NOTA GEOLOGICA

Saline lake turbidites in the La Coipa area, Northern Chile

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ABSTRACT

An unusual and very distinctive occurrence of evaporitic gypsum in association with clastic turbidites was deposited in a still, anoxic lake environment in the La Coipa area of Northern Chile. The sequence of exceptionally fine-grained, red-coloured mudstones and graded sandstones is characterised by abundant small gypsum nodules and veins. The nodules probably resulted from the recrystallization of gypsum-anhydrite transported by turbidity currents and slumps from the shallow lake margins into deeper water. Following the formation of the superficial slumps the strata were subjected to compressive thrusting. This, in turn, was followed by vertical extension and a second episode of NNE-directed thrusting. The gypsum-filled veins, produced during the vertical extension, possibly originated as a result of the dissolution of underlying evaporites. The strata, apparently, form the oldest part of the Lower Triassic La Coipa Beds, which are themselves part of a widespread succession of Triassic marine and continental rift-related sediments in Northern Chile.

Key words: Evaporites, Turbidites, Northern Chile.

RESUMEN

Turbiditas de lago salino en el área de La Coipa, norte de Chile. Una inusual y muy distintiva ocurrencia de yeso evaporítico asociado a turbiditas clásticas se depositó en un tranquilo ambiente lacustre anóxico en el área de La Coipa en el norte de Chile. La secuencia de fangolitas rojas, de grano excepcionalmente fino y de areniscas gradadas se caracteriza por abundantes y pequeños nódulos y venas de yeso. Los nódulos, probablemente, fueron el resultado de la recristalización de anhidrita-yeso transportados por corrientes de turbidez y derrumbes desde los márgenes lacustres someros a aguas más profundas. Después de los derrumbes superficiales, los estratos fueron sometidos a un corrimiento compresivo. Esto, a su vez, fue seguido por una extensión vertical y un segundo episodio de corrimiento con dirección nor-noreste. Las venas de yeso, consecuencia de la extensión vertical, posiblemente se originaron como resultado de la disolución de evaporitas subyacentes. Aparentemente, los estratos constituyen la parte más antigua de los Estratos de la Coipa del Triásico Inferior, los cuales forman parte de una sucesión de sedimentos marinos y continentales de 'rift' del Triásico, ampliamente distribuidos en el norte de Chile.

Palabras claves: Evaporitas, Turbiditas, Norte de Chile.

INTRODUCTION

A nine metre thick sequence of muddy redbeds and sandstones was deposited by turbidity currents in the La Coipa area of Northern Chile (Fig. 1). The strata contain abundant small evaporitic gypsum nodules and are cut by fibrous gypsum veins. The succession appears to form the lowest part of the lacustrine Lower Triassic La Coipa Beds (Suárez *et al.*, 1995). This occurrence of evaporite minerals in fine-grained, still-water lacustrine turbidites is very unusual (Hardie *et al.*, 1978; Schreiber, 1986). Evaporites are relatively common in the Upper Triassic to Lower Cretaceous strata of Northern Chile, but no other evaporitic sediments of Lower Triassic age have been described from the Andean Cordillera (Benavides, 1968; Suárez and Bell, 1987).

STRATIGRAPHIC RELATIONSHIP AND AGE

The muddy redbeds form a strikingly beautiful succession of parallel-bedded, bright brick-red strata, cut by white gypsum veins (Fig. 2). The main exposures (69°15'W, 26°48'S) form steep cliffs extending for about 300 m along the north side of a deep valley at an altitude of about 4,000 m near La Coipa Mine (Fig. 1). The exposures are bounded on all sides by younger superficial deposits. Due to this lack of exposed contacts with adjacent strata there is a controversy regarding the age and stratigraphic relationship of the succession. Mpodozis (referees report of May 1995) has indicated that the strata are probably Pliocene-Quaternary? in age and are the deposits of a small playa lake developed in the bottom of today's valley. By contrast, publications by Suárez and Bell (1991, 1992) and Suárez *et al.* (1995) have suggested that deposition occurred in

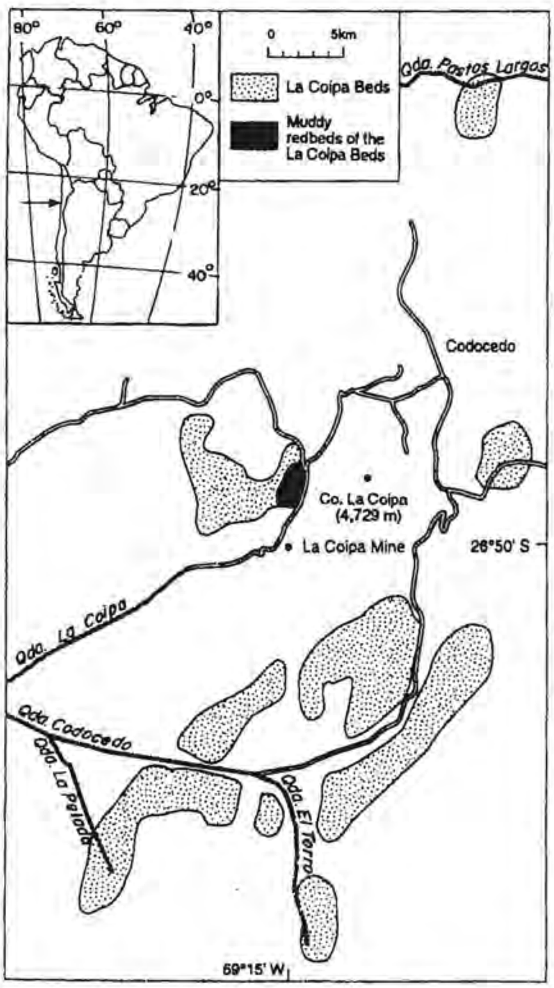

FIG. 1. Location map showing the distribution of the muddy redbeds and the Lower Triassic La Coipa Beds.

FIG. 2. Parallel-bedded mudstones and sandstones of the muddy redbed succession. Gypsum-filled veins are both oblique to and parallel with the bedding.

a large, deep lacustrine basin, as part of the Lower Triassic La Coipa Beds. No contacts with older strata or with intrusive bodies were identified during the present investigation. To the south and west of the muddy redbeds are extensive outcrops of sandstones and mudstones of the La Coipa Beds (Suárez *et al.*, 1995) (Fig. 1). The La Coipa Beds are overlain and cut by Oligocene-Miocene volcanic domes and porphyries (P. Cornejo, C. Mpodozis, C.F. Ramírez, A. Tomlinson)[1]. Evidence to support the suggestion that the muddy redbeds form part of the extensive Lower Triassic La Coipa Beds, rather than a localised Pliocene deposit, includes:

- Micropaleontological studies undertaken in both the black shales of the La Coipa Beds and in the muddy redbeds have identified algal spheres, fungal spores and fragments of large zonate spores (cf. *Polycingulaffsporites crenulatus)* which have suggested an early Triassic age (Hutter *in* Suárez *et al.*, 1995). Hutter also described biodegraded and near-pelletal, amorphous kerogen, wood fragments and plant cuticular debris. The presence of kerogen indicates deeper burial than is likely for Pliocene sediments.
- The La Coipa Beds and the muddy redbeds both display sedimentary and paleontological characteristics which suggest deposition in an extensive deep lake (Suárez *et al.*, 1995).
- The muddy redbeds have a dip of between 10° and 20° and exhibit a complex deformational history, including two episodes of compression with tight folding of gypsum veins. This degree of deformation seems very unlikely in upper Tertiary sediments.

Four sedimentary facies were described by Suárez *et al.* (1995) in the La Coipa Beds:

- Black shales, several hundred metres thick, interpreted as open and marginal lacustrine deposits.
- Conglomerates, sandstones and black shales, about 200 m thick, interpreted as subaqueous lacustrine fan delta or talus deposits.
- Cross-bedded sandstones, about 100 m thick, interpreted as fluvial deposits.
- A thin succession of muddy redbeds with gypsum nodules, interpreted as turbidites deposited in a deep saline lake, which forms the subject of the present study.

The detailed stratigraphic relationships of these four sedimentary facies have yet to be determined due to the combination of isolated outcrops and the absence of distinct marker horizons. Relative geographical positions of the outcrops suggest that the muddy redbeds underlie the black shales at the base of the succession.

The La Coipa Beds form the oldest part of a widespread succession of Triassic, marine and continental, rift-related sedimentary deposits, associated with basaltic, andesitic and silicic volcanic rocks. This sedimentation was the product of subduction-related extension and strike-slip movement on an active continental margin. The extensional tectonism, which pre-dated the break-up of Gondwana, was followed in late Triassic to early Jurassic times by a widespread marine transgression resulting from thermo-tectonic subsidence (Suárez and Bell, 1992).

MUDDY REDBED FACIES

The muddy redbeds form a nine metre thick sequence which can be subdivided into three units. From the base upwards, these comprise a two metre thick parallel-bedded unit, a three metre thick debrite (Fig. 3) and a four metre thick parallel-bedded unit. Neither the base nor the top of the whole sequence is exposed. The sediments are predominantly fine-grained clastics (approximately 75% mudstone and 15% medium to very fine-grained sandstone) together with about 10% of gypsum. Beds in the upper and lower parallel-bedded units are between 2 and 200 mm thick, with an average of about 50 mm. Individual beds retain the same thickness and are laterally continuous for the length of exposures. The thinner beds consist of red, structureless and very fine-grained mudstone. Sedigraph determinations indicate an exceptionally fine grain size of more than 90% less than 0.2 microns in diameter. Some of the mudstones exhibit barely-perceptible millimetre-scale parallel laminations. The thicker beds show normal grading from a pale grey base of fine to medium-grained sandstone up into structureless red mudstone. The sandstones comprise well-rounded and well-sorted

[1] 1993. Estudio geológico de la región de Potrerillos y El Salvador, 26º-27º Lat. S. Informe Registrado IR-93-01. *Servicio Nacional de Geología y Minería-Corporación del Cobre (Chile)*, 2 Vols., 13 mapas 1:50.000.

FIG. 3. Debris flow deposit overlying parallel-bedded mudstones and sandstones. The whole sequence is cut by oblique gypsum veins.

quartz, feldspar and volcanic grains cemented with gypsum. The rocks are hard yet poorly consolidated and the mudstones disintegrate in water to a muddy slurry. The base of some of the graded beds show well-developed load casts up to 30 mm deep. No desiccation cracks, ripples or other sedimentary structures were observed. No bioturbation is apparent and no fossils other than microfossils were recorded.

Gypsum occurs in the form of nodules, cement in the sandstones and veins. The nodules (Fig. 4) are small, scattered, subrounded structures with irregular lobate boundaries. Most are about 1 to 2 mm with the largest reaching 10 mm in diameter. Although the nodules comprise less than 10% of the total volume, they are concentrated in some places to form a large proportion of the sediment. None exhibit aggregation into 'chicken-wire texture'. The nodules are distributed throughout the whole mass of sediment, with concentrations in the thinly-bedded red mudstones. They are more abundant near the base and become less abundant upwards through each mudstone bed. No other evaporite minerals, or pseudomorphs of minerals were recorded.

Some of the nodules consist of single, clear gypsum crystals, others are white-coloured aggregates of small gypsum crystals. In some cases the crystals have overgrown the boundary of the nodule. The shape of the nodules, together with the anhedral form of most of the crystals, indicates that they are gypsum pseudomorphs after anhydrite.

The central unit of the muddy redbed facies comprises a three metre thick debrite (Fig. 3). The lower half consists of a pale grey, structureless, gypsum-cemented sandstone, which grades

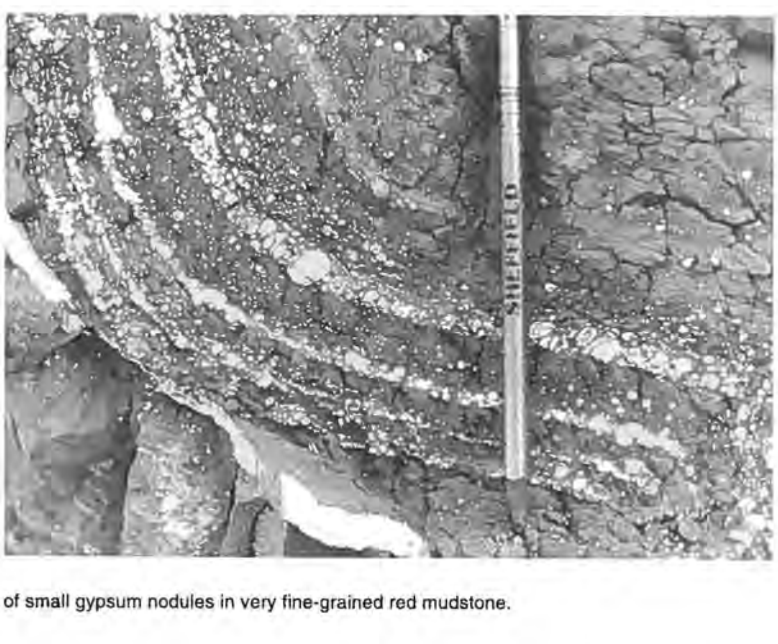

FIG. 4. Beds of small gypsum nodules in very fine-grained red mudstone.

upwards into fine mud. In the centre of this graded unit are matrix-supported slabs (intraclasts) of the parallel-bedded sediment, up to 2 m long and 200 mm thick. Some of these slabs are distorted and rounded. They are orientated subparallel to the bedding with an imbrication suggesting transport towards the west. The upper half of the debrite consists of structureless mudstone which grades up into parallel-bedded mudstone and fine-grained sandstone. Gypsum nodules are present in both the intraclasts and the structureless mudstone. The base of the debrite shows an erosive contact with the underlying parallel-bedded sediments.

INTERPRETATION OF THE MUDDY REDBED FACIES

The sedimentary facies association of the La Coipa Beds indicates deposition in a large, actively-subsiding lake (Suárez *et al.*, 1995). The surrounding uplands were dominated by volcanic rocks and granitoids. The muddy redbeds, which were deposited by turbidity currents in deep, still saline waters, represent the oldest sediments in the lake. They are apparently overlain by black mudstones deposited by turbidity currents under euxinic conditions in the deep waters of the open lake (Suárez *et al.*, 1995).

TURBIDITE DEPOSITION

The parallel-bedded units of the muddy redbed facies were deposited on a flat surface by low density turbidity currents, and by pelagic settling from muddy sediment plumes. The extremely fine grain size of the mudstones is indicative of very still water conditions. There is no evidence that any currents or wave action disrupted the settling of mud between turbidity current events. Although the bright red colour indicates oxidation, the absence of bioturbation suggests a biologically hostile and probably anoxic depositional environment. The clastic sediment probably originated under oxidizing conditions but was transported by turbidity currents into an anoxic environment.

ORIGIN OF THE DEBRITE

The three metre thick debris flow deposit (Fig. 3) was formed by the slumping of previously deposited turbidites and pelagic sediments towards the west. The slumping probably resulted from seismic shock rather than from currents, storm action or sediment overload (Johnson, 1984). The evidence for this is provided by the thin, parallel and continuous bedding of the turbidites and pelagic sediments, which indicates deposition in still water on a flat surface rather than by traction currents on a slope.

ORIGIN AND SIGNIFICANCE OF THE GYPSUM NODULES

Nodular calcium sulphate has been widely used as a criterion for inferring subaerial exposure and a saline sabkha environment in both coastal marine and lacustrine deposits (Aignar and Bachmann, 1989; Butler *et al.*, 1982; Eugster and Hardie, 1975; Handford, 1982; Hardie and Eugster, 1971; Hardie *et al.*, 1978; Kendall, 1992; Lowenstein and Hardie, 1985; Warren and Kendall, 1985). However, the sedimentary characteristics and facies association of the muddy redbeds are indicative of deposition in a still, deep-water lake rather than a sabkha.

Sulphate minerals can form at the bottom of bodies of deep water, either from geothermal brines such as those in the Red Sea (Bischoff, 1969) or by subaqueous bottom nucleation (Handford and Bassett, 1982; Rosen and Warren, 1990; Schreiber, 1986; Warren, 1982; Warren and Kendall, 1985). Both these mechanisms are unlikely in the case of the evaporites in the muddy redbeds. The absence of mineralization rules out the suggestion of geothermal brines, and bottom nucleation produces a distinctive pattern of vertical gypsum crystals.

Gypsum only crystallizes in oxygenated water and it does not normally form below the photic zone (Schreiber *et al.*, 1982). Two mechanisms have, therefore, been proposed for the transport of evaporite minerals from shallow to deep water. A rain of small crystals may result from high rates of evaporation at the surface (Anderson *et al.*, 1972; Davies and Ludlam, 1973; Dean *et al.*, 1975). Alternatively, turbidity currents may transport evaporite minerals from shallow into deeper water (Johnson, 1984; Peryt *et al.*, 1993; Peryt, 1994; Schlager and Bolz, 1977; Sturm and Matter, 1978; Vai and Ricci-Lucchi, 1977). Both mechanisms require a large body of water, saturated with the evaporite mineral, and sufficiently deep for deposition to occur beneath wave base.

The muddy redbeds formed in a deep, anoxic saline lake. This environment is commonly characterised by widespread and continuous laminations, which are normally very thin and exhibit a rhythmic and cyclic alternation of evaporite minerals with clastic, carbonaceous or carbonate layers (Anderson *et al.*, 1972; Dean and Anderson, 1982; Hardie *et al.*, 1978; Kendall, 1992; Rosen and Warren, 1990; Schreiber, 1986; Schreiber *et al.*, 1982). Fine laminae and cyclic sedimentation of this type were not observed in the muddy redbeds. They also lack the thin and continuous evaporite layers produced by a rain of crystals (Anderson *et al.*, 1972; Davies and Ludlam, 1973; Dean and Anderson, 1982; Hardie *et al.*, 1978). A rain of crystals would have produced concentrations during periods of low clastic accumulation between turbidity current events, but in the muddy redbeds the evaporite nodules are concentrated near the base rather than the top of each turbidite bed.

The occurrence and distribution of nodules within the turbidite beds suggests an origin by the transport of small crystals of gypsum-anhydrite from the saline shelf margins of the lake into deeper water. Displacement of laminae by the growth of the nodules indicates that they formed by diagenetic recrystallization, in a similar manner to those in other deep-water evaporites (Anderson *et al.*, 1972; Bischoff, 1969; Dean and Anderson, 1982; Kendall, 1992; Machel and Burton, 1991).

The absence of carbonate, either as material introduced from the lake margins by turbidity currents, or as a rain of pelagic material resulting from algal blooms, is unusual in a saline lake succession. This may indicate a cool climatic environment. Evaporites are relatively common in the Upper Triassic to Lower Cretaceous strata of northern Chile, but no other evaporitic sediments of late Triassic age have been described from the Andean Cordillera (Benavides, 1968; Suárez and Bell, 1987). This is possibly a result of the general paucity of Lower Triassic deposits, or alternatively it could be explained by deposition in an orographic desert formed by tectonic relief, outside of the normal arid climatic belt.

Deposition occurred below wave base, in an anoxic environment not affected by currents or bioturbation. The actual water depth is difficult to determine in saline lakes, where still water can be relatively shallow due to the dampening effect of density stratification (Blatt, 1992). However, the very fine-grained nature of much of the sediment suggests a water depth in excess of several hundred metres. A similar great water depth has been inferred for other examples of nodular sulphate (Anderson *et al.*, 1972; Dean and Anderson, 1982; Hardie *et al.*, 1978; Johnson, 1984; Perryt, 1994; Schreiber *et al.*, 1976).

DEFORMATION AND TECTONIC SETTING

The muddy redbeds, probably, form part of the La Coipa Beds (Suárez and Bell, 1992) which were deposited in a deep, and actively-subsiding lacustrine basin. This basin formed as a north-south elongated extensional rift associated with subduction on the active continental margin (Suárez *et al.*, 1995). The possible early Triassic age for the La Coipa Beds indicates that extension and rifting started in southwestern Gondwana before the more widely recognised and widespread middle to late Triassic extensional episode in this region (Charrier, 1979; Suárez *et al.*, 1995). Suárez and Bell (1992) identified two marine basins separated by three continental basins, between 24° and 29°S in Northern Chile. Widespread fan delta systems (both marine and lacustrine) together with abrupt lateral and vertical facies discontinuities are indicative of rift-controlled sedimentation in relatively small NNW-SSE trending basins.

The muddy redbeds dip at between 10 and 20 towards the ENE. Few joints are present, but the sediments are cut by numerous veins of fibrous gypsum (satin spar). The veins are orientated either parallel or oblique to the bedding (Fig. 5). Many of the oblique veins dip at between 38° and 55° towards the SW. Most gypsum fibres in both the bedding-

FIG. 5. Interbedded mudstones and sandstones cut by small thrust faults. The thrust fault planes are filled with gypsum veins characterised by medial scars and vertical crystal growth.

FIG. 6. Five metre thick thrust faulty zone. Both the strata and the gypsum veins are folded and disrupted.

parallel and the oblique veins are orientated nearly vertically (Fig. 5). A few veins exhibit fibrous crystals parallel or near parallel to the vein. Most veins have a medial scar indicating an origin by a crack seal mechanism.

Strata on either side of many of the oblique veins show a thrust fault displacement of between a few millimetres and several centimetres (Fig. 5). The sub-horizontal maximum compressive stress for this thrusting was directed towards the northeast.

Most of the gypsum fibres in both the bedding parallel and the oblique veins are vertically orientated. This suggests that they grew during vertical extension of the sediment. Gustavson *et al.* (1994) and Goldstein and Collins (1984) explained similar sets of veins as the product of the dissolution of underlying evaporite beds, with resulting subsidence of the sediment. Vertical extension, on pre-existing planes of weakness formed by bedding and thrust fault planes, produced fractures which were infilled by gypsum fibre growth.

Many of the gypsum veins were contorted and tightly folded by a second episode of thrust faulting. This thrusting, which was directed towards the NNE, produced an intensely disrupted subhorizontal fault zone of folded and disrupted strata up to 5 m thick (Fig. 6).

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