bedded sandstone. The sediments show no evidence for beach, shoreface or exposed tidal flat deposition (Walker and Plint, 1992) supporting the suggestion of deposition in an offshore tidal environment (Berg, 1975; Swift and Rice, 1984; Shurr, 1984; Tillman and Martinsen, 1984).

The fossils indicate a well oxygenated and biologically productive marine environment of normal salinity within the photic zone. Most fossils, except the ammonites, plants and vertebrates, are *in situ*. Articulated shells in facies F1 show no evidence of current or wave reworking.

Body fossils, or the impressions, casts or moulds of body fossils are extremely rare in facies F2 and F3. This scarcity of calcareous fossils in a near-shore marine environment of normal salinity may be the result of early diagenetic solution of carbonate shells by acid pore waters. An alternative explanation is that shelly organisms were unable to survive in a biologically hostile environment produced by shifting fine sediment and muddy water.

The trace fossils in facies F1, F2 and F3 are characteristic of a shallow marine environment, at or near wave base. A closely comparable assemblage has been described from the shallow-marine shelf sediments of the Lower Jurassic Neill Klinter Formation of East Greenland (Dam, 1990a, b). The uniform and intense bioturbation of some parts of the Apeleg Formation suggests slow and steady rates of sediment accumulation. Much of the bioturbation is the product of the bedding-parallel traces of infaunal deposit feeders (fodichnia and pasichnia). *Teredo* borings and water-worn fragments indicate that plant fossils represent land-derived drift wood. Modern lamnid sharks are largely pelagic, but do frequent coastal waters. Some live in the bathyal zone down to 800 m (Sansom, personal communication, 1997).

The abundant plants and clay point towards input by a muddy river or delta system from a densely vegetated area. Glauconite indicates relatively low rates of sedimentation on a marine continental shelf.

A very distinctive feature of the Apeleg Formation is the remarkable uniformity of the sedimentary facies and trace fossil assemblage across the whole area of the present investigation. This indicates that the depositional environment was common to a large area and remained constant, with little variation in energy levels or depositional processes, over a long period of time. The absence of lateral variations in the sedimentary facies also indicates that the outcrops represent only part of what must have been a much larger basin. The thick succession of relatively shallow-water sediments indicates that subsidence and deposition kept pace with one another. Sandstone composition indicates derivation from a volcanic arc developed on a continental basement of low-grade metasedimentary rocks. Volcanic activity kept pace with the supply of sediment as there is no evidence of the unroofing of plutons.

HYDROCARBON POTENTIAL

The depositional environment and tectonic setting of the Apeleg Formation is comparable with hydrocarbon-bearing strata, in particular the Cretaceous Sussex and Shannon sandstones of the western USA (Berg, 1975; Swift and Rice, 1984; Shurr, 1984). This suggests that the Apeleg Formation may have a hydrocarbon trapping potential. Organic material in the form of carbon flakes is common, and the sandstones are underlain by a thick succession of black, organic-rich marine shales of the Katterfeld Formation. Specimens of shale near the top of the sequence at ACB 217 (Fig. 4a) produced a strong hydrocarbon smell. There is, however, no evidence of organic coating of sandstone grains to indicate the presence or migration of hydrocarbons. In addition, the textural transformations, typical of the diagenesis of dominantly volcanic and volcaniclastic sediment, have produced a very low porosity and hence a poor reservoir potential.

PALEOGEOGRAPHY AND TECTONICS

The Apeleg Formation forms the uppermost succession of the Coihaique Group which was deposited in the Aisén Basin, a relatively shallow epicontinental sea, during Lower Cretaceous times. This sea formed as a retroarc basin (Busby and Ingersoll, 1995) to the east of an active magmatic arc on the continental margin. The north-south elongated Aisén Basin probably extended towards the south into the northern section of the Austral Basin (Biddle *et al.*, 1986). This retroarc setting is analogous to the larger Cretaceous western interior seaway of North America (Ericksen and Sligerland, 1990; Gill and Cobban, 1973; Leithold, 1994; Swift and Rice, 1984).

In the area of the present investigation the sedimentary rocks of the Coihaique Group are sandwiched between two volcanic succcessions. The lower of these is the late Jurassic to earliest Cretaceous Ibáñez Group (Covacevich *et al.*, 1994). Regionally widespread volcanism was related to continental rifting (Gust *et al.*, 1985) and subduction on the continental margin (Suárez and De la Cruz, 1994). A marine transgression across the active volcanic centres produced the algal reefs and oyster banks of the Toqui Formation. Conformably above this calcareous succession are the thick black shales of the Katterfeld Formation which represent marine sedimentation below wave base, in a partly enclosed basin with restricted circulation. The abundant carbonaceous material and restricted fauna indicate low oxygen levels.

The abrupt transition from the Katterfeld to the Apeleg Formations resulted from a change from a poorly-oxygenated restricted marine basin to an open marine environment. The change may have resulted from the opening up of the basin to an expanding and tide-generating sea, possibly related to higher sea levels, or to the opening of the South Atlantic Ocean.

Sediment in the Apeleg Formation was derived from a volcanic arc developed on a metamorphic continental basement. The abundant clay and plant fossils indicate a temperate climate and dense vegetation. Sediment was transported into the shallow epicontinental sea by a major river or delta system and redistributed by strong tidal currents.

The Apeleg Formation is unconformably overlain by a maximum of about 1,000 m of subaerial lavas, tuffs and volcaniclastic sediments of the Divisadero Group (Niemeyer *et al.*, 1984; Suárez and De la Cruz , 1994). However, the diagenetic features of the sandstones are indicative of burial in excess of 2 or 3 km. This suggests that a much greater stratigraphic thickness, which has since been removed by erosion, must have overlain the formation.

Niemeyer *et al.* (1984) suggested a peak of magmatic activity in the Patagonian batholith, to the west of the Aisén Basin, between about 120 and 130 Ma, coinciding, at least in part, with the deposition of the Apeleg Formation. Radiometric data indicate that magmatic activity ranged from 160 to 9 Ma (Niemeyer *et al.*, 1984) with a major episode between 128 and 100 Ma. This timing indicates that subduction-related magmatism was contemporaneous with the deposition of the Apeleg Formation. Volcanic activity dominated the formation of both the Ibáñez and Divisadero Groups, but was less important during the deposition of the Coihaique Group. However, the presence of tuffaceous sandstones in the Apeleg Formation, together with a volcanic provenance for much of the clastic debris, indicates that magmatic activity continued during the deposition of the Coihaique Group. The Apeleg Formation is lacking in soft-sediment deformation structures, and there is little evidence of turbidity current or mass-flow deposition. These features suggest slow rates of sedimentation on flat surfaces in a tectonically stable area.

Despite the evidence for an active subduction zone to the west, the Aisén Basin was characterised by regionally uniform depositional conditions with slow rates of sedimentation and a lack of seismic activity. These features point towards an origin as a thermal sag rather than by tectonically driven subsidence.

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