THE CHINCHES FORMATION: AN EARLY CARBONIFEROUS LACUSTRINE SUCCESSION IN THE ANDES OF NORTHERN CHILE

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RESUMEN

Rocas metasedimentaria de probable edad carbonífera inferior afloran en dos franjas entre los 25° y 29° S en el norte de Chile. La más occidental está formada por turbiditas con intensa deformación, rocas volcánicas básicas y un "mélange" tectónico, y están ubicados 100 km al oeste de los afloramientos menos deformados de la Formación Chinches, que constituyen la franja oriental.

La Formación Chinches es una serie de rocas sedimentarias clásticas, de grano fino, que alcanzan un espesor mínimo de 2.500 m. Las tres facies sedimentarias que la constituyen corresponderían a depósitos de relleno de una cuenca lacustre profunda. La facies dominante es una secuencia monótona de lutitas laminadas y areniscas con estratificación paralela, dispuesta en unidades de hasta 1.000 m de espesor, acumuladas en un ambiente lacustre profundo. Las rocas de este grupo están cubiertas por siltitas con "ripple marks" y areniscas de grano muy fino, que forman unidades de 25 m de potencia. La mayoría de los "ripples" se formó por la actividad de las olas, encontrándose fenómenos de interferencia, que indican frecuentes cambios en la dirección del viento. En esta facies se encontraron escasas impresiones vegetales y trazas, junto a las huellas de un anfibio. Su origen se interpreta como el producto de sedimentación en "lake flats" expuestos a la acción del viento. La tercera facies, en unidades de hasta 20 m de espesor, está formada por areniscas con estraficación cruzada, junto a delgados niveles de calizas oolíticas, pisolíticas y estromatolíticas. Estas rocas representan, probablemente, a depósitos lacustres costeros, expuestos a la acción del viento.

La fracción detrítica de la Formación Chinches, predominantemente andesítica y riolítica, indica la cercanía de un arco magmático, mientras que los depósitos contemporáneos de la Cordillera de la Costa representan una asociación de prisma de acreción. El gran espesor de los sedimentos lacustres de la Formación Chinches, acumulados en un margen continental activo, podría indicar que ésta representa el relleno de una cuenca "pull apart", producida por movimientos de rumbo asociados con subducción oblicua.

ABSTRACT

Low-grade metasedimentary rocks of probable early Carboniferous age occur in two north-south elongated strips in the region between 25° and 29° S in northern Chile. The western, coastal strip consists of intensely deformed turbidites, basic volcanic rocks and a tectonic "mélange". These rocks are separated by a 100 km-wide graben from the less-deformed Chinches Formation in the east.

The predominantly fine-grained clastic sedimentary rocks of the Chinches Formation have a minimum thickness of 2,500 m. The three sedimentary facies which comprise this formation are believed to be the product of the infilling of a deep lake. The dominant facies comprises thick, monotonous sequences of laminated shales and parallel-bedded sandstones, in units up to 1,000 m thick. These are interpreted as a deep-water lacustrine deposit. Rocks of this facies are overlain by well-sorted, ripple-marked and parallel-bedded siltstones and very fine-grained sandstones, in units up to 25 m thick. Most of the ripples originated by wave activity, with interference sets indicating frequent changes in wind direction. Fossils include rare plant impressions, the tracks of an amphibian and other sparse trace fossils. The facies is interpreted as the product of deposition in shallow-water wind-dominated lake flats. The third facies, in units up to 20 m thick, comprises cross-bedded sandstones, together with thin oolitic, pisolithic and stromatolitic limestone. These rocks were probably deposited on a wave-exposed lake shore.

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The dominantly andesitic and rhyolitic provenance of the Chinches Formation is indicative of an adjacent volcanic arc, and contemporaneous deposits of the coastal region were probably deformed in an accretionary wedge. This indicates that the region was an active continental margin in early Carboniferous times. The great thickness of lacustrine sediments, deposited on an active continental margin, suggests that the Chinches Formation infilled a pull-apart basin produced by strike-slip movement associated with oblique subduction.

INTRODUCTION

This study of the Chinches Formation forms part of an investigation into the Paleozoic metasedimentary basement of the Andean complex in the area between 25° and 29° S in northern Chile. Paleozoic rocks in this area form two north-south elongated strips, separated by a 100 km-wide graben infilled with younger rocks (Fig. 1). The low-grade metasediments in each strip exhibit contrasting depositional and tectonic environments. In the western, coastal region are intensely-deformed deep-sea turbidites and basic volcanic rocks of the Las Tórtolas Formation and the Chañaral "mélange" (Bell, 1982, 1984), whereas in the Andean region in the east are the less-deformed clastic sediments of the Chinches Formation (Mercado, 1982).

The investigation reported here was carried out in April 1983, in association with geologists of the Servicio Nacional de Geología y Minería.

The rocks belonging to this formation at Quebrada Chinches were first found and described by Davidson *el al.* (1978). The unit was subsequently mapped and studied farther south in El Patón area by Muzzio (1980). Descriptions of equivalents successions in the Maricunga-Pedernales area were previously made by Segerstrom (1967), Kubanek and Zeil (1971), Cisternas (1977) and Cisternas *et al.* (1978). The outrops southwest of Salar de Maricunga were included in 1:100.000 scale regional maps by Mercado (1982) and Sepúlveda and Naranjo (1982).

The Chinches Formation has been tentatively correlated with other occurrences of late Paleozoic rocks in northern Chile and northwestern Argentina. These include the Las Placetas Formation (Reutter, 1974) in the interior of Vallenar (29° S), sediments in Río Hurtado (31° S) (Cornejo and Mpodozis, 1979) and other sequences extending southwards to 35° S (Caminos, 1979; Hervé *et al.*, 1981).

AGE AND DISTRIBUTION OF THE CHINCHES FORMATION

The Chinches Formation is preserved as a number of fault-bounded blocks and as roof pendants in a massive Paleozoic batholith. Davidson *et al.* (1978), Mpodozis and Davidson (1979), Muzzio (1980), and Mercado (1982) concluded, on the basis of regional correlations, that the formation was Devonian or Carboniferous in age. The base of the formation is unknown, but it is unconformably overlain by sedimentary and volcanic rocks of possible Carboniferous to Permian and younger ages (Mpodozis and Davidson, 1979; Muzzio, 1980). Intrusive rocks with K-Ar biotite absolute ages of 287 ± 4 and 260 ± 5 m.y. also indicate a Carboniferous or older age (Muzzio *in* Sepúlveda and Naranjo, 1982).

Paleoniscoid fish scales from Quebrada Chinches (27° 06'S and 69° 20'W) suggest an early Carboniferous age (D.L. Dineley, written commun.).

The rocks studied during the present investigation are distributed over an area of approximately 120 km from north to south and 50 km from west to east (Fig. 1) and at altitudes from 3,200 to 4,500 m. Correlations between the isolated exposures are based on lithological comparisons alone, and for this reason the strata are described separately from each of the main geographical areas:

- Between Salar de Maricunga and Salar de Pedernales.
- In Quebrada Colorado, east of Salar de Maricunga.
- Southwest of Salar de Pedernales.

In the present study, the outcrops from these three different areas would be considered as belonging to the same lithostratigraphic unit.

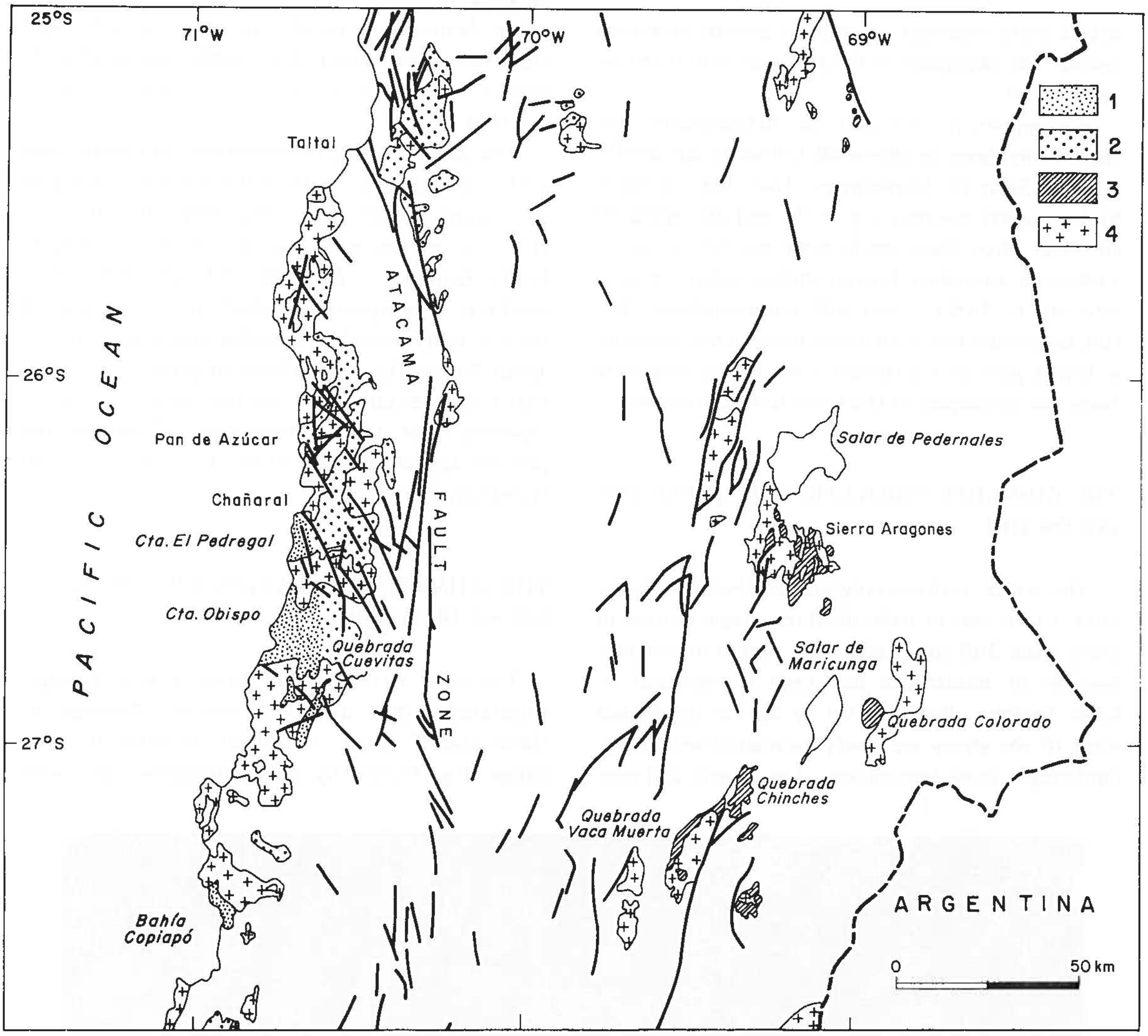

FIG. 1. Geological map showing the distribution of the Chinches Formation and other Paleozoic rocks between 25° and 29° S in northern Chile. (1) Chañaral mélange, (2) Las Tortolas formation, (3) Chinches formation, (4) Late Palaeozoic granitoids (Carboniferous-Permian).

THE CHINCHES FORMATION BETWEEN SALAR DE MARICUNGA AND SALAR DE PEDERNALES

The Paleozoic rocks of the area between Salar de Maricunga and Salar de Pedernales (Fig. 1) were briefly described by Cisternas (1977) and Cisternas *et al.* (1978) and they have been tentatively correlated with the strata east of Salar de Maricunga (Kubanek and Zeil, 1971) and with those southwest of Salar de Maricunga (Davidson *et al.*, 1978).

Exposures in this area are scattered and generally very poor. The rocks comprise shales and fine to coarse-grained sandstones which have been subjected to contact metamorphism, associated with the Pedernales Batholith (Cisternas, 1977). Sandstone composition ranges from quartz arenite to arkosic arenite. The lithic clasts indicate a provenance of low-grade metasediments, felsic and basic volcanic rocks and granitoids. Sedimentary structures are rarely preserved. The strata are massive or finely-bedded, with beds up to 10 cm thick. A few graded beds, load casts, mudflakes and ripple cross-laminations were observed. No fossils were recorded apart from poorly preserved traces. The thickness of the sequence could not be determined.

Sandstones in this area are lithologically distinct from those in Quebrada Colorado and southwest of Salar de Marincunga. They have a much higher quartz content (up to 90 and averaging 40 to 50%), they also contain more microcline (up to 15%) and abundant detrital and secondary muscovite (up to 30%). These differences indicate that this succession had a different provenance and that it forms part of a different sedimentary sequence from the remainder of the Chinches Formation.

THE CHINCHES FORMATION IN QUEBRADA COLORADO

The strata in the deeply incised Quebrada Colorado, to the east of Salar de Marincunga, consist of more than 500 m of siltstones with a minor proportion of mudstones and very fine-grained arkosic arenites. Beds are up to 50 cm thick, and most of the strata are finely laminated with abundant ripple cross laminations. Load casts and convolute laminations are also present. The abundant small-scale, straight-crested ripple marks (Fig. 2) have a low ripple index and are commonly symmetrical.

The sequence is predominantly unfossiliferous with a few slightly bioturbated horizons. A length of tetrapod trackway, comprising 10 footprints (Fig. 3), was recorded on the north side of Quebrada Colorado (26°58'S and 68°55'W). The trackway was apparently made by an amphibian with a body length (excluding head and tail) of about 26 cm (Bell and Boyd, in press). This is the first fossil referable to a tetrapod vertebrate to be reported from the Carboniferous of any of the present-day continental areas which once made up Gondwanaland.

THE CHINCHES FORMATION SOUTHWEST OF SALAR DE MARICUNGA

The most extensive exposures of the Chinches Formation occur in the Quebradas Chinches, El Hielo and El Patón, southwest of Salar de Maricunga (Fig. 4), strictly representing the type local-

FIG. 2. Small-scale stright-crested ripple marks in Quebrada Colorado.

ity of the formation. Here the sediments are essentially a fine-grained clastic sequence consisting of approximately 75% shale and 25% fine to very fine-grained sandstone. A few thin beds of conglomerate, finely-banded ashy tuff and stromatolitic, oolitic and pisolithic limestone are also present. A minimum thickness of 2,500 m has been recorded in both Quebrada Chinches (Mercado, 1982) and during the present study in Quebrada El Patón (Fig. 4).

The rocks in this area comprise three distinct sedimentary facies, characterized both by lithology and sedimentary structures:

- Parallel-laminated shale facies in successions up to 1,000 m thick.
- Ripple-marked siltstone facies in units up to 25 m thick.
- Cross-bedded sandstones with limestone facies in units up to 20 m thick.

Coarsening-upwards sequences of parallel-laminated shales overlain by ripple-marked siltstones, in turn overlain by cross-bedded sandstone and limestone have been recorded in the Quebradas Chinches, El Hielo and El Patón. However, the distribution of these three facies has not been mapped in detail (Fig. 4), and no complete stratigraphic sections have yet been measured through the formation.

Parallel-laminated Shale Facies

The Chinches Formation consists predominatly of very thick sequences of shale with a minor proportion (less than 25%) of parallel-bedded fine-grained sandstone, together with very rare conglomerates. In the south and east of Quebrada Chinches this facies forms a sequence about 500 m thick and in Quebrada El Patón probably in excess of 1,000 m. The thinly-bedded shales are finely to very-finely laminated. Laminae tend to be discontinous, wavy and non-parallel with the wavyness produced by small, low-amplitude ripples in the siltstones. Clay horizons commonly exhibit shrinkage cracks, with as many as six separate cracked laminae in a 10 cm vertical section (locality CP 347). Some shale horizons contain small calcareous nodules, but these are uncommon.

The shales are interbedded with parallel-bedded fine to medium-grained sandstones, both as individual beds and in sequences up to 25 m thick (for example in Quebrada El Patón south of locality CP 384) (Fig. 4). Individual sandstone beds are between 20 cm and 2 m thick and are either massive or finely laminated. Some beds are normally graded but inverse grading is also common. This

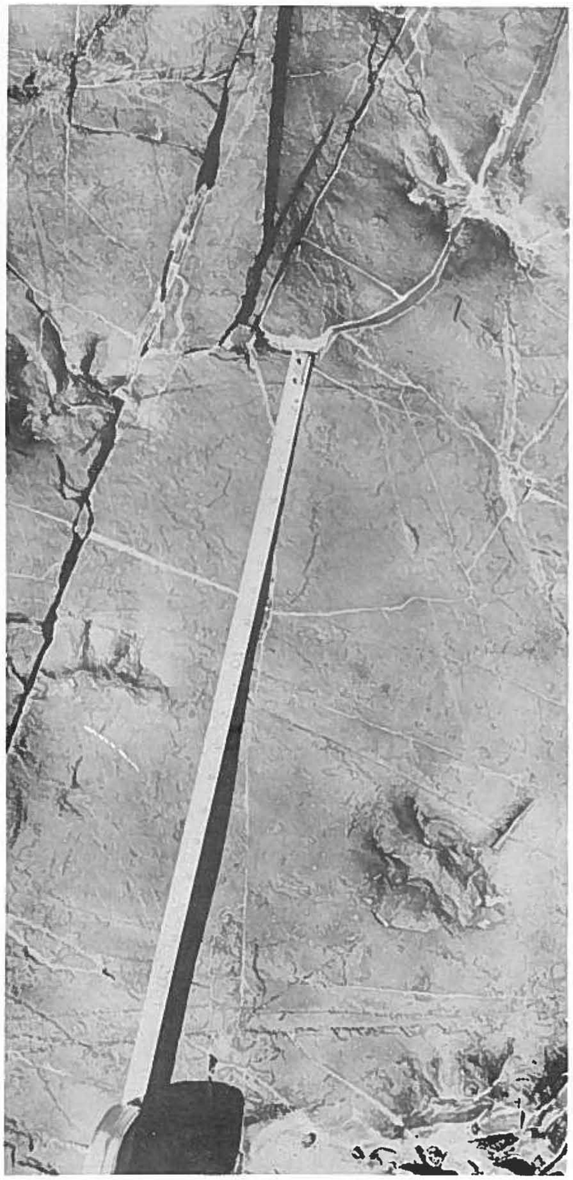

FIG. 3. Footprints of amphibian in Quebrada Colorado.

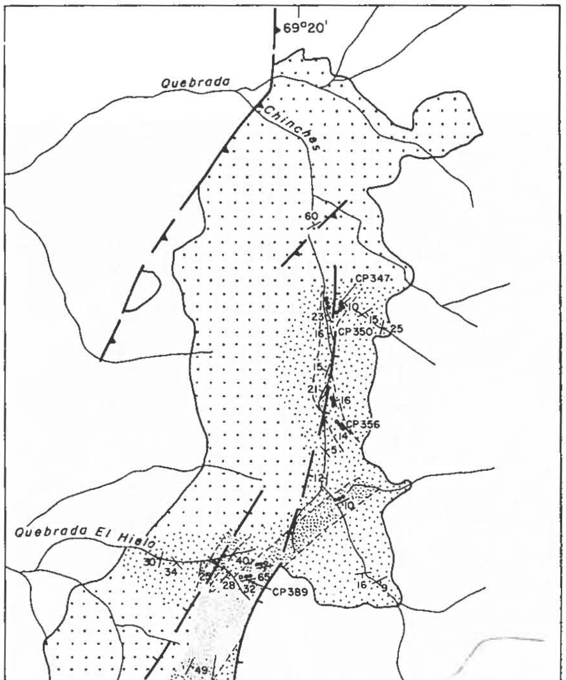

FIG. 4. Geological map of the area southwest of Salar de Maricunga. The distribution of the facies shown in the Chinches Formation has not been mapped in detail. (1) Rock types younger than the Chinches formation, (2-4) Chinches formation, (2) Undifferentiated facies, (3) Ripple-marked siltstone and cross-bedded sandstone with limestone facies, (4) Parallel-laminated shale facies, (5) Limestone, (6) Normal fault, (7) Reverse fault, (8) Orientation of bedding, (9) Geological contact within the Chinches formation.

inverse grading is upwards from siltstone or very fine-grained sandstone to medium-grained sandstone. A few beds are coarse-grained with scattered granules and pebbles. No definite Bouma sequences or erosive bottom structures have been recorded.

A single bed of poorly-sorted matrix-supported conglomerate in Quebrada Chinches (locality CP 350) comprises angular to rounded clasts of sandstone, shale and porphyritic volcanic rocks up to 25 cm in diameter.

The only fossils recorded are sparse indistinct traces on bedding planes. Bioturbation is absent.

Ripple-marked Siltstone Facies

Sequences consisting predominantly of well-sorted, ripple-marked and parallel-bedded siltstones and very fine-grained sandstones, up to 25 m thick, have been recorded in Quebradas Colorado, Chinches, El Patón and El Hielo. The most characteristic sedimentary structures are ripple marks, commonly forming interference patterns (Fig. 5). Many of these ripples have formed on the tops of parallel-laminated sequences and ripple-cross laminations are rare. Well-developed flaser-bedding is absent. Most of the ripple marks are parallel and symmetrical with straight and gently undulating crests, these crests are commonly pointed and they occasionally bifurcate. Some ripples have flattened crests and others exhibit small secondary ridges in the axes of their troughs. The wave length is generally very short and in several localities it is exceptionally short, with a minimum of 7.5 mm. The ripple index (Tanner, 1967), calculated from 34 ripple sets, varies between 3 and 25, with an average of 9. Linguoid and asymmetrical ripples and tongue-shaped erosion grooves cutting across ripple crests were observed at locality CP 384. In a few localities (CP 384, 386) small-scale symmetrical wave ripples form ladders in the troughs of larger asymmetrical ripples. The orientation of ripple crests (Fig. 6) shows no obvious preferred orientation.

A horizon of randomly-orientated impressions of reed-like plants up to 1 m long and 4 cm wide was recorded in the south of Quebrada El Hielo (locality CP 386). However, with the exception of a few trace fossils, this facies is essentially unfossiliferous.

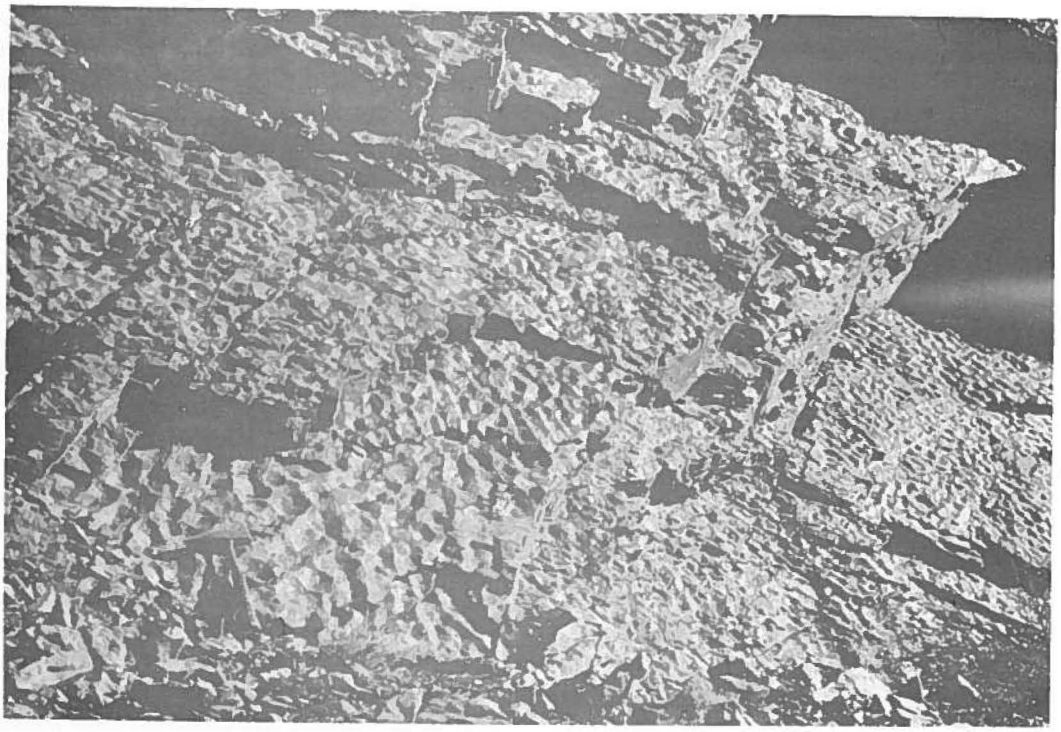

FIG. 5. Repeated patterns of interference ripples in Quebrada El Hielo.

Cross-bedded Sandstone With Limestone Facies

Cross-bedded, well-sorted medium to coarse-grained sandstones in successions up to 20 m thick, together with thin oolitic, pisolithic and stromatolitic limestone, occur in Quebradas Chinches and El Hielo (Fig. 4). The tabular, low-angle cross-bedding forms sets between 20 cm and 1 m thick. Foreset orientations (Fig. 6) do not indicate a preferred direction of transport. Unlike the other two facies, these strata show evidence of contemporaneous erosion. This evidence takes the form of mudflakes in the sandstones and shallow channels infilled with cross-bedded sandstone. Most of the sandstones are arkosic arenites, they are fine to very fine-grained and only rarely medium to coarse-grained. Most sandstones are well-sorted with angular to well-rounded clasts. The sandstones are mineralogically immature, with a low quartz content (ranging from 5 to 30 with an average of 20%). Most quartz grains are single, large crystals and several with embayed outlines originated as phenocrysts in quartz-feldspar porphyry. Feldspar content is very high, averaging 50% (Fig. 7). Partly sericitized andesine is the most abundant, but rare grains of microcline and myrmekite are also present. Heavy minerals (zircon, muscovite, biotite, opaque ore and apatite) are very rare. These minerals are absent in some specimens but others have concentrations of opaque ore and zircon, comprising up to 30% of some laminae (Fig. 8). Andesitic tuff, trachytic feldspathic lava and rhyolite clasts indicate a predominantly volcanic provenance. A minor component comprises clasts of fine-grained sedimentary rocks, and calcareous debris is commonly present. Granitoid clasts are very rare.

The sandstones exhibit a complex diagenetic history. They contain little or no matrix but are well cemented. Most sand grains have a very thin and often incomplete rim of iron oxide (Fig. 7). This rim is overgrown by quartz and albite which is in optical continuity with the detrital grains. The contacts between quartz grains are commonly sutured but few grains show undulose extinction and the rocks exhibit no significant tectonic fabric. In some specimens the quartz and albite cement, and parts of some detrital grains, have been extensively replaced by calcite.

Thin limestone horizons are widespread in Que-

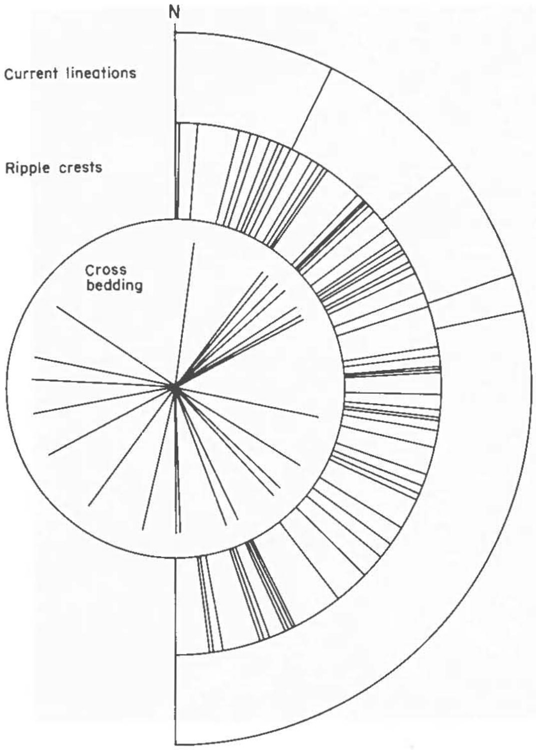

FIG. 6. Current and wind direction data in the Chinches Formation.

bradas Chinches, El Hielo (Fig. 4) and Vaca Muerta but they comprise only a very minor proportion (less than 1%) of the dominantly clastic Chinches Formation. The limestones comprise both pisolithic and oolitic grainstones and stromatolites. Tabular and domal stromatolites are both overlain by and interbedded with the cross-bedded pisolithic and oolitic limestones. Most limestone beds are less than 0.5 m thick, in places exceeding 6 m but the strata are very impersistent along strike. Cross-bedded sandstones associated with the limestones contain variable proportions of intermixed ooids, pisoids, intraclasts of broken stromatolite and shell debris. A 12 m thick ripple and dune cross-bedded sandstone sequence in Quebrada Chinches (CP 349) includes five interbedded pisoid horizons up to 0.5 m thick. 200 m along strike the same succesion thins to a 20 cm to 1 m thick stromatolitic bioherm overlain by up to 2 m of pisolithic limestone (Figs. 9 and 10). In Quebrada El Hielo (CP 389) a 6 m thick bed of massive oolitic limestone is overlain by 20 cm to 1 m thick siltstone and sandstone beds interstratified with thin parallel and ripple cross-bedded pisoid horizons. Some of the oolitic sands are bound together by thin stromatolitic biostromes.

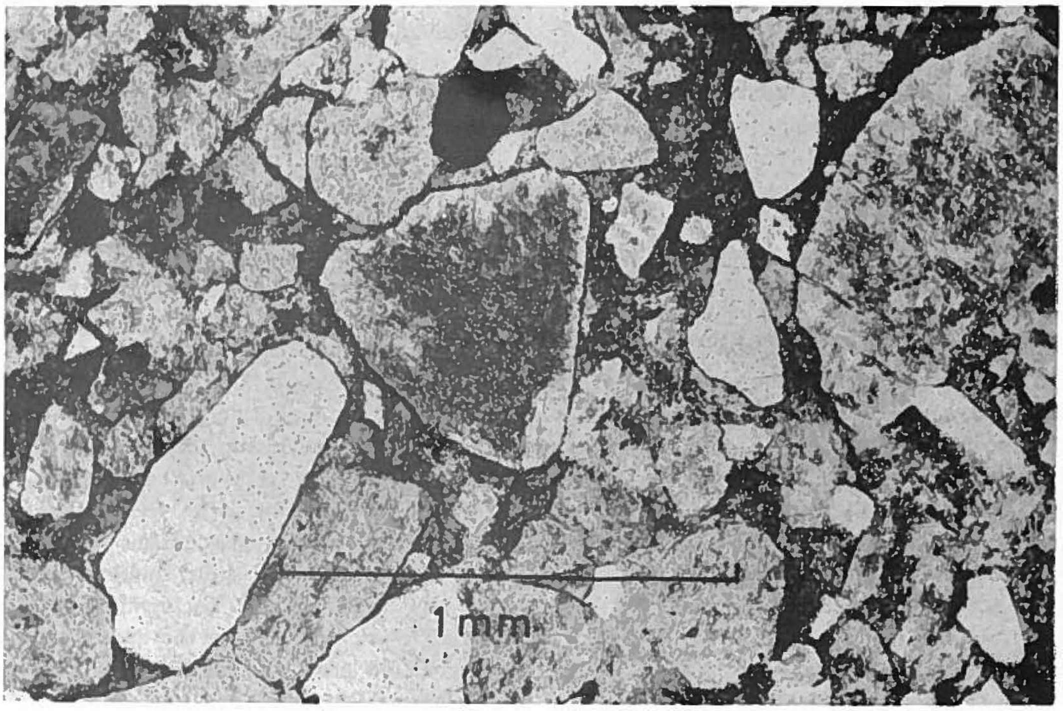

FIG. 7. Thin section showing poorly-sorted feldspathic sandstone with iron-oxide rimmed grains. Locality CP 350.

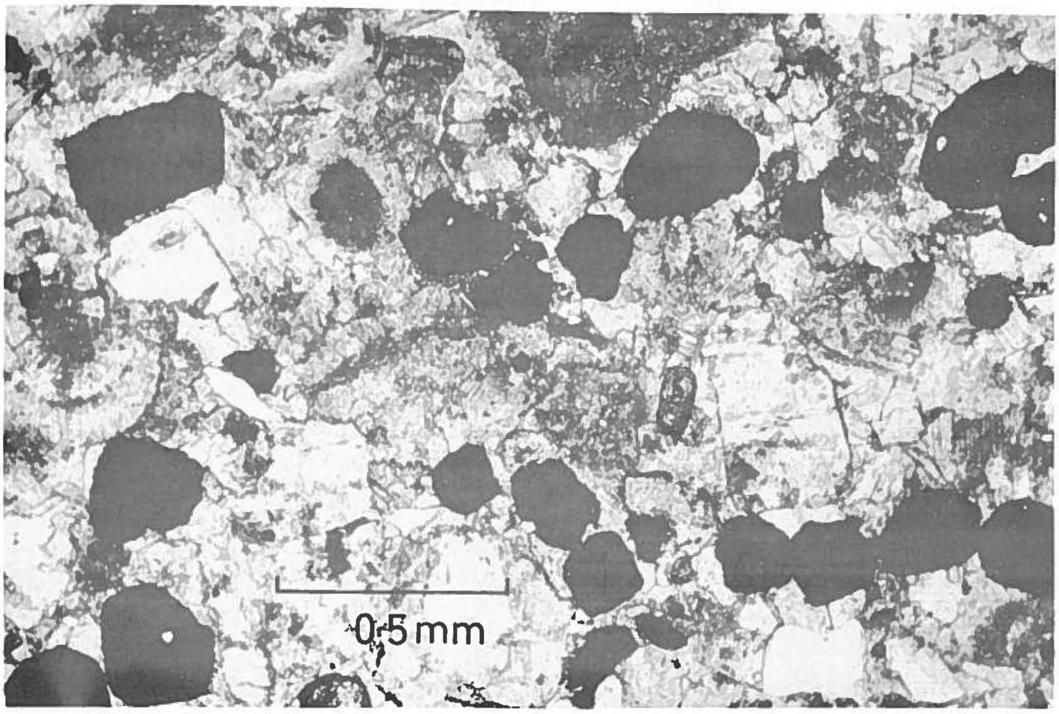

FIG. 8. Thin section of arkosic arenite with heavy-mineral concentration. Locality CP 389.

Pisoids and ooids are variable in size, with some limestones well-sorted an others very-poorly sorted. The average diameter of the grains is between 0.5 and 1 mm with a maximum of 25 mm. Most of the pisoids, particularly the smaller ones, are spherical but some are sub-spherical to disc-shaped. The ooids consist of radiating sparite and are symmetrical with evenly-developed, fine concentric laminae (Fig. 11). The niclei of most ooids comprise microcrystalline calcite, but the majority of the pisoids have nuclei of quartz, plagioclase or trachytic volcanic rocks. Broken, curved calcareous shell fragments (probably mulluscs) up to 4 mm long and 0.2 mm thick are also commonly encrusted with laminated calcite (Fig. 12). The pisolithic and oolitic limestones are commonly cross-bedded and some specimens show heavy-mineral concentrations similar to those in the sandstones.

Fish scales and teeth, consisting of blades (up to 3 mm long) and rings (up to 0.3 mm in diameter) of collophane, were observed in thin sections CP 347.18, .23, .24 and 356.1. Paleoniscoid fish scales and teeth (D.L. Dineley, written commun.) were also recorded in thinly-bedded shales a few centimetres above the pisoid limestone at locality CP 347 (Fig. 10).

A variety of different types of stromatolite (Krumbein, 1983) are present. The biostromes (Eggleston and Dean, 1976) illustrated by Sepúlveda and Naranjo (1982) from Quebrada Vaca Muerta have parallel columns 2 to 3 cm in diameter and with gently convex laminae (Preiss, 1976). Biostromes in Quebrada Chinches are up to 85 cm thick and comprise finely-laminated domes up to 10 cm in diameter (Fig. 13). These stromatolites also encrust and form morphologically continuous overgrowths on pisoids, suggesting that both the pisoids and stromatolites were produced by the same organisms. Domed stromatolitic bioherms in Quebradas Chinches and El Hielo have a circular cross section up to 20 cm in diameter and are up to 6 cm high with slightly divergent and branching columns, 2 to 4 mm wide. These columns are roughly circular in cross section, and have very regular rectangular laminae, 0.1 to 0.3 mm wide (Fig. 14). The columns comprise parallel sparite crystals up to 1 mm long. Laminae are defined in some specimens by aggregations of impurities and changes in grain size, and in others by layers of secondary chamosite and dolomite. The spaces between columns are filled with sparite, dolomite and chamosite. Entrapped clastic debris

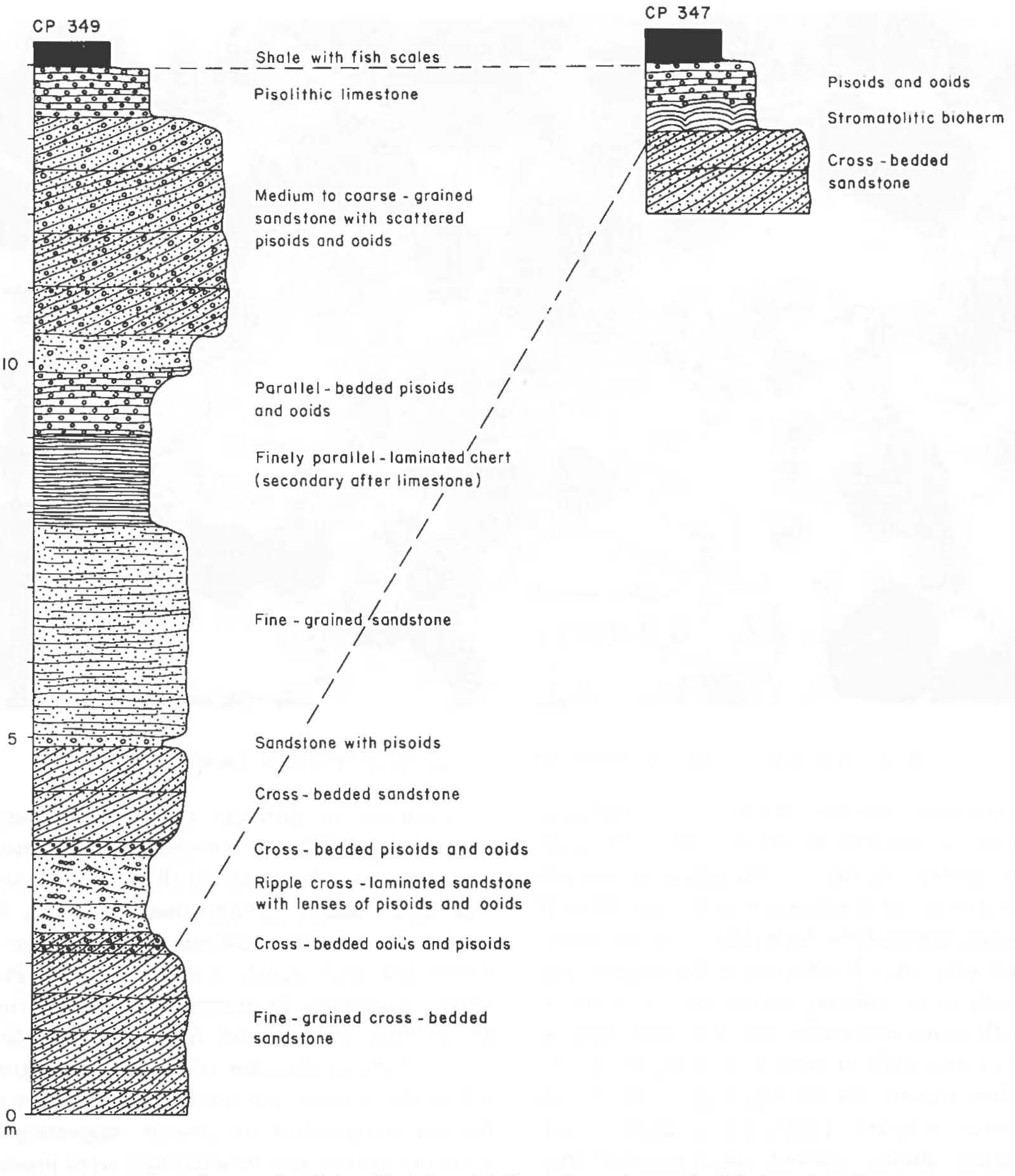

FIG. 9. Measured sections at localities CP 349 and 347 to show changes in lithology in a limestone sequence over a distance of 200 m.

is very rare and the regularity and parallelism of the laminae indicate that the stromatolites grew by precipitation of calcite from clean water (Krumbein, 1983; Walter, 1976; Schäfer and Stapf, 1978) rather than by entrapment and binding of micrite (Logan *et al.*, 1974). Recrystallization of the stromatolites has destroyed internal structures, and the organisms which produced them are therefore indeterminate.

The pisolithic and oolitic grainstones have little matrix and frequently exhibit stylolites, they are usually cemented by sparite (Fig. 11). In most localities the limestones are partly replaced by secondary chert which has selectively replaced layers and laminae within the limestone. In places radiating chalcedony forms a pore-filling cement.

Volcanic Rocks

Sepúlveda and Naranjo (1982) described rare horizons of finely-banded ashy tuff up to 50 cm thick in Quebrada Vaca Muerta. A single horizon of rhyolotic tuff was also recorded in Quebrada

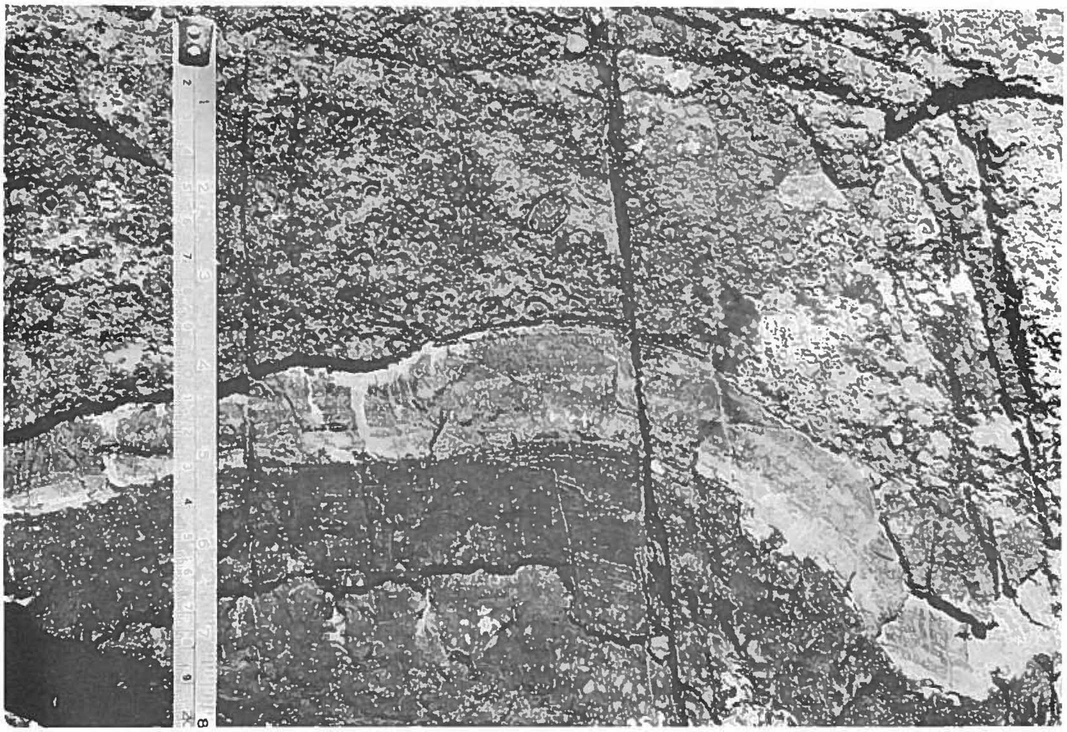

FIG. 10. Stromatolitic bioherm overlain by pisoids and ooids. Locality CP 347.

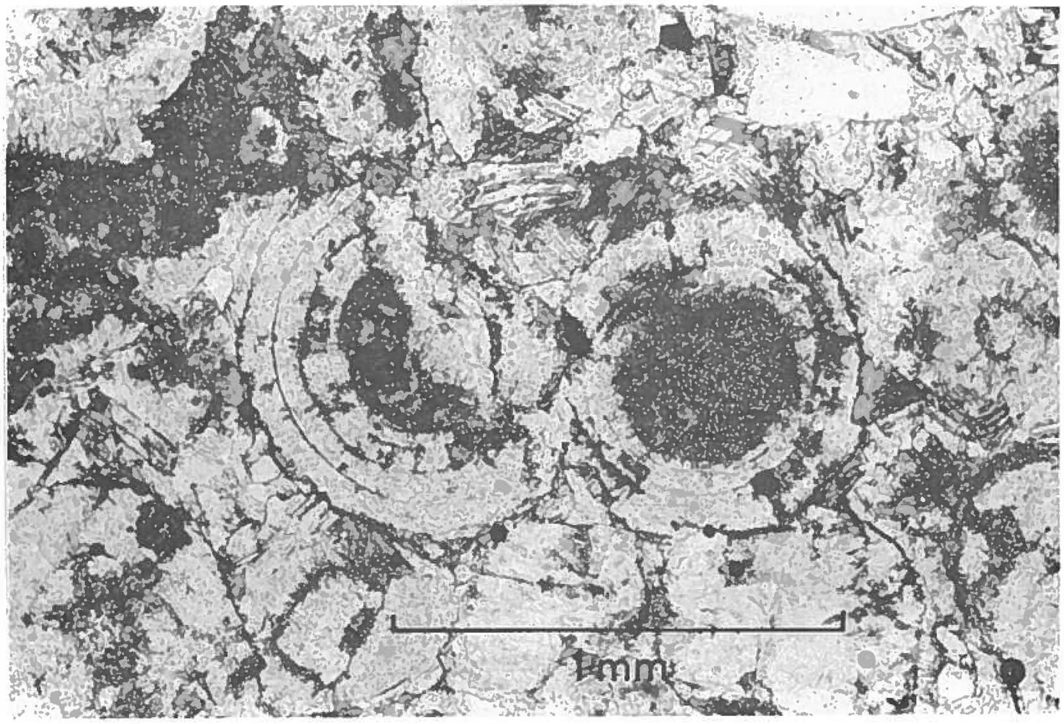

FIG. 11. Thin section of oolitic grainstone. Locality CP 389.

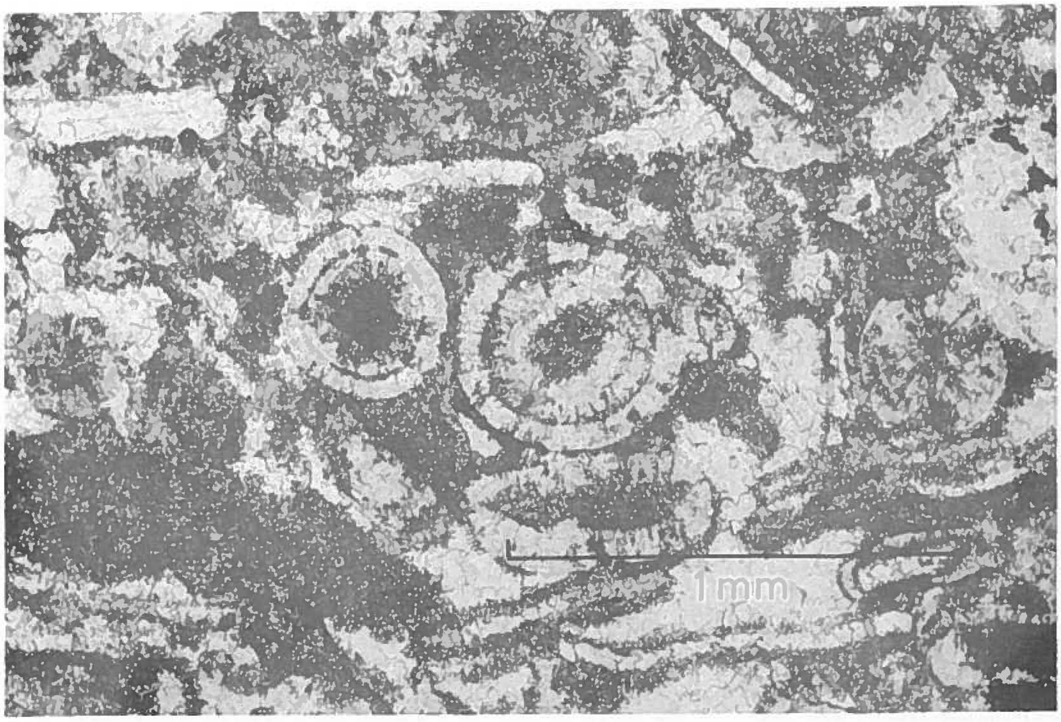

FIG. 12. Ooids and encrusted shell fragments in thin section of limestone. Locality CP 389.

FIG. 13. Stromatolite biostromes in Quebrada Chinches. Locality CP 356.

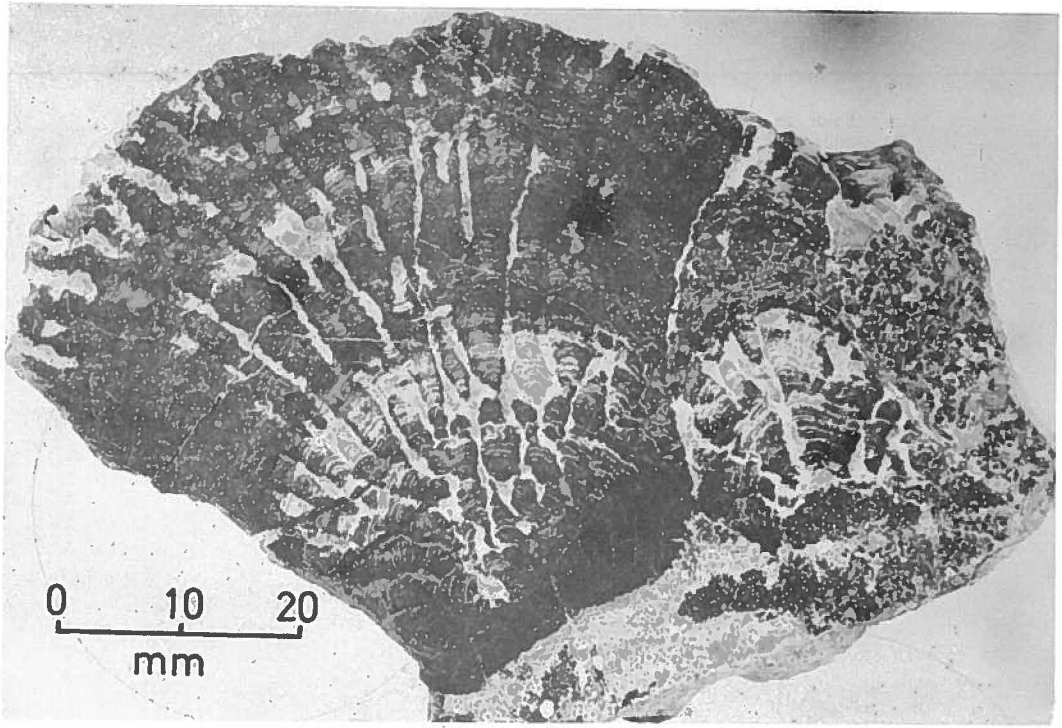

FIG. 14. Polished section of stromatolite bioherm showing branching columns and fine, regular laminae. Locality CP 356.

Chinches during the present investigation. The abundant clasts of andesine and volcanic rocks in the sandstones southwest of Salar de Marincunga are also probably a product of the same contemporaneous andesitic and rhyolitic volcanic activity.

DEFORMATION

The rocks of the Chinches Formation are folded into very large-scale and open monoclinal folds with wavelengths of hundreds of metres to kilometres. Tectonic cleavege is rare and no overturned strata were recorded. The folding in the area southwest of Salar de Maricunga is about axes plunging gently towards the south-southwest, but a distinct pattern of deformation is shown in each of the other sub-areas (Fig. 15). The Chinches Formation at Quebrada Chinches and Quebrada Patón is overlain, with an angular unconformity, by Upper Paleozoic rhyolites and Triassic-Jurassic sediments which are themselves folded about south-southwest to north-northeast axes, clearly related to Tertiary high angle reverse faults (Mpodozis and Davidson, 1979).

INTERPRETATION OF THE DEPOSITIONAL ENVIRONMENT

Muzzio (1980) described at Quebrada Patón, ripple marks, cross bedding and rain imprints and associated them to "transitional" environments. Sepúlveda and Naranjo (1982) suggested, on the evidence of the lithology and sedimentary structures, and the presence of stromatolites, that the Chinches Formation was a tidal-flat deposit. However, little evidence to support this later interpretation has been found during the present study. In particular there are none of the marine fossils, ex-

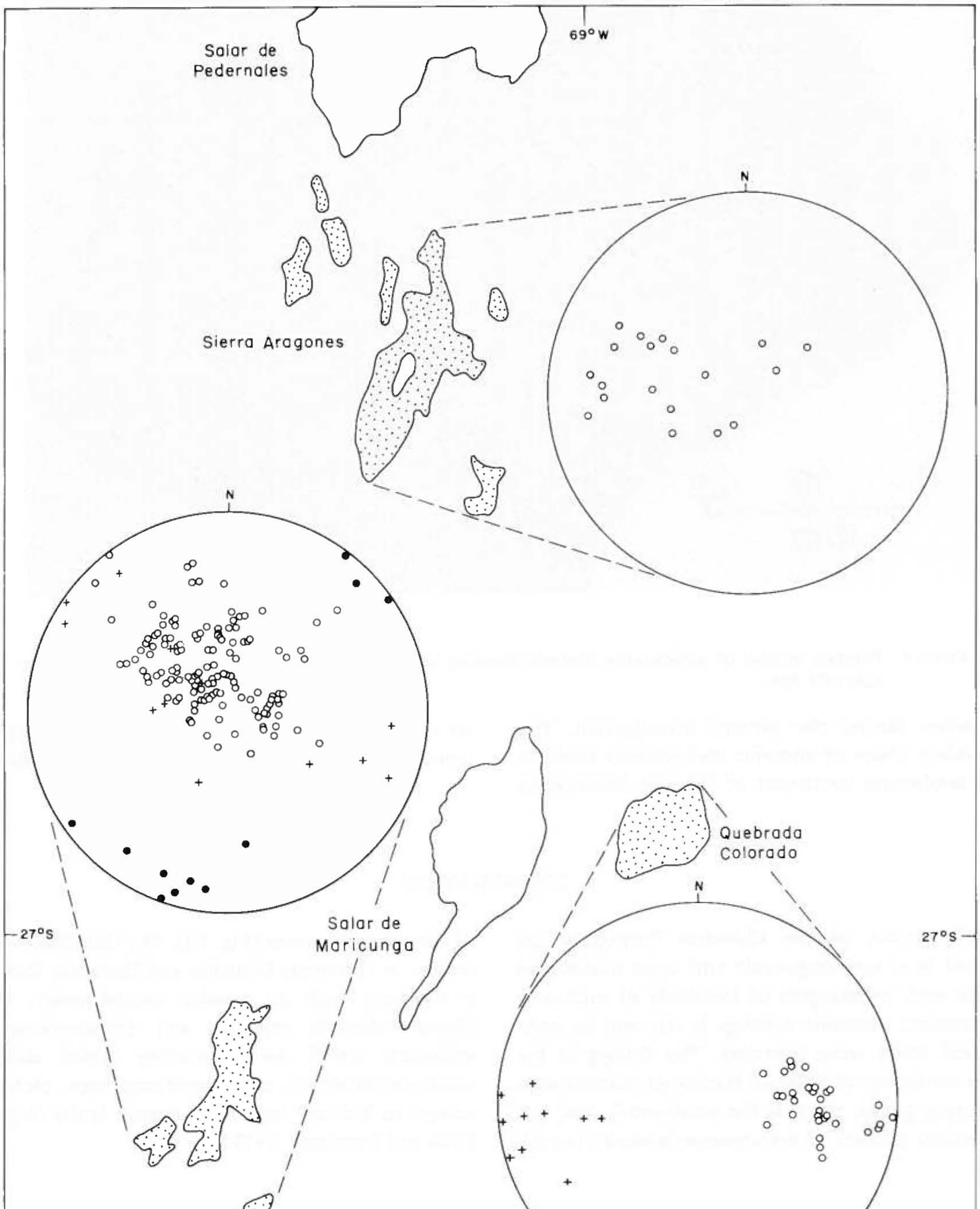

FIG. 15. Deformation in the Chinches Formation. Open circles represent poles to bedding planes. Filled circles are axes of minor folds. Crosses are poles to cleavage planes.

tensive bioturbation or reversals of current direction which are common in tidal-flat environments (Klein, 1971; Reineck, 1972; Evans, 1975).

The predominance of fine-grained sediments in the Chinches Formation indicates a low-energy, partly or completely enclosed depositional basin. Some of the sedimentary features resemble those of modern low-gradient and partly-enclosed, mud-dominated tidal flats or lagoons such as the Laguna Madre of Texas and the Gulf of California (Fisk, 1959; Thompson, 1975). These muddy tidal flats have few channels and consist of smooth plains of very low relief where wind and tide-driven sheets of water transport fine-grained sediment in suspension. However, most sediments in these flats show intense bioturbation and interfingering eolian sediments (Fisk, 1959; Thompson, 1975) both features which are absent in the Chinches Formation.

The fossils, sedimentary structures, facies and sequences in the Chinches Formation are closely comparable with those found in both ancient and modern lake deposits (Picard and High, 1972; Van Dijk *et al.*, 1978; Link and Osborne, 1978; Galloway and Hobday, 1983; Sturm and Matter, 1978). Fossils are very uncommon, they include fish-scales and teeth, stromatolites, thin-shelled molluscs and plants. The tracks of an amphibian have been recorded but other trace fossils are rare and no significant bioturbation has occurred. The absence of marine fossils in a fine-grained clastic sequence, deposited at least in part under shallow-water conditions, is indicative of a brackish or fresh-water environment. The sparse biota is characteristic of lake margins, which with their lack of tides, lower wave energy and more variable water chemistry, show less physical and biological reworking than marine shorelines (Galloway and Hobday, 1983; Link and Osborne, 1978; Picard and High, 1972). The presence of thin stromatolitic and pisolithic horizons in a predominantly fine-grained pelitic sequence is a feature of many lake deposits (Link and Osborne, 1978; Picard and High, 1972; Sanders, 1968; Schäfer and Stapf, 1978; Surdam and Wolfbauer, 1975). The absence of saline deposits suggests a lake with an outlet and a throughflow (Eugster and Surdam, 1973). Sand grains are rimmed with iron-oxide, and plant fossils are preserved only as impressions and not as carbonized remains. These features both suggest an oxidizing environment during the early stages of diagenesis.

The three sedimentary facies recognized in the Chinches Formation are believed to be the products of distinct lacustrine environments:

- The parallel-laminated shale facies was deposited in a deep-water lake.
- The ripple-marked siltstone facies formed in shallow-water, wind-dominated lake flats.
- The cross-bedded sandstone with limestone facies was deposited on a lake shore.

Parallel-laminated Shale Facies as a Deep-water Lacustrine Deposit

Thick-successions of laminated shales and parallel-bedded sandstone are the most abundant rock types of the Chinches Formation. They are interpreted as the product of sedimentation both from suspension and from low-density turbidity currents in a deep-water lake.

It has been suggested that deep-water lacustrine sedimentation is produced almost entirely from suspension (Collinson, 1978) but density currents are also very important in redistributing lake sediments (Sturm and Matter, 1978; Link and Osborne, 1978; Galloway and Hobday, 1983). The majority of these currents are periodic to semi-continuous low-density turbidity currents, possibly produced during periods of high river discharge (Sturm and Matter, 1978). They deposit thin to thickly-bedded and faintly-graded and laminated sands interbedded with laminated silts and shales (Galloway and Hobday, 1983; Link and Osborne, 1978). High-density currents produced by occasional catastrophic flooding or landslides produce extensive massive to graded sands, and beds up to 1.5 m tick have been recorded in Lake Brienz (Switzerland) (Sturm and Matter, 1978). The role of high-density currents in lacustrine environments is also indicated by graded bedding and sole marks recorded in the Ridge Basin Group of California (Link and Osborne, 1978). A continuous rain of fine-grained sediment, supplied by overflows and interflows (Sturm and Matter, 1978), produces massive to horizontally laminated shale interbedded with the turbidity deposits.

Most of the shales in the Chinches Formation were probably deposited by low-density turbidity currents, with parallel-laminated sandstones, the products of periodic high-density currents. The absence of Bouma sequences and sole markings suggests that most of the currents had a relatively low energy. A matrix-supported conglomerate in Quebrada Chinches indicates the operation of mass-flow processes, and suggests that the deposition may have been near the unstable margin of the basin (Potter *et al.*, 1980). Inverse grading in some of the horizontally-bedded sediments may be the result of grain-flow conditions produced by the density currents (Collinson and Thompson, 1982).

Vertical successions showing abundant and repeated mud cracks are common in the shales of the Chinches Formation. Mercado (1982) ascribed these structures to subaerial dehydration, and similar repeated sets of cracks have been described as dessication features by Smoot (1978). However, the mud-cracked strata in the Chinches Formation show no erosional structures or other evidence of subaerial exposure. They therefore probably originated as synaeresis structures produced by subaqueous flocculation and shrinkage of the mud (Donovan and Foster, 1972; Potter *et al.*, 1980) rather than by subaerial dehydration.

Ripple-marked Silstone Facies as a Shallow-water Lake-flat Deposit

The sequences of ripple-marked siltstones and very fine-grained sandstones in the Chinches Formation are interpreted as shallow-water lake-flat deposits. The abundant ripple marks have low ripple-index values (Tanner, 1967), which, together with their symmetry, bifurcating crests and short wave length, indicate an origin by wave activity (Reineck and Singh, 1980). This dominace of wave-formed over current-formed structures suggests deposition in still water. The development of successions of wave-rippled, very fine-grained sandstones and siltstones (in successions up to 25 m thick) indicates significant wave-induced sediment transport and deposition in very shallow water. Shallow-water lacustrine environments are characterized by broad, wind-dominated flats, periodically inundated and exposed in response to changes in wind velocity and direction (Galloway and Hobday, 1983). Wind-forced currents are capable of carrying large volumes of sediments, and wind surge causes the redistribution of the sediment. This accounts for the regular depth of some lakes subjected to extreme wind action. Typical deposits of modern wind-dominated lake flats are massive to laminated clays, rippled sands and silts and graded parallel laminations (Galloway and Hobday, 1983) comparable with those of the Chinches Formation.

The repeated development of near-perpendicular sets of interference ripples (Fig. 5) is indicative of regular, probably daily, changes in wind direction. However, the orientation of these structures does not indicate distinct preferred wind directions (Fig. 6).

Cross-bedded Sandstone with Limestone Facies as Lake-Shore Deposits

The cross-bedded sandstones and thin stromatolitic and oolitic limestones were probably deposited on a relatively high-energy wave-exposed lake shore (Buchheim and Surdam, 1978). Cross-bedded sandstones were produced by the migration of subaqueous sand dunes up to 1 m or more in height, and shallow channels and mudflakes are indicative of contemporaneous erosion. These structures are characteristic of many sedimentary environments including lake shores (Link and Osborne, 1978; Van Dijk *et al.*, 1978). Heavy-mineral concentrations in the cross-bedded sandstones are produced by wind and wave sorting (Collinson, 1978; Reineck and Singh, 1980).

There is no evidence in the Chinches Formation for prograding fluvio-lacustrine deltas (Van Dijk *et al.*, 1978), possibly indicating that underflow transferred most sediment directly into deeper water (Houbolt and Jonker, 1968).

Thin oolitic and stromatolitic limestones are indicative of lake-shore environments (Link and Osborne, 1978; Picard and High, 1972; Sanders, 1968; Schäfer and Stapf, 1978; Surdam and Wolfbauer, 1975). Ooids, pisoids and stromatolite fragments in the sandstones provide evidence for reworking by waves in shallow water and a similar mixture of sand grains, pisoids and ooids has been recorded in the lacustrine Green River Formation (Smoot, 1978). Limestones and cross-bedded sandstones in the Chinches Formation show abrupt lateral and vertical facies changes (Fig. 9) similar to the complex inter-relationship of facies described from lake-shore environments by Link and Osborne (1978), Van Dijk *et al.* (1978), and Picard and High (1972).

Stromatolites (Krumbein, 1983) are commonly associated with marine tidal environments (Walter, 1976; Wray, 1977; Logan *et al.*, 1974) but many examples of both fossil and modern lacustrine stromatolites have been recorded (Bradley, 1929; Eardley, 1983; Link and Osborne, 1978; Picard and High, 1972; Sanders, 1968; Surdam and Wolfbauer, 1975; Tucker, 1978). The presence of stromatolites is indicative of a shallow-water, photic environment with abnormal salinity levels (Surdam and Wolfbauer, 1975). Modern stromatolites forming in Lake Constance are characteristic of shallow-water, near-shore areas of low sedimentation (Schäfer and Stapf, 1978).

The carbonates of the Chinches Formation have undergone partial silicification similar to that of modern carbonates in Lake Constance (Schäfer and Stapf, 1978) and Mesozoic lacustrine carbonates in Libya (Selley, 1982).

SEDIMENTARY SEQUENCES

The three facies identified in the Chinches Formation form upward-coarsening sequences up to 1,000 m thick. These are interpreted as the products of progressive changes from deep to shallow water. Such shallowing, regressive sequences are normally produced by the gradual infilling of an initially deep basin and an advancing shoreline (Hallam and Bradshaw, 1979). Shallow-water limestones in the north of Quebrada Chinches are overlain by a very thick sequence of parallel-laminated shales which were probably deposited in deep water. This stratigraphic relationship suggests that an episode of rapid subsidence separated two regressive cycles.

Progressive infilling of lake basins normally produces an upward-coarsening sequence with a thickness approximately equalling the original lake depth (Van Dijk *et al.*, 1978; Galloway and Hobday, 1983). Like those of the Green River Formation (Picard and High, 1972), the upward-coarsening regressive sequences of the Chinches Formation are dominated by deeper-water deposits. The thick successions of fine-grained clastic sediments suggest a lake with an initial depth of at least 500 m and possibly as much as 1,000 m.

With a total thickness in excess of 2,500 m, the Chinches Formation is exceptionally thick for a lacustrine deposit. Most lake sequences are relatively thin, with the majority of well-studied examples in the western United States of America, less than 250 m thick, and few exceeding 1,000 m (Feth, 1964; Picard and High, 1972). Occurrences of very thick lake deposits include a 5 to 6 km thick Devonian sequence in Scotland (Donovan and Foster, 1972) and the more than 9 km thick Pliocene Ridge Basin Group of California (Link and Osborne, 1978).

CLIMATIC CONDITIONS DURING DEPOSITION OF THE CHINCHES FORMATION

Lacustrine shore-line deposits are commonly associated with emergent features, including evaporites and eolian or fluvial sediments (Hardie *et al.*, 1978; Galloway and Hobday, 1983; Picard and High, 1972). The absence of these features in the shallow-water facies of the Chinches Formation is indicative of a wet climate. This suggestion is supported by the presence of thick shale sequences which imply a wet climate and a high rate of sedimentation (Potter *et al.*, 1980). Helwig (1972) also recorded Carboniferous lacustrine deposits in Bolivia (18° S and 65° W). He interpreted these as indicating a high rate of precipitation and low temperatures related to the widespread Carboniferous (Gondwana) glaciation. A melioration of this climate only occurred in the late Carboniferous. This intepretation is supported by paleomagnetic data which indicate that northern Chile was in the south temperate zone during Devonian to early Carboniferous times. The region moved northwards from about 75° S in the late Devonian to 40° S by the mid-Carboniferous (Smith *et al.*, 1981; Ziegler, 1981). Contrasting climatic evidence is provided by the amphibian tracks in Quebrada Colorado which suggests a tropical or subtropical climate. This paleoclimatic anomaly is similar to those in Bolivia which Helwig (1972) accounted for in terms of the accretion of exotic terranes.

TECTONIC SETTING

Rocks of the Chinches Formation have been tentatively correlated with other late Paleozoic sequences in northern Chile and Argentina (Davidson *et al.*, 1979; Muzzio, 1980; Mercado 1982; Sepúlveda and Naranjo, 1982). The north-south elongated exposures of the Chinches Formation (Fig. 1) could reflect the original shape of the sedimentary basin. However, the margins of the basin are unknown and the elongation may be the product of subsequent tectonic activity.

Deformed turbidites of the Las Tórtolas Formation and the Chañaral "mélange" in the coastal region 150 km to the west (Fig. 1) formed an accretionary wedge produced by late Paleozoic subduction beneath the continental margin (Bell, 1982; 1984). The orientation of tectonic structures in the accretionary complex suggests that subduction was towards the northeast, oblique to the present day continental margin (Bell, 1984). This deformation was possibly comtemporaneous with the deposition of the Chinches Formation, suggesting that the lacustrine basin formed parallel to an active continental margin. Independant evidence for active subduction is provided by the interbedded tuffs and andesitic and rhyolitic detritus in the formation.

The great thickness of the Chinches Formation is indicative of deposition in a rift (Helwig, 1972) or a pull-apart basin (related to strike-slip faulting). These basins are difficult to distinguish in the geological record, but the unusual thickness favours a pull-apart basin (Steel and Gloppen, 1980). The initial depositional environment in strike-slip fault zones is often lacustrine and, like the Chinches Formation, these lakes are long and narrow and contain thick sediment columns (Reading, 1980).

In its tectonic setting, rock types and exception thickness, the Chinches Formation bears a remarkable resemblance to the 9,000 m thick lacustrine Ridge Basin Group of California, a sequence which was deposited in a 40 km long and 15 km wide pull-apart basin produced by strike-slip displacement along the San Gabriel fault (Crowell, 1974; Link and Osborne, 1978). A possible modern-day equivalent to the Carboniferous tectonic setting of northern Chile is provided by the North Island of New Zealand where oblique subduction has produced an accretionary wedge together with a strike-slip fault zone adjacent to a volcanic arc (Lewis, 1980).

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