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REDEFINITION, STRATIGRAPHY AND FACIES OF THE LO VALDÉS FORMATION (UPPER JURASSIC-LOWER CRETACEOUS) IN CENTRAL CHILE

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ABSTRACT

Lo Valdés Formation was informally divided in three members (Spilitas, Arenáceo and Calcáreo). A redefinition of the Lo Valdés Formation is proposed here which reduces this lithostratigraphic unit to the "Arenáceo" and "Calcáreo" members; the "Spilitas" member is treated as a separate unit, termed the Baños Morales Formation. The new Baños Morales Formation (formerly "Spilitas" member of the Lo Valdés Formation) is 760 meters thick and consists predominantly of porphyry andesite and volcanic breccia, while intercalated sedimentary rocks are rare and restricted to four units, each a few meters thick. The type locality for the Baños Morales Formation is on the southern side of the El Volcán valley, in the high Andes southeast of Santiago (70°02`57``W and 33°49`41``S). Ammonites and other molluscs from the sedimentary rocks intercalated with the andesitic rock sequence indicate an early-middle Tithonian age for the Baños Morales Formation. The Lo Valdés Formation as re-defined here conformably overlies the Baños Morales Formation. Its type locality is located on the southern side of the El Volcán River (70°02`52``W and 39°49`50``S). The unit consists of siliciclastic and carbonate sedimentary rocks separated into three formal members (from base to top), the Escalador, Placa Roja and Cantera Members. The Lo Valdés Formation is late Tithonian to Hauterivian in age, based on abundant and relatively diverse ammonite assemblages.

The lithological composition and biotic content of the Lo Valdés Formation suggest shoreface, offshore transition and offshore environments. The carbonate content increases upsection. The Escalador Member represents shoreface facies, with transgressive shallow marine intervals and a storm-dominated shelf facies. Offshore transition facies are reflected in the Placa Roja Member by rhythmically-bedded siltstone, calcareous siltstone, wackestone and packstone. The presence of disseminated pyrite and high content of organic matter indicate reducing and low-energy environments. An offshore (outer-ramp) environment is present in the Cantera Member towards the top of the section and is represented by an increase in silty wackestone and mudstone and a decrease in faunal richness and abundance. The re-definition of Lo Valdés Formation, and assignation of the new Baños Morales Formation show that two main events occurred in the Andean Basin during the Late Jurassic – Early Cretaceous transition. The Baños Morales Formation records a dominance of andesitic lithologies that indicates volcanic events with quiescence, the latter evidenced by decimetre-scale sedimentary layers. A prominent lithological change, from volcanic dominance to the exclusively marine succession of the Lo Valdés Formation, marked the second event during this time in the Andean Basin.

Key words: Lo Valdés Formation, Baños Morales Formation, Chile.

RESUMEN

Redefinición, Estratigrafía y Facies de la Formación Lo Valdés (Jurásico Superior – Cretácico Inferior) en Chile central. La Formación Lo Valdés fue informalmente dividida en tres miembros (Spilitas, Arenáceo y Calcáreo). Una redefinición de la Formación Lo Valdés, incluyendo la reducción de las unidades litoestratigráficas de los miembros Arenáceo y Calcáreo, mientras que el miembro Spilitas es tratado como una unidad separada, denominada la Formación Baños Morales. La nueva Formación Baños Morales (anteriormente el miembro Spilitas de la Formación Lo Valdés) tiene 760 metros de potencia, y predominantemente consiste de andesitas porfiricas y brechas volcánicas, con sólo cuatro unidades sedimentarias de algunos metros intercaladas en estas litologías volcánicas. La localidad tipo de la Formación Baños Morales, está en la ladera sur del valle del río Volcán, en la

cordillera de los Andes, al sureste de Santiago (70°02`57``W y 33°49`41``S). Ammonites y otros moluscos provenientes de los niveles sedimentarios intercalados en las secuencias de rocas andesíticas indican una edad titoniana temprana a media para la Formación Baños Morales. La Formación Lo Valdés sobreyace concordantemente a la Formación Baños Morales. Su localidad tipo está ubicada en la ladera sur del valle del rio Volcán (70°02`52``W y 39°49`50``S). La unidad consiste de rocas siliciclásticas y carbonáticas y aquí es separada en tres miembros (de base a techo) como los Miembros Escalador, Placa Roja y Cantera. La Formación Valdés abarca del Titoniano tardío al Hauteriviano, basado en la abundancia y riqueza relativa de ammonites.

La composición litológica y el contenido biótico de la Formación Lo Valdés permiten interpretar ambientes de costero, de transición a costa afuera y de costa afuera. El contenido carbonático aumenta hacia la parte superior de la sección. El Miembro Escalador representa un ambiente costero con intervalos de transgresión de aguas someras y una facies de tormenta en plataforma. Facies de un ambiente de transición de costa afuera están reflejados en el Miembro Placa Roja por intercalaciones rítmicas de lutitas, lutitas calcáreas, wackestone y packstone. La presencia de pirita diseminada y altos contenidos de materia orgánica indican ambientes de reducción y baja energía. Ambientes de costa afuera (rampa externa) están presentes en el Miembro Cantera hacia el techo de la sección y son representados por un incremento en wackestone lutítico y mudstone y un decrecimiento en la abundancia de fauna. La redefinición de la Formación Lo Valdés, y la asignación de la nueva Formación Baños Morales muestran que existen dos eventos principales en la Cuenca Andina durante la transición del Jurásico Tardío – Cretácico Temprano. La Formación Baños Morales contiene una dominancia de litologías andesíticas que indican eventos volcánicos con una pausa, que está evidenciado por capas sedimentarias decimétricas. Un cambio litológico fuerte, de la dominancia volcánica a la Formación Lo Valdés exclusiva sedimentaria marina, marca un segundo evento durante este tiempo en la Cuenca Andina.

Palabras Clave: Formación Lo Valdés, Formación Baños Morales, Chile.

INTRODUCTION

The Lo Valdés Formation crops out east of Santiago, Chile, in the Chilean high Andes (Figure 1). The unit was originally defined by González (1963), who placed the type locality at Lo Valdés (Figure 1) and described a 1635 m thick succession of mostly volcanic rocks overlain by a marine succession rich in invertebrate fossils. The Lo Valdés Formation conformably overlies continental red-beds of the Río Damas Formation, assigned to the Kimmeridgian, and conformably underlies continental deposits of the Colimapu Formation of Aptian-Albian age (*e.g.* Klohn 1960, Thiele 1980). Here we describe the lithostratigraphy of three well-exposed sections of this volcano-sedimentary sequence in the El Volcán valley (the type locality), in Cajón del Morado, where the complete succession is exposed, being continuous and of relatively easy access; and in the Cruz de Piedra valley, that previously has been described as belonging to the Baños del Flaco Formation (Figure 1).

Biro (1964, 1980) is the only author that provided detailed documentation of the biostratigraphy and lithology of the Lo Valdés Formation at its type locality, while Hallam *et al.* (1986) added information on the succession of facies and depositional environments. Biro (1964) re-measured the type section to a total of 1456 m thickness and divided the unit into three lithostratigraphic members (from bottom to top):

1) "Spilitas", or spilite lower member, 762 m thick, dominated by porphyric andesite ("spilite") and volcanic breccia, and restricted layers of sandstone, limestone and siltstone. He assigned this member to the lower-middle and lower part of the late Tithonian (Comment: "Late" only if it a formal subdivision of the Tithonian, such as the Late Cretaceous).

2) "Arenáceo", or sandstone middle member, 72 m thick, composed mainly of sandstone and minor conglomerate and breccia. Biro (1964) assigned this member to the middle part of the late Tithonian.

3) "Calcáreo", or calcareous member; 622 m thick upper member, consisting of limestone, siltstone and calcareous sandstone; this unit was assigned to the latest Tithonian to Hauterivian, or possibly Barremian (Biro 1964).

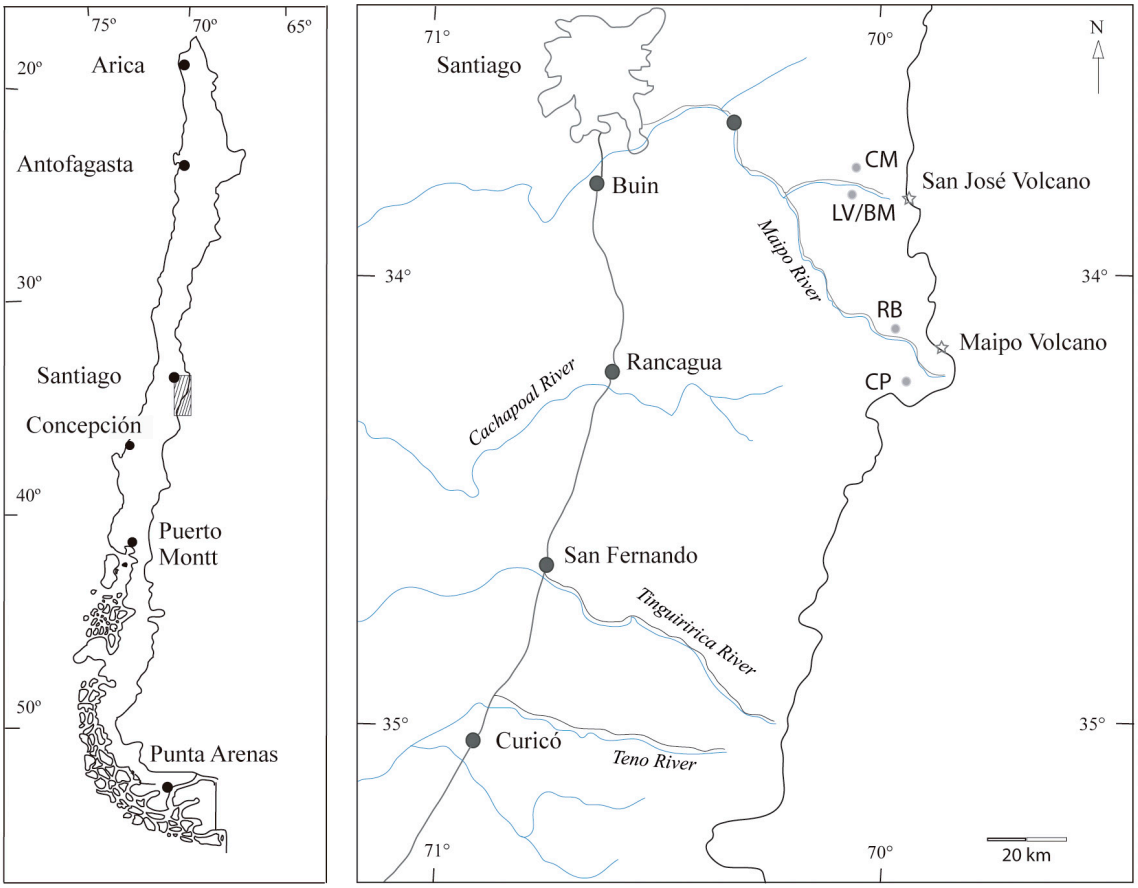

FIGURE 1. Map of Chile showing the location of outcrops of the Lo Valdés and Baños Morales Formations. CM: Cajón del Morado; LV: Lo Valdés; BM: Baños Morales at Cerro Catedral; RB: Rio Barroso; CP: Cruz de Piedra.

Assignation of the Lo Valdés Formation to the early Tithonian to Hauterivian, or even Barremian, is based on the presence of ammonites throughout the section (Biro 1964, Hallam *et al.* 1986)

This explicit difference in rock composition marks an important lithic change that includes breaks in deposition from volcanics events interspersed with periods of quiescence, evidenced by decimetre-thick sedimentary layers, and finally, an exclusively marine sedimentary succession marking a second event in the basin. We here propose a formal separation of the volcanic "Spilitas" member from the overlying sedimentary units of the Lo Valdés Formation *sensu stricto*. This suggestion is based on the concept of *formations* as homogeneous stratigraphic and sedimentological units (*e.g.*, lithology, mineralogical composition, texture, primary sedimentary structures and fossil content; Coe *et al.* 2003, Catuneanu 2006, Nichols 2009, North American Stratigraphic Code 2005). We propose to separate the volcanic "Spilitas" member from the sedimentary "arenáceo-calcáreo" members of Biro (1964) and propose the name Baños Morales Formation for the spilite-dominated member overlying the Rio Damas red-beds. The Lo Valdés Formation is reserved for the sedimentary succession overlying this volcanic-dominated unit.

The Baños Morales Formation proposed here is thus defined as a predominantly volcanic unit of andesite porphyry and sparse intercalated sedimentary layers. According to the classical definition by González (1963) and detailed description of Biro (1964), this unit, the former "Spilítas member", is 760 m thick.

The Lo Valdés Formation as redefined here is 519 m thick at its type locality and consists of sedimentary rocks ("arenáceo" and "calcáreo" members). At the type locality, an andesitic dike of 20 m thickness occurs between 73 to 93 m. This dyke is post-sedimentary and was therefore not considered to form part of the sedimentary column. It is not included in the description of the Lo Valdés Formation.

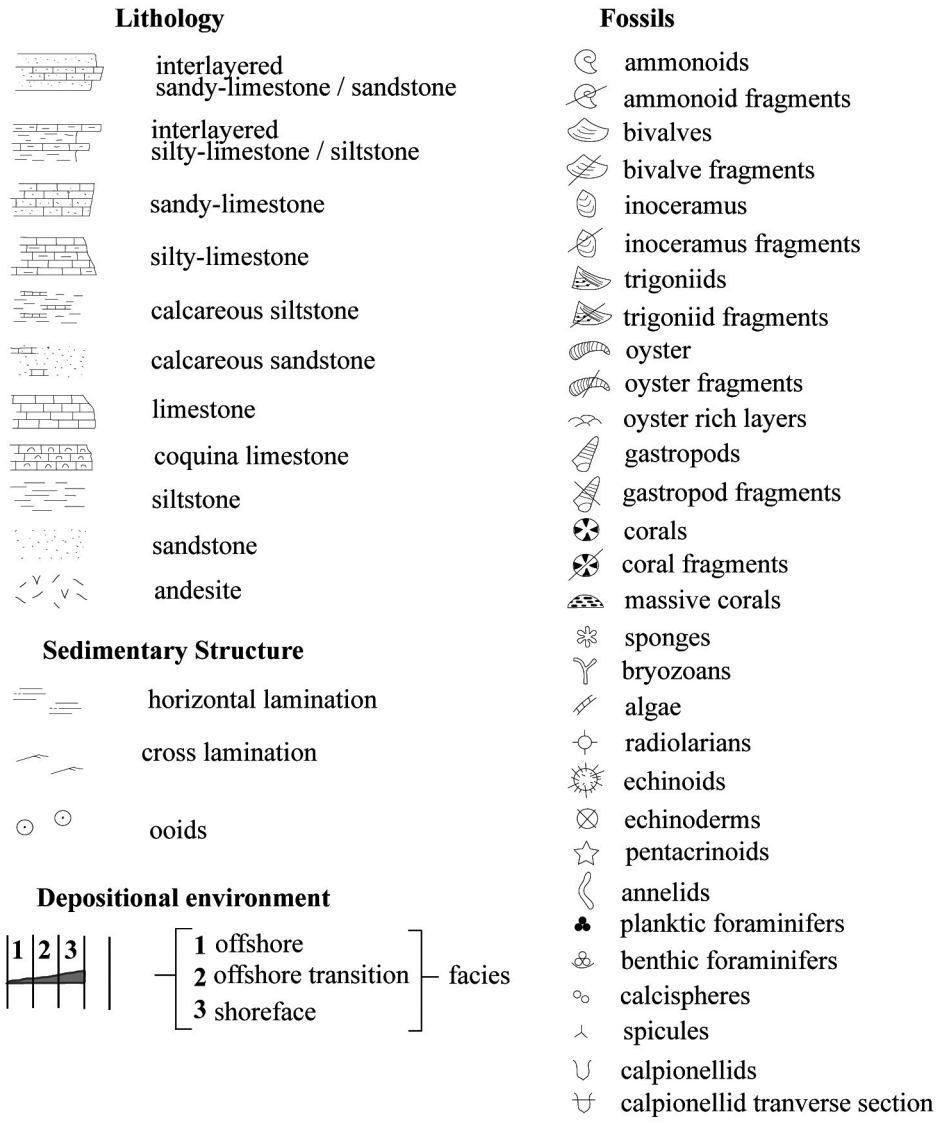

FIGURE 2. Key to symbols and abbreviations used in the stratigraphic columns.

2. BAÑOS MORALES FORMATION

Definition

The Baños Morales Formation is here proposed to replace the "Spilitas" member of the Lo Valdés Formation, as defined by Biro (1964). It is a predominantly volcanic unit consisting of andesite porphyry. Four meter-thick sedimentary units are intercalated in the sequence and consist of coarse- to medium-grained siliciclastic and calcareous rocks. The type locality of this new stratigraphic unit is located south of Baños Morales Village, on the south side of the El Volcán River valley, at 70°02`57``W and 33°49`41``S (BM locality, Figure 1). The Baños Morales Formation overlies the Río Damas Formation and underlies the Lo Valdés Formation as redefined here. Both contacts are sharp but conformable (Figure 3).

Lithostratigraphy

At the type locality, the unit is 760 m thick (Figure 3). Two members are differentiated, the La Cuesta and Placa Verde Members.

The La Cuesta Member forms the base of the Baños Morales Formation. It is 117 m thick, consisting of volcanic rocks intercalated with decimetre-scale sedimentary layers. Just above the underlying Río Damas Formation isa 15 m thick interval of silty limestone containing scarce fragments of bivalves and scarce ammonoids. Upsection, between 15and 87.5 m from the base, limestone alternates with andesite. The limestone forms units of between 1 and 5 m thickness. The sedimentary rock is silty and contains scarce fragments of bivalves. Andesite porphyries form units between 5 and 30 m thickness and present idiomorphic phenocrystals of plagioclase in a fine-crystalline, chloritized matrix (Figure 3). Between 87.5 and 117 m, silty wackestone contains fragments of inoceramids and other bivalves, as well as abundant calcispheres (Figure 3).

The Placa Verde Member is 643 m thick and consists of andesite. Between 117.5 and 418.5 m, andesite porphyry is present and characterized by up to 2.4 mm long phenocrystals of plagioclase within a chloritized matrix; pillows and ellipsoidal structures are common and reach diameters of 0.1 to 0.5 m. The unit underlies a porphyritic andesite with up to 5 mm long phenocrystals of plagioclase within a chloritized matrix, occurring from 418.5 to 637.5 m (Figure 3).

Between 637.5 and 653.25 m, mixed clastic-carbonate sedimentary rocks are composed of a 0.7 m thick, fine conglomerate at the base of the unit, underlying a 0.8 m thick calcareous sandstone, a 0.1m thick unit of silty limestone, a 0.9 m thick calcareous sandstone, 0.15 m silty limestone, a 2.1 m thick sandy limestone with fragmentary echinoderms, and an 11 m thick unit of silty limestone (Figure 3). Biro (1964) described ammonoids, inoceramids, oysters, trigoniids and other bivalves from these carbonate and clastic layers.

From 653.25 to 760.25 m, a 107 m thick unit of andesite with plagioclase phenocrystals within a chloritized matrix forms the top of the Baños Morales Formation (Figure 3), which is conformably overlain by the Lo Valdés Formation.

The Baños Morales Formation at Cajón del Morado (70°01`00``W and 33°46`24``S) is 591 m thick (Figures 1- 5) and also overlies the Río Damas Formation conformably. The La Cuesta Member is 220 mthick, being composed of andesite and intercalated sedimentary layers. At the base, a unit up to 30 m thick is composed of calcareous siltstone with planar lamination. Upsection, between 30 and 81 m, an 8 m thick andesite underlies 15 m of well-sorted calcareous sandstone. It is fine-grained with horizontal lamination, along with a few ooids and disseminated pyrite. This unit underlies 17 m of andesite, 6 m of calcareous siltstone and 5 m of well-sorted, fine-grained, calcareous sandstone with horizontal lamination and disseminated pyrite (Figure 5). From 81 to 170 m, is an 89 m thick unit of andesite with plagioclase phenocrysts within a chloritized matrix. The andesite underlies a 50 m thick calcareous siltstone with horizontal lamination, rich in organic matter and disseminated pyrite. The siltstone contains radiolarians, fragments of inoceramids and other bivalves.

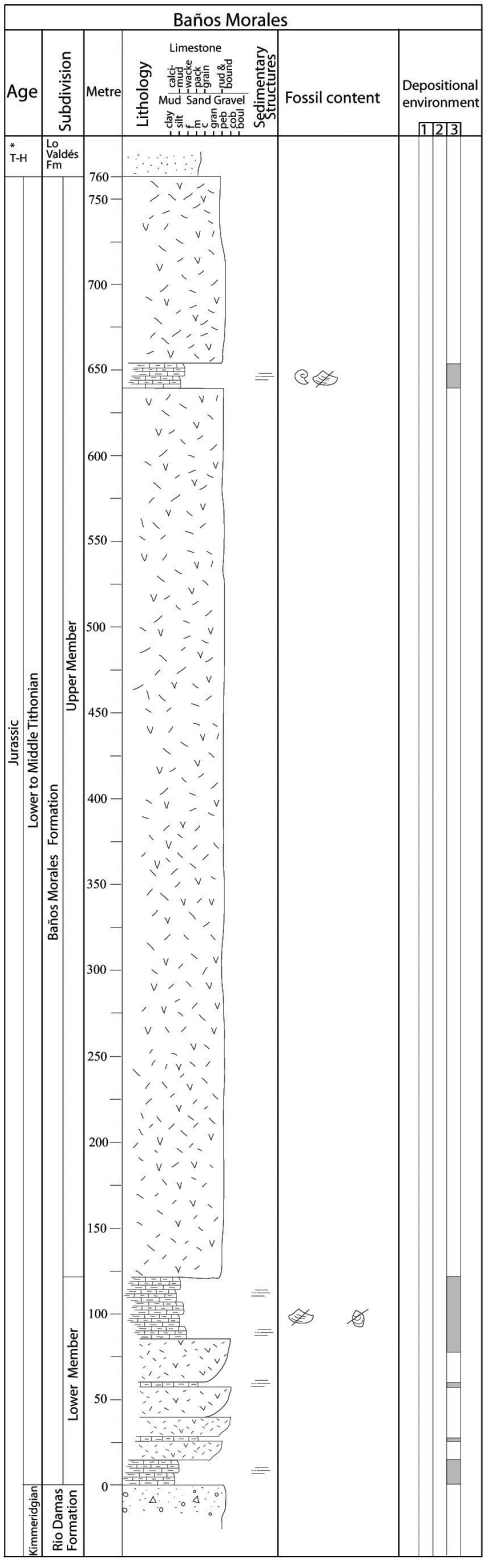

FIGURE 3. Cross section of the Baños Morales Formation at its type locality, with differentiation of lithological members. * T-H: Upper Tithonian to Hauterivian.

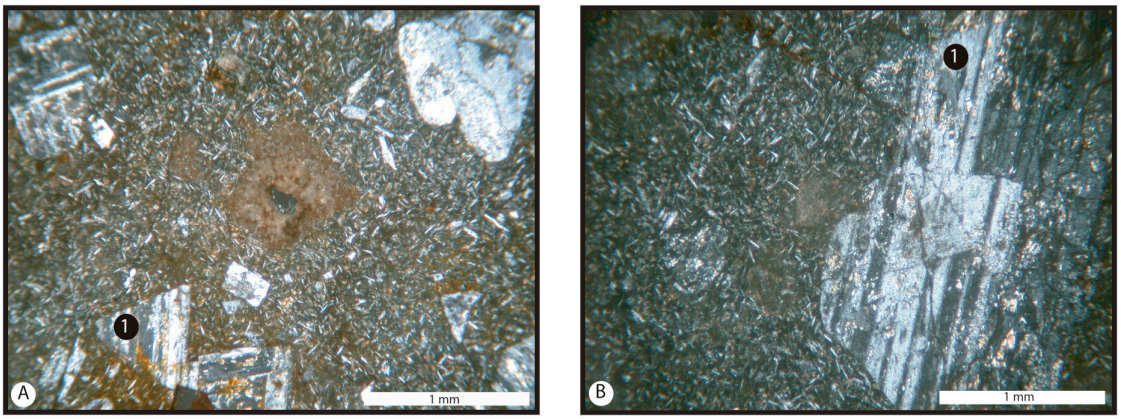

FIGURE 4. Andesite in the Baños Morales Formation. **A1**: Andesite with phenocrystals of plagioclase within chloritic matrix. **B1**: Andesite with large phenocrystals of plagioclase.

The Placa Verde Member is 371 m thick. Between 220 and 591 m, andesite shows plagioclase phenocrystals, sericitic alteration and a chloritized matrix. It also contains scarce beds of volcanic breccias (Figure 5).

Fauna and age

To date, the only detailed paleontological research on the Baños Morales Formation (the former Spilitas member of the Lo Valdés Formation) was done by Biro (1964). His ammonite assemblage was re-studied here. We identified *Aulacosphinctes windhauseni*, *Aulacosphinctes* cf. *proximus*, *Virgatosphinctes* cf. *andesensis*, *Windhauseniceras humphreyi*, *Wichmanniceras* aff. *mirum* and *Paraulacosphinctes striolatus* in sedimentary layers between andesite units at the type locality and at Cajón del Morado (Figure 6). In Argentina, a similar assemblage was considered to represent the early to middle Tithonian (Leanza 1980, Riccardi 2008, Parent *et al.* 2011). We agree with Biro's (1964) interpretation.

Depositional Setting

The Baños Morales Formation is dominated by andesitic rocks with plagioclase phenocrystals. The rock matrix is chloritized. Pillows and ellipsoidal structures are frequent and indicate submarine lava flows (Biro 1964). Restricted units of volcanic breccia are also present. A detailed description of the volcanic rock sequence is beyond the scope of this paper in which we focus on the sedimentary units of the Baños Morales Formation and the overlying Lo Valdés Formation. The depositional environment interpretation of sedimentary units of the Baños Morales Formation is based on siliciclastic and carbonate basin models of Wilson (1975), Burchette and Wright (1992), Coe *et al.* (2003) and Nichols (2009).

Sedimentary units of the Baños Morales Formation predominantly consist of limestone, siltstone and sandstone. The first few meters of the formation are characterized by silty limestone with fragmentary fossils of bivalves and ammonoids. This unit is interpreted to represent an environment between the storm wave base and inner ramp during a transgressive event, which took place in an instable regimen. The latter is reflected by the fact that silty limestone beds are intercalated with dominantly volcanic rocks. The sedimentary units contain scarce fragments of bivalves, and would indicate an inner to mid-ramp environment during a transgression. A silty wackestone unit at the top of the La Cuesta Member contains fragments of bivalves and abundant calcispheres, representing a mid-ramp environment in a transgressive event. At the type locality of the Placa Verde Member, a decimeter-thick, fine conglomeratic bed in the lower part of the formation is interpreted to represent a high-energy shoreface facies marking marine transgression. Higher up within this sedimentary unit, is a rhythmic succession of calcareous sandstone and sandy wackestone layers that contains abundant oysters and trigoniids corresponding to the lower shoreface to offshore zone, indicating a transgressive environment and shallow water of less than 30 m (Francis & Hallam 2003). The

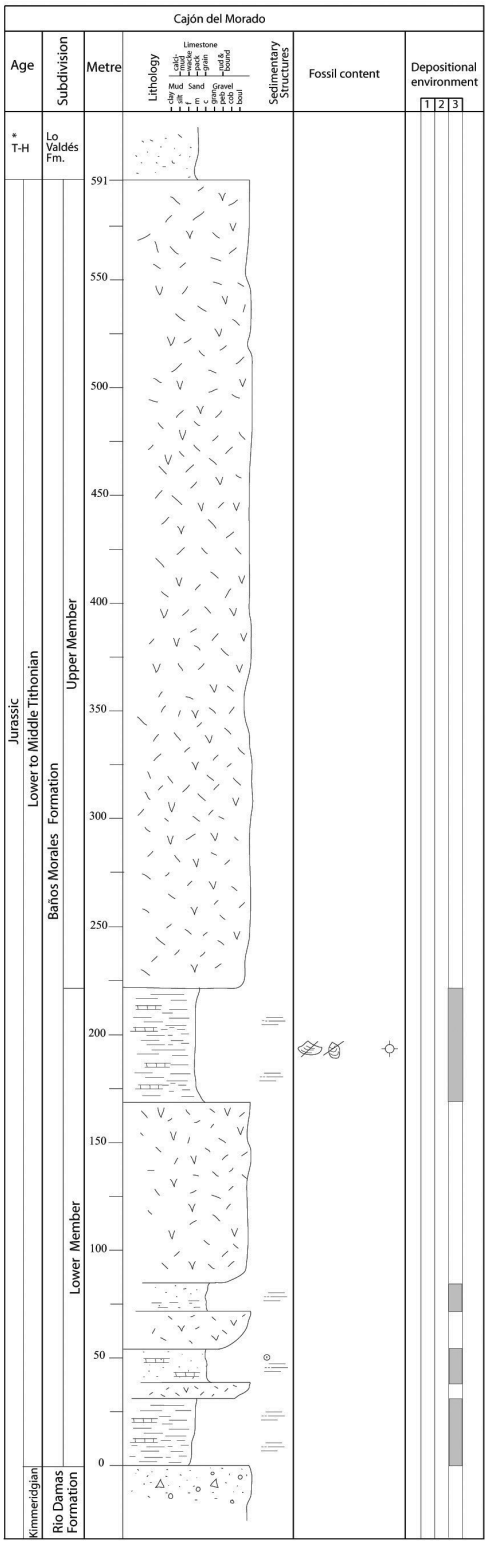

FIGURE 5. Stratigraphic column of the Baños Morales Formation at Cajón del Morado, with differentiation of lithological members.
* T-H: Upper Tithonian to Hauterivian.

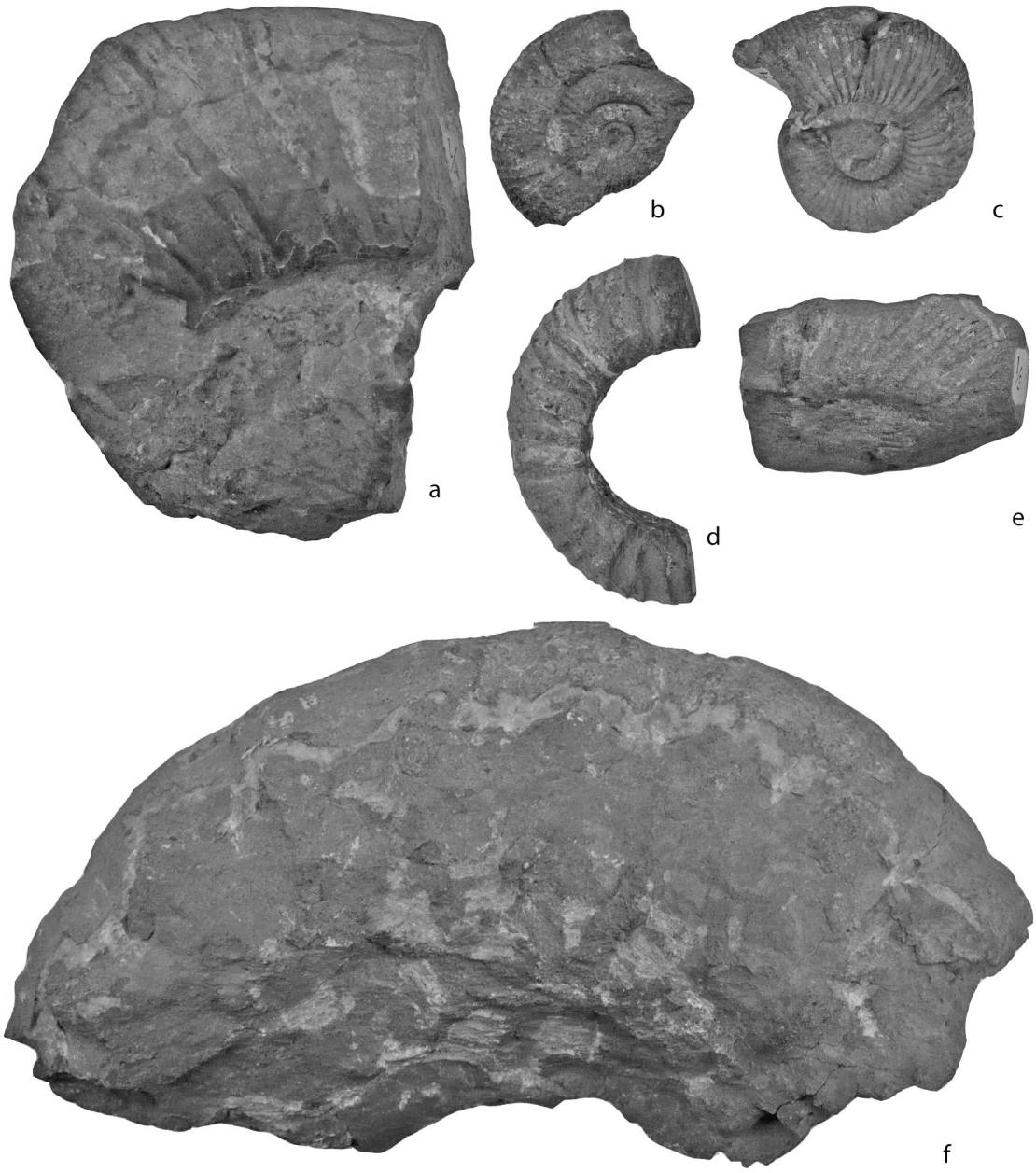

FIGURE 6. Ammonoids from sedimentary rocks interlayered with volcanic beds in the Baños Morales Formation. **a, e:** *Virgatosphinctes* cf. *andesensis*, CPUC/LV/I-4 and CPUC/LV/I-5. **b:** *Wichmanniceras* aff. *mirum* CPUC/LV/II-2. **c:** *Paraulacosphinctes striolatus* CPUC/LV/I-4. **d:** *Aulacosphinctes windhauseni* CPUC/LV/I-2.. **f:** *Windhauseniceras humphreyi* CPUC/LV/II-1. All figures are x1. These fossils, collected and tentatively identified by Biro (1964), were re-classified here.

upper part of the unit is composed of sandy mudstone and silty mudstone with ammonoids, inoceramids, oysters, others bivalves and scarce trigoniids, that are interpreted as representing an inner ramp / offshore transition environment reflecting the continuing transgressive event, in turn interrupted by the volcanics events recorded within the succession.

3. LO VALDÉS FORMATION

Redefinition

The Lo Valdés Formation as defined here is a sedimentary succession consisting of sandstone, calcareous sandstone, siltstone, calcareous siltstone, sandy limestone, silty limestone and limestone. Three lithostratrigraphic members are differentiated, denominated here the Escalador, Placa Roja and Cantera Members. The Escalador Member forms the basal unit and consists of sandstone with a variable calcareous content. Upsection, the Placa Roja Member is dominated by siltstone, while the uppermost Cantera Member is composed mainly of carbonates. The type locality of the Lo Valdés Formation corresponds to the site determined by González (1963) along the southern side of the El Volcán River at Catedral Hill, at 70°02`52`` W and 39°49`50`` S (Lo Valdés section, Figure 1). The Lo Valdés Formation conformably overlies the Baños Morales Formation and underlies an unnamed volcanoclastic breccia (see below).

Lithology and thickness

Lo Valdés Section (Type locality).

At the type locality, the total thickness of the Lo Valdés Formation is 539 m (Figures 7, 8). The Escalador Member forms the base of the unit and is approximately 73 m thick (Figs. 7- 8). The unit consists of well-sorted and fine-grained calcareous sandstone with occasional horizontal and cross-lamination, ammonoids, inoceramids, oysters, trigoniids and other bivalves, rare gastropods and corals (*Actinastrea scyphoidea*). The topmost part of the Escalador Member, from 63 to 73 m, is composed of unfossiliferous, calcareous sandstone (Figure 8).

A green andesitic unit is present (Figure 8) between the Escalador Member and underlying the Placa Roja Member. This 21 m thick “andesite” is easily mistaken in outcrop for a stratiform unit, but it represents a dyke structure which cuts the sequence. Its discordant nature is evident from the regional context and stratigraphical placement of the dyke at other localities. At Laguna Ruhillas, for instance, the dyke cuts through the Cantera Member. At Cajón del Morado, on the other hand, the andesitic dyke structure was not identified in the Lo Valdés Formation.

The Placa Roja Member is 193 m thick and consists of siltstone, calcareous siltstone and silty limestone (Figure 8). The base of the Placa Roja Member, between 94 m and 193 m, is formed by a 99 m thick unit of rhythmically bedded siltstone and calcareous siltstone, which contains ammonoids, oysters, inoceramids and other bivalves, rare gastropods, radiolarians, benthic foraminifers as well as calcispheres, and high concentrations of organic matter (Figure 8).

Between 193 m and 242 m of the section, rhythmically bedded, calcareous siltstone and silty limestone form a 49 m thick unit with horizontal lamination, disseminated pyrite and organic matter. The calcareous siltstone layers reach between 0.75 m and 0.85 m in thickness (Figure 8). The silty mudstone forms layers 0.9 m to 1 m thick and contains ammonoids, bivalves, calcispheres and occasional annelids. Oyster biostromes are present at 213 m, with 1.2 m thickness, at 216 m with 0.5 m thickness, and at 234 m with 0.4 m thickness. Oyster shells are small, with a maximum length of 30 mm.

Between 242 m and 251 m, a 9 m thick unit consists of rhythmically bedded calcareous siltstone with horizontal lamination forming layers of up to 0.5 m thick, and rhythmically bedded, silty mudstone to silty wackestone with horizontal lamination forming 1 m thick beds. These layers contain ammonoids, bivalves, gastropods, calcispheres, and rare foraminifers.

From 251 m to 287 m, a 36 m thick unit of silty limestone and calcareous siltstone forms the topmost part of the Placa Roja Member. Silty limestone (wackestone to mudstone) layers are 2 to 3 m thick, while calcareous siltstone forms layers of 0.3 to 0.5 m thick. These layers contain disseminated pyrite and

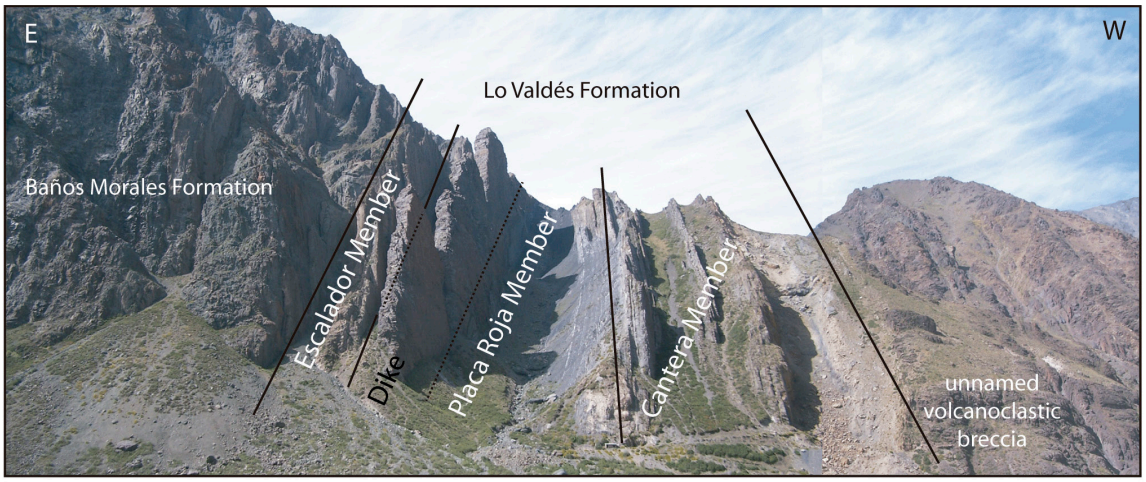

FIGURE 7. Cross section of the Lo Valdés Formation at Lo Valdés (type locality), with differentiation of lithological members.

organic matter. The faunal content increases upsection and comprises ammonoids, fragments of oysters, inoceramids and other bivalves, calcispheres, rare echinoderms and algae. Layers rich in oysters are present at 253 m, 262 m and 286 m.

The Cantera Member is 252 m thick and consists of sandy and silty limestone and calcareous siltstone (Figure 8). The base of the member, from 287 m to 390 m, is a 103 m thick unit of sandy wackestone. Some layers present increased amounts of disseminated pyrite. Ammonoids and bivalves are rare in the first 34 m, but the faunal content increases between 321 and 372 m, and ammonoids, oysters, inoceramids, other bivalves and echinoderms are present. A 0.9 m thick layer rich in oysters is present at 321 m.

Upsection, from 390 m to 446 m, a 56 m thick unit of sandy wackestone is highly fossiliferous (Figure 8); we identified abundant oysters, inoceramids and other bivalves, and rare ammonoids, gastropods, bryozoans and echinoderms.

Between 446 m and 539 m, sandy wackestone is intercalated with calcareous siltstone (Figure 8). The sandy wackestone layers are 2 to 3 m thick, while calcareous siltstone forms layers of between 0.1 and 0.5 m thick. From 446 m to 490 m, fauna are scare and consist of bivalves, sponge spicules, calcispheres and possible calpionellids. Upsection, between 490 and 539 m, ammonoids and bivalves are more abundant and accompanied by scarce sponge spicules, fragments of echinoderms, calcispheres and rare foraminifers.

An unfossiliferous volcanoclastic breccia with angular clasts of silty limestone overlies the Lo Valdés Formation with a conformable contact. The unit presents a visible thickness of 100 m (Figs. 7, 8) and was originally defined as part of the Lo Valdés Formation (González 1963, Biro 1964), but is here considered to form a separate lithostratigraphic unit. According to Godoy *et al.* (1988) the breccia forms the base of the Colimapu Formation, but Fock *et al.* (2006) suggested that it represents a fault breccia forming part of the El Diablo-El Fierro Fault System.Cajón del Morado Section

A 588 m thick section in the Cajón del Morado Valley (70°01`50``W and 33°46`39``S) is here proposed to form a paratype locality of the Lo Valdés Formation. The three members defined previously (Escalador, Placa Roja, Cantera: Figures 9-10) are also identified in this section. The Escalador Member is 160 m thick and overlies the Baños Morales Formation with a sharp and possibly disconformable contact. The lowermost unit, between 0 m and 10.6 m, consists of cross-laminated, well-sorted, fine-grained, calcareous sandstone with fragments of oysters and other bivalves as well as gastropods (Figure 10).

Upsection, between 10.6 m and 35 m, well-sorted fine-medium grained calcareous sandstone and sandy mudstone contains occasional bivalves and gastropods, scarce algae, sponges and corals (faceloids, Placocoeniidae, *Cladophyllia qiebulaensis*). The uppermost 6 m consist of sandy wackestone with abundant

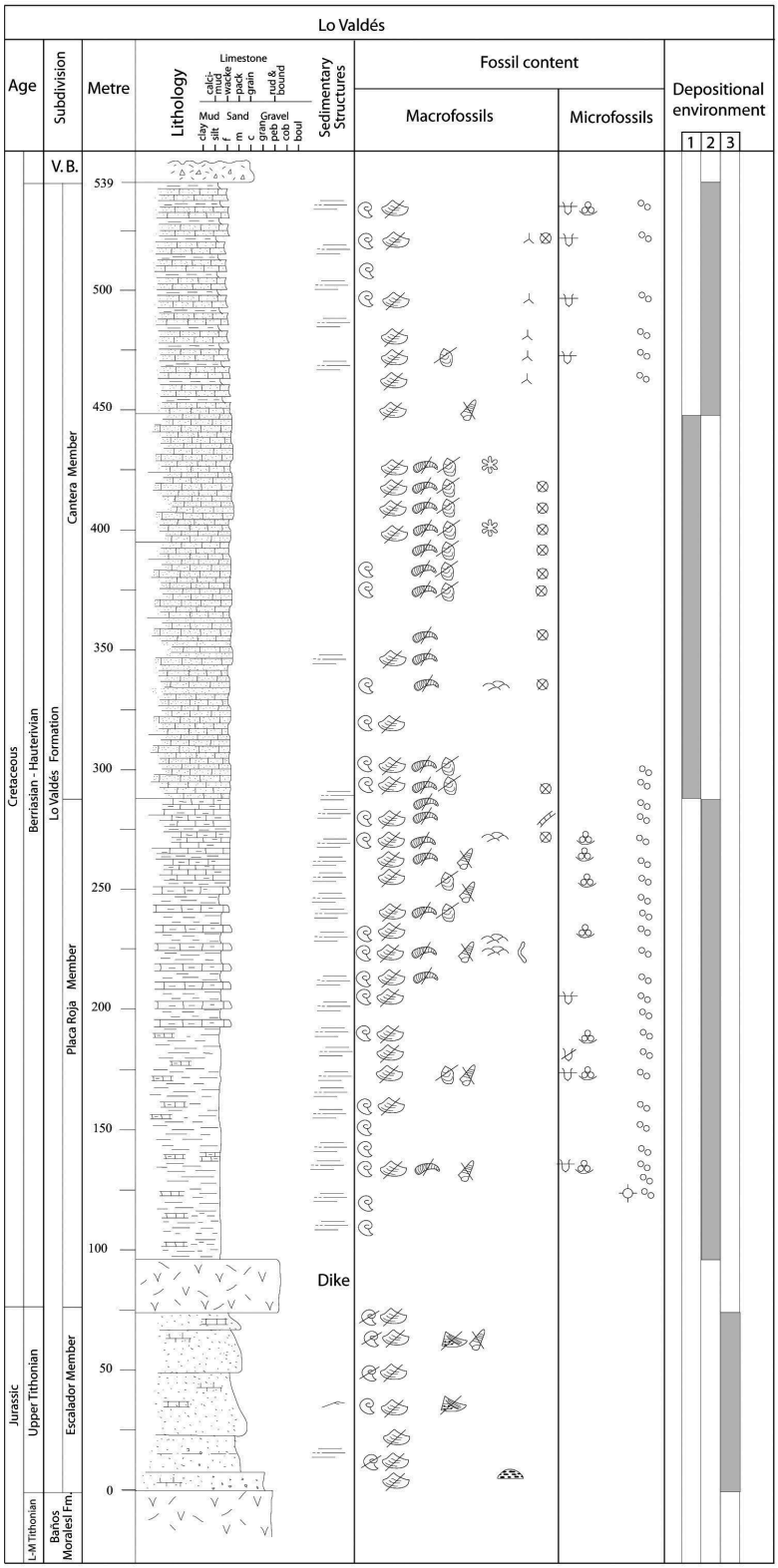

FIGURE 8. Stratigraphic column of the Lo Valdés Formation at the type locality, with differentiation of lithological members. V.B.: unnamed volcanoclastic breccia.

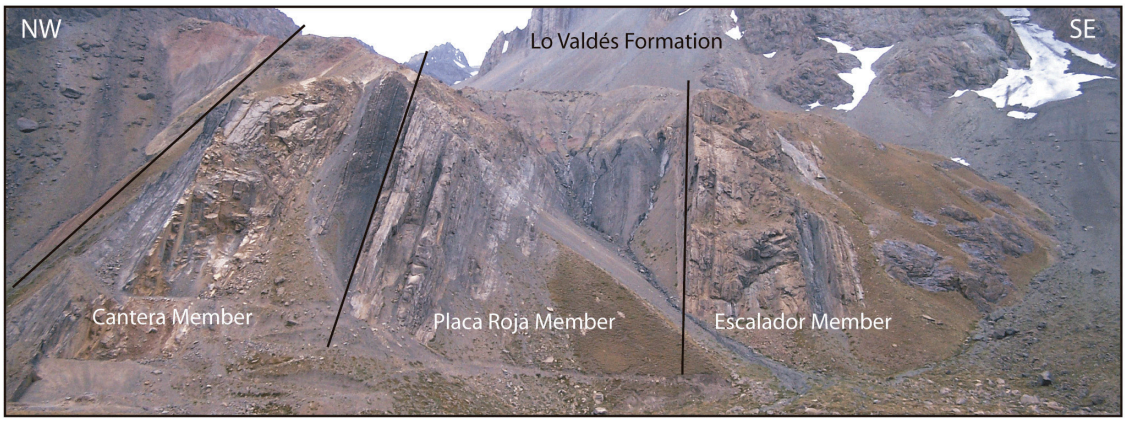

FIGURE 9. Cross section of the Lo Valdés Formation at Cajón del Morado, with differentiation of lithological members.

ammonoids, bivalves and rare algae (Figure 10). Between 35 m and 61.5 m of the section, horizontally laminated, well-sorted, fine-grained, calcareous sandstone contains ammonoids, inoceramids and other bivalves as well as rare gastropods (Figure 10).

At 61.5 m, a 6.5 m thick calcareous sandstone is interlayered with three fossiliferous levels of calcareous sandstone, each 0.15 m thick, with abundant ammonoids, inoceramids and other bivalves, scarce gastropods, bryozoans and algae.

From 68 to 84 m, a horizontally laminated, sandy packstone is present and contains ammonoids, fragments of inoceramids, trigoniids and other bivalves as well as algae (Figure 10).

A 36 m thick unit of calcareous sandstone with occasional ooids (Figure 10) is present between 84 and 120 m and contains ammonoids, oysters, inoceramids, trigoniids and other bivalves, as well as rare bryozoans and algae.

At 120 m, a 9 m thick unit of silty mudstone contains scarce fragments of ammonoids and bivalves. Overlying this unit, between 129 and 144 m, a 15 m thick interval of sandy packstone and sandy wackestone forms 0.1 m to 0.2 m thick layers. This unit contains scarce ammonoids, rare fragments of oysters, inoceramids, trigoniids, other bivalves and bryozoans (*e.g.*, at 138 m).

The uppermost unit of the Escalador Member, between 144 and 160 m, is 16 m thick and consists of calcareous sandstone with scare fragments of ammonoids, oysters, inoceramids and other bivalves. Isolated fragments of indeterminate algae are registered in the topmost layers (Figure 10).

The Placa Roja Member is 217 m thick (from 160 to 376 m of the section) and consists of siltstone, calcareous siltstone and silty limestone (Figure 10).

The lowermost unit, between 160 and 174 m, consists of calcareous siltstone, silty wackestone and silty packstone, forming layers of 0.3 to 0.7 m thickness. These deposits have visible organic matter and also contain scarce ammonoids, oysters and other bivalves, rare fragments of gastropods and echinoderms (Figure 10).

Upsection, from 174 to 273 m, a 99 m thick unit consists of rhythmically bedded layers of siltstone and calcareous siltstone with abundant organic matter (Figure 10). The interval between 174 and 256 m is relatively rich in ammonoids and calcispheres, and also contains scarce fragments of inoceramids, oysters and other bivalves, as well as rare gastropods, algae and benthic foraminifers, sponge spicules, radiolarians, foraminifers, and possible calpionellids. Several layers contain disseminated pyrite (Figure 10). Between 256 and 263 m, the proportion of calcareous siltstone gradually increases and ammonoids are the dominant faunal elements, accompanied by common inoceramids and other bivalves. At 257 m, a two cm-thick level with abundant oysters was identified. Upsection, between 263 to 273 m, a 9 m thick calcareous siltstone interlayered with a thin-bedded siltstone forming layers between 0.03 and 0.15 m thick contains bivalves

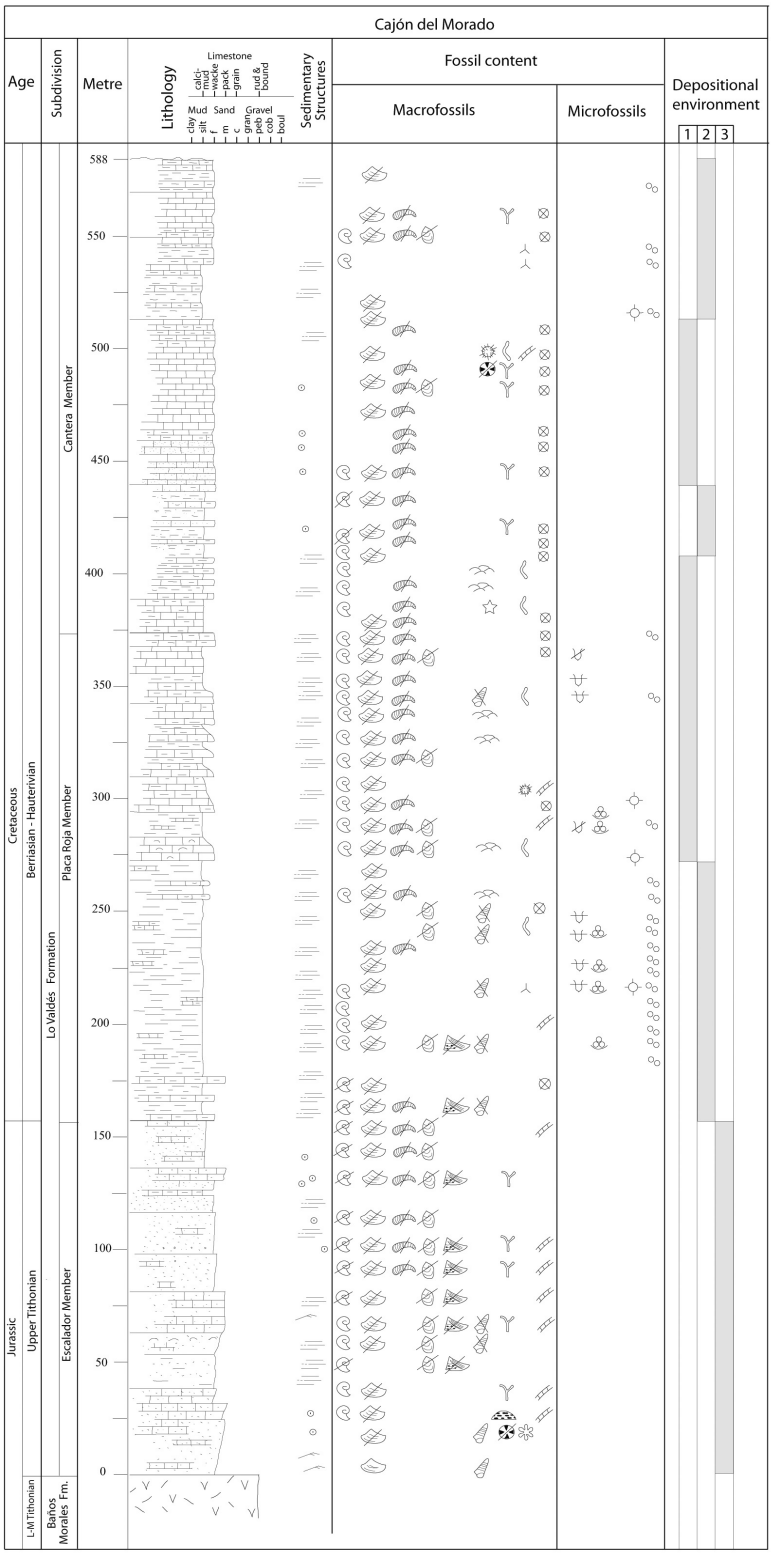

FIGURE 10. Stratigraphic column of the Lo Valdés Formation at Cajón del Morado, with differentiation of lithological members.

and calcispheres (Figure 10). Between 273 and 286 m, a 13 m th ick unit of silty mudstone and silty wackestone presents abundant ammonoids, oysters and other bivalves, as well as rare radiolarians and annelids. The unit also contains two layers rich in oysters which reach 4 m (between 274 and 278) and 1 m (between 280 and 281 m) in thickness.

The unit underlies 14 m of calcareous siltstone, between 286 and 302 m, with a 2 m thick, horizontally laminated wackestone interlayered between 290 and 292 m. Disseminated pyrite and organic matter are abundant. The faunal assemblage is formed by ammonoids, rare oysters, inoceramids, algae, foraminifers, abundant calcispheres and possible calpionellids (Figure 10).

Upsection, between 302 and 345 m, are silty mudstone interlayers with calcareous siltstone. Horizontal lamination, disseminated pyrite and organic matter are common and the faunal assemblage includes abundant ammonoids, rare oysters and other bivalves (Figure 10).

Three wackestone intervals are present within this unit from 317 to 319.5 m, from 331 to 333.7 m (2.7 m thick), and from 341 to 343.5 m (2.5 m thick). A 0.2 m thick layer of calcareous siltstone is present between 333.2 and 333.4 m (Figure 10) and contains some ammonoids, scarce oysters and other bivalves, annelids and calcispheres. In the uppermost meters of the unit (341 to 345 m), the proportion of ammonoids increases. Layers rich in oysters are also abundant and were detected at 330.7 m (0.15 m thick) and at 341 m (0.5 m thick).

Between 345 and 376 m, silty mudstone forms layers of 1.5 to 2 m in thickness, which are intercalated with 0.4 m to 0.5 m thick beds of calcareous siltstone and calcareous sandstone (Figure 10). In the upper part of this interval, approximately at 368 m, the faunal abundance and richness increase. This unit contains abundant ammonoids, oysters and inoceramids, scare echinoderms and possible calpionellids. At 369 m, a 1 m thick oyster biostrome is interlayered with silty wackestone containing abundant ammonoids; it overlies a 1 m thick, unfossiliferous, calcareous sandstone (Figure10).

The top of this member is characterised by a 5 m thick (371 to 376 m) horizontally laminated silty wackestone with disseminated pyrite and organic matter, abundant calcispheres, scarce ammonoids, oysters, and echinoderms (Figure10).

The contact between the Placa Roja Member and overlying Cantera Member is gradual, and characterised by an increase in carbonate content. At the base of Cantera Member, between 376 and 412 m, is silty mudstone interlayered with calcareous siltstone (Figure 10). This interval contains ammonoids, common fragments of oysters and other bivalves and rare annelids, echinoderms and pentacrinoids. A 2 m thick, oyster-rich layer is present from 396 to 398 m.

The interval between 412 and 441 m is not well exposed. It consists of calcareous sandstone of variable thickness and interlayers of silty wackestone and centimetre-thick calcareous sandstone (Figure 10). Fauna are scarce and consist of ammonoids, oysters and other bivalves, bryozoans and echinoderms.

Upsection (441 to 513 m), were recorded a 72 m thick wackestone (Figure 10). In the lower part, from 441 to 454 m, scare ammonoids, oysters, echinoderms and bryozoans are present. The faunal abundance decreases further in the middle part of the unit between 454 and 483 m. Only rare oysters and echinoderms were detected; disseminated pyrite is also present. The faunal abundance increases again in the upper part of the unit (483 to 513 m), where fragments of oysters and inoceramids are present, together with a few layers showing abundant fragments of corals, echinoids, bryozoans, annelids, algae and sponge spicules (Figure 10).

From 513 to 557 m, calcareous siltstone is interlayered with silty mudstone and mudstone . These lithologies contain ammonoids, fragments of oysters, inoceramids, other bivalves and echinoderms (Figure 10).

From 557 to 568.5 m, an 11.5 m thick wackestone contains an oysters, scare fragments of bryozoans and echinoderms.

Between 568.5 and 582 m, silty mudstone interlayers with calcareous siltstone form units of 1 to 2.5 m thickness (Figure 10). Layers of silty mudstone increase in thickness upsection and reach individual thicknesses of 1 to 5 m; fossils are scarce in this interval and only consist of bivalves. The contact with the overlying unit is not exposed.

Cruz de Piedra section

Sections in the Cruz de Piedra area were first documented by Corvalán (1956) as Tithonian to Hauterivian in age. Klohn (1960), Charrier (1981) and Aguirre-Urreta and Charrier (1990) assigned the section to the Baños del Flaco Formation, based on the predominantly siliciclastic character of the succession and the faunal assemblage. Nevertheless, our survey leads us to conclude that deposits at Cruz de Piedra rather correspond to lithologies typical of the Lo Valdés Formation (see below).

The Cruz de Piedra section is 150 m thick and located in the Cruz de Piedra Creek (69°56`25``W and 34°14`40``S), approximately 9 km southeast of the Chilean Police Border Station "Avanzada Cruz de Piedra" (Figure 1). The section encompasses the Escalador and Placa Roja Members of the Lo Valdés Formation (Figure 11).

The Escalador Member is 50 m thick; its lower contact conformably overlies green sandstone of the Rio Damas Formation. The Escalador Member is unfossiliferous and consists of monotonous, fine-grained calcareous sandstone with cm- thick layers of coarse, calcareous sandstone (Figure11).

The thickness of the Placa Roja Member is approximately 100 m. It consists of rhythmically bedded layers of calcareous siltstone and silty limestone with horizontal lamination and high concentrations of organic matter (Figure 11). Individual layers of calcareous siltstone are between 0.8 and 0.5 m thick, whereas interlayered silty wackestone forms layers of 0.5 to 0.3 m thick. Ammonoids and calcispheres are abundant, but oysters, inoceramids and other bivalves, gastropods, echinoderms and radiolarians are also present. The upper limit of this member is not exposed due to overlying Holocene sediments. Previously, Charrier (1981), described a section in the "Nacientes del Estero Cruz de Piedra", where the Mesozoic succession is inverted, but more complete.

Faunal assemblage and age

Biro (1964) analysed the biostratigraphy of the Lo Valdés Formation as redefined here and differentiated six biozones based on the ammonoid assemblages. The principal faunal elements described by Biro (1964) and Hallam *et al.* (1986) are *Corongoceras alternans*, *Substeueroceras koeneni*, *Argentiniceras noduliferum*, *Spiticeras damesi*, *Cuyaniceras transgrediens*, *Favrella angulatiformis* and *Crioceras andinum*. These taxa were also identified during our survey and allow for an assignation of the Lo Valdés Formation to the Late Tithonian to Hauterivian (*e.g.* Leanza 1980, Aguirre-Urreta 2001, Parent 2003, Rawson 2007, Riccardi 2008, Parent *et al.* 2011). A detailed systematic description of the ammonite assemblage and biostratigraphic discussion of the Lo Valdés Formation is presently in preparation.

4. DEPOSITIONAL FACIES OF THE LO VALDÉS FORMATION

Hallam *et al.* (1986) grouped the Lo Valdes Formation into four major facies: (1) *Rhaxella*-rich, biosparitic limestone and sandy limestone (Tithonian), (2) Crinoid-oyster-rich, biosparitic limestone (upper Valanginian), (3) organic-rich biosparite, and (4) laminated microsparite limestone and shale (basal Tithonian, Berriasian-Hauterivian) (Reading 1978 and Hallam 1981; in Hallam *et al.* 1986).

Since the last facies interpretation for the Lo Valdés Formation and the new detailed redefinition and description, this traditional subdivision was challenged by the development of facies concepts and the introduction of new models for carbonate and siliciclastic basins (*e.g.* Burchette and Wrigth 1992, Wright and Burchette 1996, Coe *et al.* 2003, Nichols 2009). Here we present these new concepts for the Lo Valdes Formation and discuss depositional facies based on lithofacies (macro and microfacies) and fossil content. These characteristics are summarized in Figure12 and a depositional model is presented in Figure 13.

4.1. Shoreface facies (inner ramp)

Shoreface facies of the Lo Valdés Formation are represented by calcareous sandstone and sandy limestone with abundant fossils. In the Lo Valdés, Cajón del Morado and Cruz de Piedra sections, calcareous sandstone is widely distributed and frequently contains herringbone cross-bedding and horizontal bedding. Sediment grains are subangular to subrounded, well sorted, and consist of volcanic rock fragments, plagioclase and bioclasts (Figure 14A). The matrix is glauconitic. The fauna encompass ammonoids,

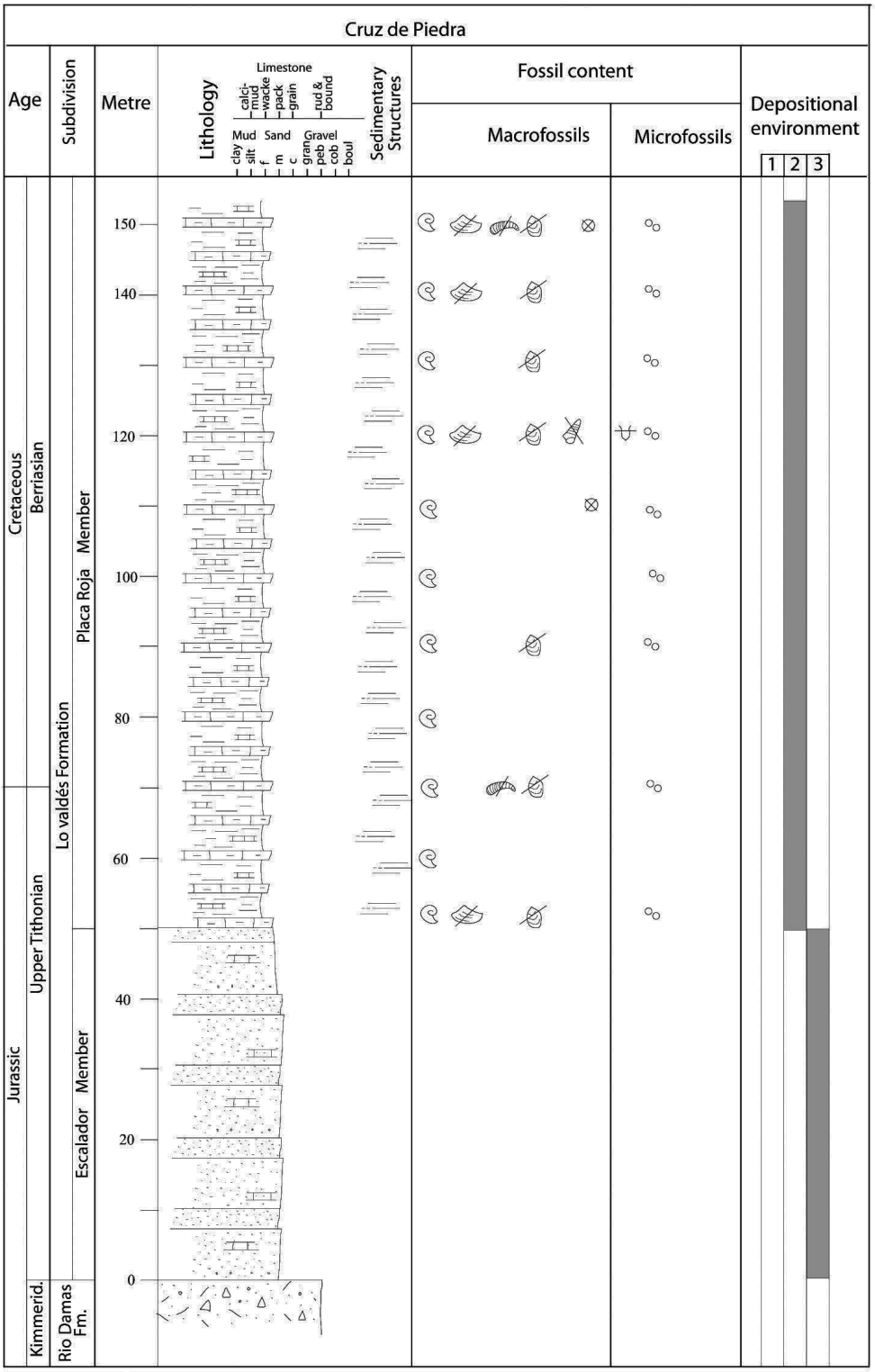

FIGURE 11. Cross section of the Lo Valdés Formation at the Cruz de Piedra section, with differentiation of lithological members.

Depositional Environment	Lithology	Description	Characteristic Fossils
Offshore (Outer ramp)	limestone	wackestone	echinoderms, echinoids, sponges
	silty limestone	mudstone, wackestone	sponges annelids, echinoderms, calcispheres, pentacrinoids
Offshore transition (Mid-ramp)	silty limestone	mudstone, wackestone, packstone, sediment structures: planar lamination disseminated pyrite	echinoderms, algae, calcispheres, rare radiolarians, benthic foraminifers?, calpionellids?,
	calcareous siltstone	C-org-rich siltstone sediment structures: planar lamination disseminated pyrite	annelids, algae, sponges, foraminifers, calpionellids?, echinoderms, rare annelids, bryozoans
Shoreface (Inner ramp)	sandy limestone	sandy packstone	oysters, inoceramids, trigoniids.
		sandy wackestone wackestone, shell fragments	inoceramids, oysters
	calcareous sandstone	clasts: volcanic rocks, fossils, plagioclase, subangular to subrounded, well sorted; matrix: fine-grained, carbonate sediment structures: herringbone, planar lamination, few ooids	oysters, inoceramids, trigoniids, corals

FIGURE 12. Depositional facies of the Lo Valdés Formation

abundant oysters, trigoniids, inoceramids and other bivalves as well as rare gastropods and bryozoans (Figure 14B), red algae (*Marinella lugeoni*, Figure 14C), green calcareous algae (dasycladaceans, Figure 14D) and corals (Family Placocoeniidae, Figure 14E).

The sandy limestone is represented by sandy packstone and wackestone. Sandy packstone (Figure 14F) is frequently cross- or horizontally laminated and contains sparse transported ooids. The fossil assemblage consists of ammonoids, abundant inoceramids, trigoniids, oysters (Figure 14F) and other bivalves, as well as rare gastropods, corals (*e.g.*, *Cladophyllia qiebulaensis* (Figure 14G), *Actinastrea scyphoidea)*, bryozoans, sponges and algae.

4.2. Offshore transition facies (mid-ramp)

Offshore transition facies are represented predominately by siltstone, calcareous siltstone and silty limestone. As compared to shoreface environments, sandstone and calcareous sandstone are characteristically absent and faunal diversity is significantly higher.

Siltstone and calcareous siltstone are composed of silt-sized siliciclastic and carbonate sediment with abundant organic matter (Figure 15A) and disseminated pyrite. Horizontal lamination is widely distributed. Fossil assemblages are dominated by ammonoids and calcispheres (Figure 15A), inoceramids and other bivalves. Gastropods and serpulids (Figure 15B), algae, sponge spicules (Figure 15A), echinoderms, benthic foraminifers (Figure 15C), radiolarians and scare, possible calpionellids also occur.

Offshore transition environments are dominated by silty limestone and also represented by mudstone, wackestone and packstone, with planar lamination and disseminated pyrite. The fauna encompass abundant ammonoids and calcispheres, while serpulids, bivalves, gastropods, echinoderms, algae, radiolarians, serpulids and benthic foraminifers are rare. In the Cajón del Morado and Lo Valdés sections, some layers contain abundant oysters.

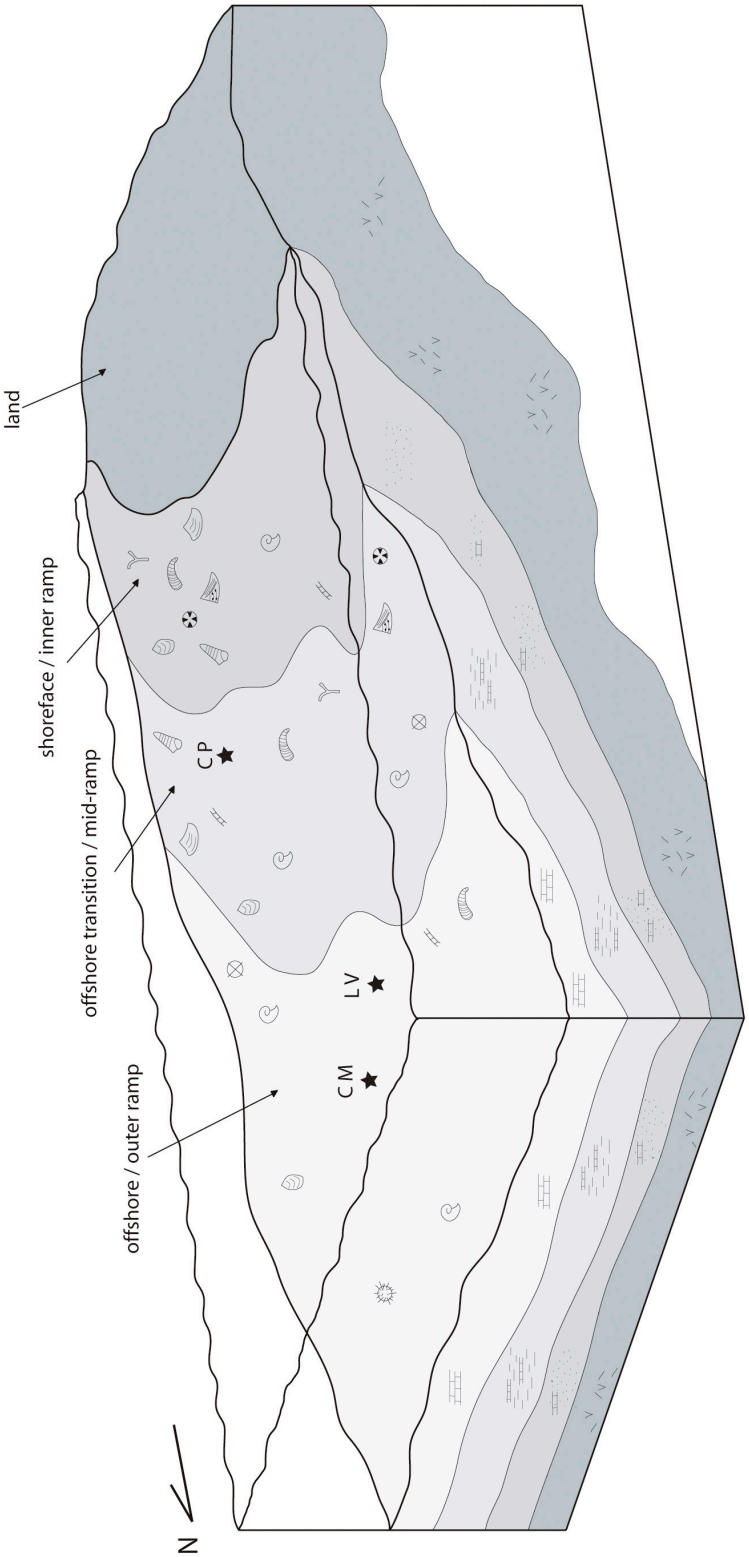

FIGURE 13. Depositional model of the Lo Valdés Formation as a progradational sequence. LV: Lo Valdés section. CM: Cajón del Morado section. CP: Cruz de Piedra (Salazar 2012).

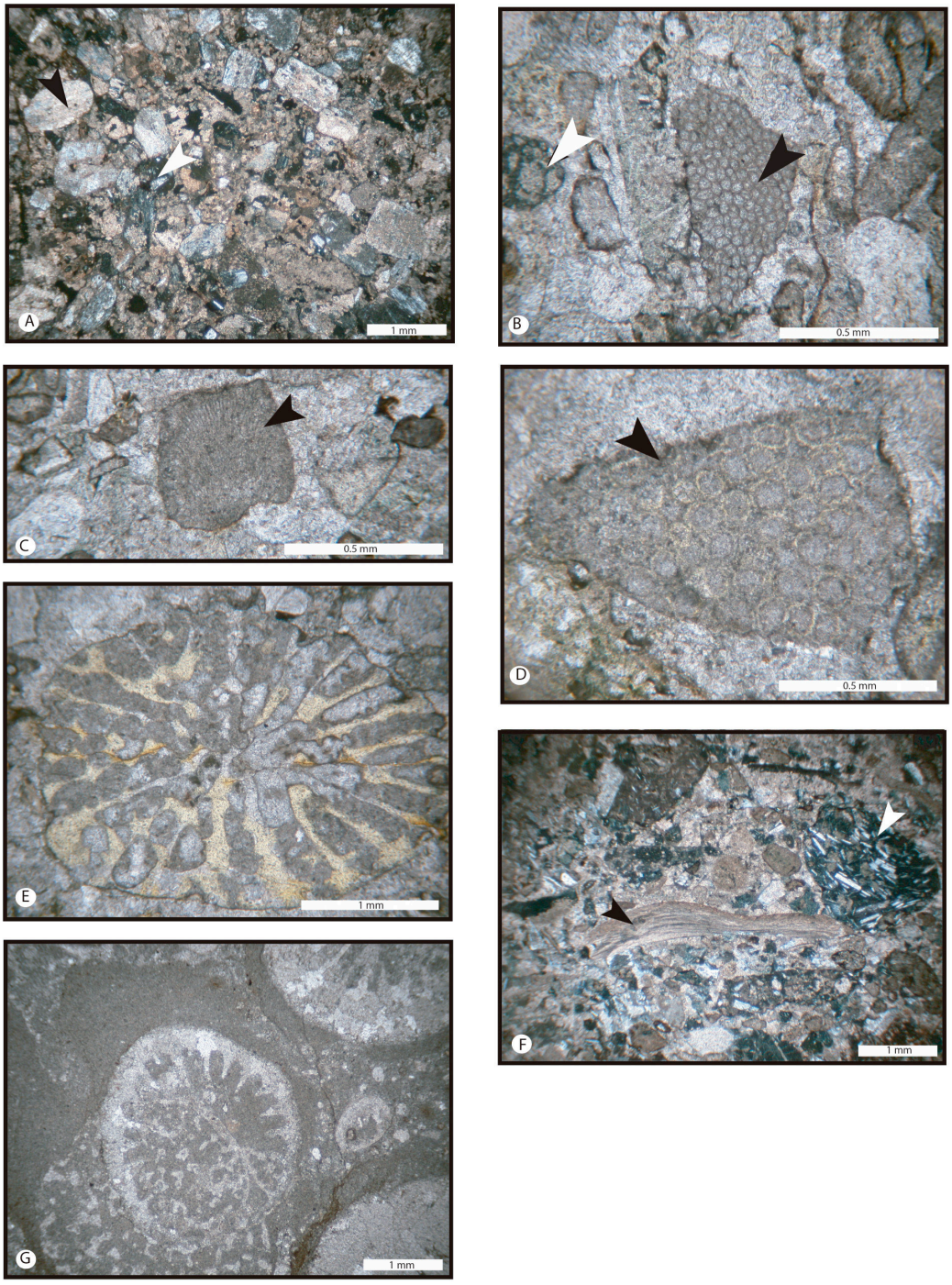

FIGURE 14. **A:** Calcareous sandstone. Plagioclase (black arrow), volcanic rock fragment (white arrow). **B:** Calcareous sandstone. Bryozoans (black arrow), andesitic rock fragments (white arrow). **C:** Red algae, ancestral rhodophyte *Marinella lugeoni* (black arrow). **D:** Green algae, tangential section of a dasycladacean (black arrow). **E:** Coral, Family Placocoeniidae. **F:** Sandy packstone, oyster fragment (black arrow), andesitic rock fragment (white arrow). **G:** Coral, *Cladophyllia qiebulaensis*.

4.3. Offshore facies (outer ramp)

Offshore facies in the Cajón del Morado and Lo Valdés sections of the Lo Valdés Formation are represented by silty to sandy limestone, limestone and occasional calcareous siltstone; sandstone is characteristically absent. The silty-limestone shows planar lamination and corresponds to either mudstone or wackestone; limestone consists of wackestone. In the calcareous siltstone, organic matter and disseminated pyrite are common.

The faunal diversity is lower than in the offshore transition facies and includes scare ammonoids, bivalves, annelids, sponges, bryozoans, unidentified echinoderms, echinoids (Figure 15D-E), pentacrinoids (Figure 15G), algae, radiolarians (Figure 15F), calcispheres and possible calpionellids.

4.4. Depositional setting

Lithologies of the Lo Valdés Formation are dominated by fine-to middle-grained siliciclastic deposits such as sandstone and siltstone. Carbonate is also constantly present and its amount increases upsection. In consequence, the upper part of the studied sections is composed mainly of limestone with a varying degree in siliciclastic input.

Upper and lower shoreface are represented by transgressive intervals formed by calcareous sandstone and sandy limestone. The calcareous sandstone contains cross-bedding that indicates periods of high energy transport in subtidal, shallow water environments, while levels with horizontal bedding should correspond also to episodes of high energy (*e.g.* Tucker 2001, Middleton 2003). Authigenic glauconite is a frequent component and is considered by numerous authors as an indicator of shallow marine conditions during a transgressive stage (Amorosi 1995, Harris and Whiting 2000, Hesselbo and Hugget 2001). It is commonly present in sandstone formed on the shelf and in epicontinental seas.

Ammonoids and bivalves such as trigoniids, oysters and inoceramids are dominant faunal elements in the inner ramp-shoreface facies of the Lo Valdés Formation, while a single unit rich in corals is present in the Lo Valdés and Cajón del Morado sections (Figs. 7, 8, 10). Shallow marine shoreface facies are commonly characterised by abundant bivalves and a general correlation exists between shell thickness (*e.g.*, trigoniids) and higher energy conditions (Scholler & Ulmer-Scholler 2003). Trigoniids occupied shallow-water habitats of less than 15 m (Stanley 1977) to a maximum depth of 30 m (Francis & Hallam 2003), occurring in coarse-grained sediments and transgressive, moderate-energy environments. Also wackestone/mudstone, grainstone, and packstone/wackestone are frequently associated with inner ramp carbonate environments (Wright 1986, Burchette and Wright 1992).

The offshore transition facies in the Lo Valdés Formation are mud-rich deposits of the inner shelf that are frequently bioturbated intensively, except for cases where the rates of mud deposition out-paced the rate at which organisms could rework the sediment. In these cases, organic matter is often concentrated and the resulting shelf mud sediments are dark grey or black (Nichols 2009). The presence of disseminated pyrite as isolated, silt-sized particles and the high concentration of organic matter in the Chilean deposits may indicate reducing environments. The silty wackestone and packstone contain abundant autochthonous bioclasts, and an association of packstone and carbonate sediments deposited below fair weather wave base dominated the mid-ramp deposit. The volume of carbonate sediments in the mid-ramp zone exceeds that in the inner ramp (Wright 1986, Burchette and Wright 1992).

In the transitional zone from shoreface to offshore transition environments, trigoniids, inoceramids and gastropods decrease in abundance and disappear completely. On the other hand, ammonoids increase in abundance and serpulids are common (Figs. 7, 8, 10).

The transition from proximal to distal offshore conditions is gradual and frequently characterised by a decrease in fine-grained siliciclastic input from the continent and an increase in carbonate. In the Lo Valdes Formation, offshore facies are characterised by limestone and silty mudstone and wackestone, whereas calcareous siltstone and sandy limestone are restricted to a few isolated layers (Figs. 7, 8, 10). In general, layers are dark grey due to abundant organic matter and disseminated pyrite is present as isolated silt-sized particles. These characteristics suggest that the sea floor was poorly oxygenated.

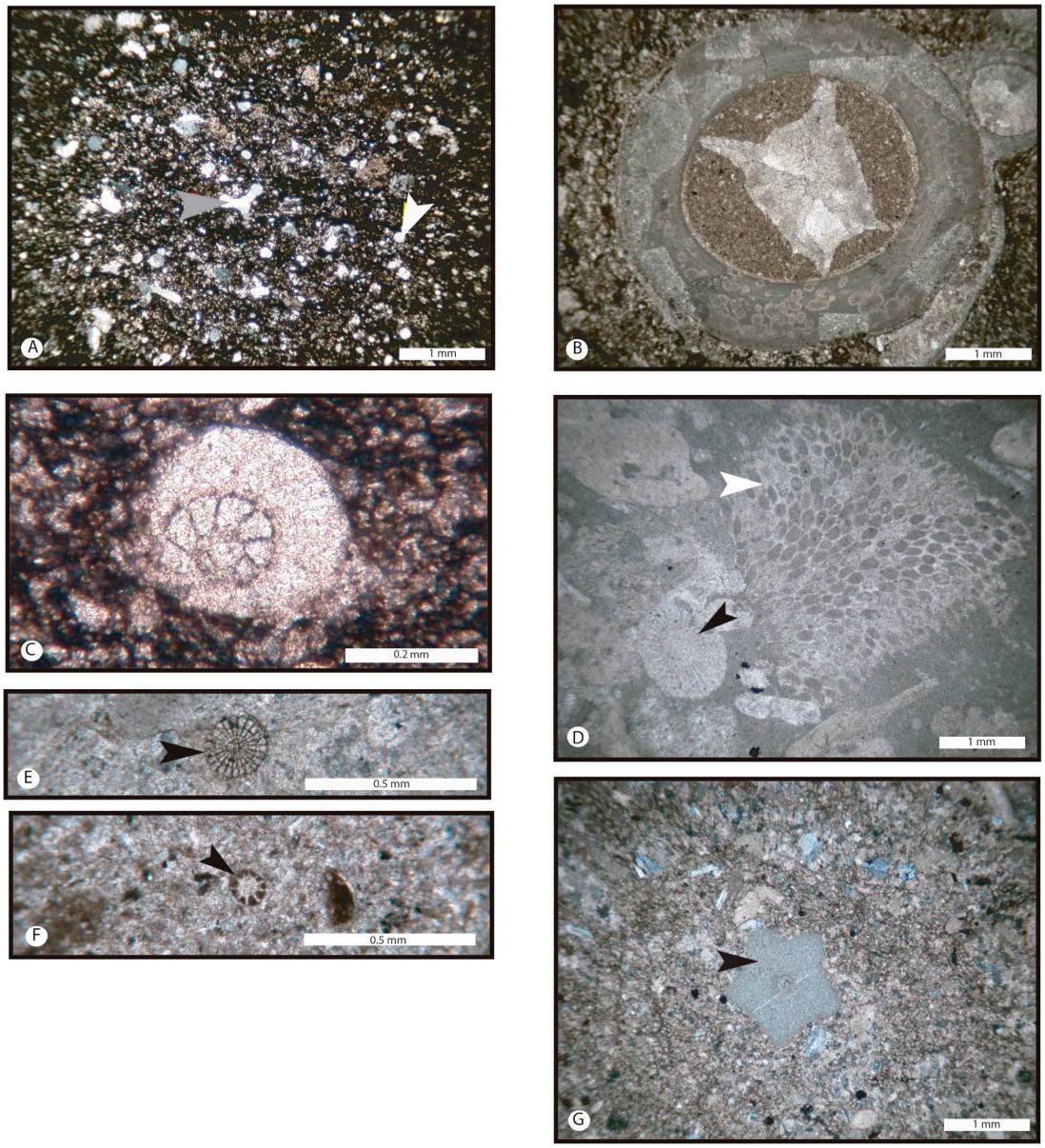

FIGURE 15. **A:** Calcareous siltstone with abundant organic matter, calcispheres (white arrow) and sponge spicules (grey arrow). **B:** Serpulid. **C:** Benthic foraminifer. **D:** Echinoid spine (black arrow) and bryozoan (white arrow). **E:** Echinoid spine (black arrow) **F:** Radiolarians (black arrow). **G:** Pentacrinoid (black arrow) in mudstone.

Outer-ramp offshore environments are frequently characterised by silty wackestone and mudstone redeposited into deeper water, below the storm wave base (Wright 1986, Burchette and Wright 1992). Faunal diversity decreases in the outer ramp-offshore facies and faunal abundance is low, being mainly restricted to rare bivalves, ammonoids and echinoderms.

CONCLUSIONS

Here we propose a redefinition of the Lo Valdés Formation in its type area in the Andes of Central Chile. Based on the predominantly volcanic character of the "Spilítas" member of Biro (1964), a formal separation of this unit is suggested for the Lo Valdés Formation *sensu stricto* and the name Baños Morales Formation is proposed here. At its type locality, Catedral Hill on the southern side of the El Volcán River valley (70°02`57``W and 33°49`41``S, Figure 1), the Baños Morales Formation is 760 m thick. It conformably overlies the Rio Damas Formation and underlies the Lo Valdés Formation, as defined below. An early to middle Tithonian (Late Jurassic) age was assigned to the Baños Morales Formation based on ammonites collected by Biro (1964) from sediment layers intercalated between the andesite and re-studied here.

The Lo Valdés Formation, as redefined, corresponds to the "Arenáceo" and "Calcáreo" members of the Valdés Formation in the description of Biro (1964) and only consists of sedimentary rocks. At the type locality, on the southern side of the El Volcán River at Catedral Hill (70°02`52`` W and 39°49`50`` S, Figure 1), the unit is 539 m thick. The Lo Valdés Formation is here divided (from bottom to top) into the Escalador, Placa Roja and Cantera Members. The Escalador Member consists of sandstone and calcareous sandstone and contains ammonoids, inoceramids, oysters, trigoniids and other bivalves. The Placa Roja Member is composed of siltstone, calcareous siltstone and silty limestone and contains ammonoids, inoceramids, oysters, trigoniids, other bivalves, rare gastropods and annelids. The Cantera Member consists of sandy limestone and limestone, containing rare ammonoids and bivalves. The presence in the Lo Valdés Formation of *Corongoceras alternans*, *Substeueroceras koeneni*, *Argentiniceras noduliferum*, *Spiticeras damesi*, *Cuyaniceras transgrediens*, *Favrella angulatiformis* and *Crioceras andinum* indicates a late Tithonian to late Hauterivian age.

The lithological composition and biotic content of the Lo Valdés Formation allow for a differentiation into shoreface, offshore transition and offshore environments. The Escalador Member represents shoreface facies with transgressive shallow marine intervals. Offshore transition facies are present in the Placa Roja Member and are reflected by rhythmically bedded siltstone, calcareous siltstone, wackestone and packstone. The presence of disseminated pyrite and a high concentration of organic matter indicate low oxygen and low energy environments. Offshore (outer-ramp) environments are identified towards the top of the section (Cantera Member) and are reflected by an increase in silty wackestone and mudstone and a decrease in faunal richness and abundance.

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Anexo
Lo Valdés Formation
Lo Valdés section (type locality)

Members	Meters	Lithology	Description	Fossils
Cantera Member	446-539	sandy wackestone / calcareous siltstone	-wackestone - siltstone clasts: silt, carbonate, subangular to subrounded; matrix: fine-grained, silt, carbonate and organic matter; - sedimentary structures: horizontal lamination	ammonoids, calcispheres, rare inoceramids, trigoniids, other bivalves, sponge spicules, echinoderms, benthic foraminifera
	390-446	sandy wackestone	wackestone	ammonoids, oysters, inoceramids, other bivalves, gastropods, bryozoans, echinoderms
	287-390	sandy wackestone	wackestone disseminated pyrite	ammonoids, oysters, inoceramids, other bivalves, echinoderms
Placa Roja Member	242-287	silty limestone / calcareous siltstone	- silty limestone: wackestone, mudstone, -siltstone clasts: silt, carbonate, subangular to subrounded; matrix: fine-grained, silt, carbonate and organic matter, disseminated pyrite - sedimentary structures: horizontal lamination	ammonoids, oysters, inoceramids, other bivalves, gastropods, calcispheres, rare benthic foraminifers, echinoderms, algae
	193-242	calcareous siltstone / silty limestone	-siltstone clasts: silt, carbonate, subangular to subrounded; matrix: fine-grained,silt, carbonate and organic matter, disseminated pyrite - silty limestone: mudstone - sedimentary structures: horizontal lamination	ammonoids, oysters, inoceramids, other bivalves, calcispheres, annelids, rare benthic foraminifers
	94-193	siltstone / calcareous siltstone	clasts: silt, carbonate, volcanics, subangular to subrounded; matrix: fine-grained, silt, carbonate and organic matter, disseminated pyrite sedimentary structures: horizontal lamination	ammonoids, gastropods, oysters, inoceramids, other bivalves, calcispheres, rare radiolarians, benthic foraminifers, calpionellids?
	73-94	andesite	andesite, matrix chloritized	dike
Escalador Member	43-73	coarse calcareous sandstone	coarse calcareous sandstone clasts: volcanics, plagioclase, shell fragments, subangular to subrounded, well sorted; matrix: fine-grained, carbonate, silt or mud	ammonoids, inoceramids, oysters, trigoniids, other bivalves, gastropods
	0-43	calcareous sandstone	gradual change from coarse and medium to fine clasts: volcanics, plagioclase, subangular to subrounded, well sorted; matrix: fine-grained, carbonate, silt or mud	ammonoids, other bivalves, gastropods, corals

Cajón del Morado section

Members	Meters	Lithology	Description	Fossils
Cantera Member	513-582	calcareous siltstone / silty limestone	mudstone, wackestone - siltstone: clasts: carbonate, shell fragments matrix: fine-grained, silt, carbonate and organic matter sedimentary structures: horizontal lamination	ammonoids, oysters, inoceramids, other bivalves, echinoderms, sponge spicules, calcispheres, rare radiolarians, bryozoans
	441-513	limestone	wackestone	ammonoids, oysters, inoceramids, echinoderms, echinoids, bryozoans, corals, algae, sponge spicules
	376-441	silty limestone / calcareous siltstone	- limestone: mudstone, wackestone - siltstone: clasts: carbonate, shell fragments matrix: fine-grained, silt, carbonate and organic matter, disseminated pyrite sedimentary structures: horizontal lamination	ammonoids, oysters, other bivalves, rare annelids, bryozoans, echinoderms and pentacrinoids
Placa Roja Member	273-376	calcareous siltstone /silty limestone	wackestone-mudstone carbonate and shell fragments sedimentary structures: lamination disseminated pyrite, organic matter	ammonoids, oysters, inoceramids, trigoniids, gastropods, echinoderms, algae, calcispheres, rare radiolarians, benthic foraminifers, calpionellids? and annelids
	174-273	siltstone / calcareous siltstone	silty limestone: wackestone-packstone clasts: silt, carbonate, volcanics matrix: fine-grained, silt, carbonate and organic matter; disseminated pyrite sedimentary structures: horizontal lamination	ammonoids, inoceramids, trigoniids, other bivalves, gastropods, oysters, algae, sponges, calcispheres, foraminifers, calpionellids?
	160-174	calcareous siltstone / silty limestone	siltstone, silty limestone: wackestone-packstone clasts: silt, carbonate, volcanics, fine-grained, matrix: silt, carbonate and organic matter	ammonoids, oysters, other bivalves, gastropods, echinoderms
Escalador Member	144-160	calcareous sandstone	clasts: subangular to subrounded, well sorted; volcanics, plagioclase, shell fragments; matrix: fine-grained, carbonate	ammonoids, oysters, inoceramids, other bivalves, algae
	120-144	silty limestone / sandy limestone	- silty limestone: mudstone - sandy limestone: packstone, wackestone	ammonoids, inoceramids, trigoniids, other bivalves, bryozoans
	35-120	calcareous sandstone / sandy packstone	- calcareous sandstone clasts: volcanics, plagioclase, shell fragments; subangular to subrounded, well sorted; matrix: fine-grained, carbonate - sandy packstone - sedimentary structures: horizontal lamination	ammonoids, oysters, inoceramids, trigoniids, other bivalves, gastropods, algae.
	0-35	sandy wackestone / calcareous sandstone	- wackestone, shell fragments - calcareous sandstone clasts: volcanics, shell fragments, plagioclase, fine-grained, subangular to subrounded, well sorted; matrix: carbonate, fine-grained - sedimentary structures: herringbone, ooids	ammonoids, bivalves, inoceramids, gastropods, corals, algae.

Cruz de Piedra section

Members	Meters	Lithology	Description	Fossils
Placa Roja Member	50-150	calcareous siltstone / silty wackestone	-siltstone clasts: silt, carbonate, subangular to subrounded; matrix: silt, fine-grained,carbonate and organic matter; -wackestone sedimentary structures: horizontal lamination	ammonoids and calcispheres abundant, fragments bivalves, scare oysters, inoceramids, gastropods, echinoderms
Escalador Member	0-50	fine sandstone	clasts: quartz, lithics, plagioclase, carbonate, subangular to subrounded, well sorted; matrix: fine-grained,carbonate, mud	

REFERENCES

AGUIRRE-URRETA, M.B.
2001 Marine Upper Jurassic-Lower Cretaceous stratigraphy and biostratigraphy of the Aconcagua-Neuquén Basin, Argentina and Chile. Journal of Iberian Geology, 27: 71-90.

AGUIRRE-URRETA, M.B. and CHARRIER, R.
1990 Estratigrafía y amonites del Tithoniano-Berriasiano en las nacientes del Río Maipo, Cordillera Principal de Chile Central. Ameghiniana, 27 (3-4): 263-271.

AMOROSI, A.
1995 Glaucony and Sequence Stratigraphy: A conceptual framework of distribution in siliciclastic sequences. Journal of Sedimentary Research, B65: 419-425.

BIRO, L.
1964 Estudio sobre el límite Titoniano y el Neocomiano en la Formación Lo Valdés, Provincia de Santiago, principalmente en base a Ammonoideos. Memoria de Título (Inédito), Universidad de Chile, Departamento de Geología: 118 p.

BIRO, L.
1980 Estudio sobre el límite entre el Titoniano y el Neocomiano en la Formación Lo Valdés, provincia de Santiago (33° 50`lat. Sur), Chile; principalmente sobre la base de ammonoideos. Actas II Congreso Argentino Paleontología Bioestratigrafía. I Congreso Latinoamericano de Paleontología, Buenos Aires 1978, 1: 1237-1252.

BURCHETTE, T. and WRIGHT, V.
1992 Carbonate ramp depositional systems. Sedimentary Geology, 79: 3-57.

CATUNEANU, O.
2006 Principles of Sequence Stratigraphy. Elsevier. Amsterdam, Boston, Heidelberg, 375 p.

CHARRIER, R.
1981 Geologie der chilenischen Hauptkordillere zwischen 34° und 34°30‘ südlicher Breite und ihre tektonische, magmatische und paläogeographische Entwicklung. Berliner geowissenschaftliche Abhandlungen, A, 36, 270 p.

COE, A., BOSENCE, D., CHURCH, K.; FLINT, S., HOWELL, J. and WILSON, R.
2003 The Sedimentary Record of Sea-Level Change. Cambridge University Press. Cambridge, 287 p.

CORVALÁN, J.
1956 Über marine Sedimente des Tithon und Neocom der gegend von Santiago. *Geologischen Rundschau*, Vol. 43, No. 3, p. 919-926.

FOCK, A., CHARRIER, R., MAKSAEV, V. and FARÍAS, M.
2006 Neogene exhumation and uplift of the Andean Main Cordillera from apatite fission tracks between 33°30‘ and 34°00‘S. Backbone of the Americas-Patagonia to Alaska. Geological Society of America Meeting: 102. Mendoza.

FRANCIS, A. and HALLAM, A.
2003 Ecology and evolution of Jurassic trigoniid bivalves in Europe. Lethaia, 36 (4): 287-304.

GODOY, E., CASTELLI, J.C., LÓPEZ, M.C. and RIVERA, O.
1988 …Y Klohn tenía razón: la Formación Colimapu recupera sus miembros basales. In Congreso Geológico Chileno, No. 5, Actas, Vol. 3, p. H101-H120. Santiago.

GONZÁLEZ, O.
1963 Observaciones geológicas en el valle del río Volcán. Revista Minerales 81: 20-54.

HALLAM, A., BIRO-BAGOCZKI, L. and PÉREZ, E.
1986 Facies analysis of the Lo Valdés Formation (Tithonian-Hauterivian) of the High Cordillera of central Chile, and the palaeogeographic evolution of the Andean Basin. Geological Magazine 123 (4): 425-435.

HARRIS, L. and WHITING, B.
2000 Sequence-stratigraphic significance of Miocene to Pliocene glauconite-rich layers, on- and offshore of the US Mid-Atlantic margin: Sedimentary Geology, 134: 129-147.

HESSELBO, S. and HUGGETT, J.
2001 Glaucony in ocean-margin sequence stratigraphy (Oligocene-Pliocene, offshore New Jersey, U.S.A.; ODP Leg 174A): Journal of Sedimentary Research, 71: 599-607.

KLOHN, G.
1960 Geología de la Cordillera de los Andes de Chile central, Provincias de Santiago, O’Higgins, Colchagua y Curicó. Instituto de Investigaciones Geológicas Chile. Boletín N° 8: 95 p.

LEANZA, H. A.
1980 The Lower and Middle Tithonian ammonite fauna from Cerro Lotena, Province of Neuquén, Argentina. Zitteliana 5: 3-49.
MIDDLETON, G.
2003 Enciclopedy of Sediments and Sedimentary Rocks, 1st edition, Kluwer Academic Publishers, 821 p.
NICHOLS, G.
2009 Sedimentology and Stratigraphy, 2nd edition, Wiley Blackwell, 432 p.
PARENT, H.
2003 The ataxioceratid ammonite fauna of the Tithonian (Upper Jurassic) of Casa Pincheira, Mendoza (Argentina). Journal of South American Earth Sciences. 16: 143-165.
PARENT, H., SCHERZINGER, A. and SCHWEIGERT, G.
2011 The Tithonian-Berriasian Ammonite Fauna and Stratigraphy of Arroyo Cieneguita, Neuquén-Mendoza Basin, Argentina. Boletín del Instituto de Fisiografía y Geología. 79-81: 21-94.
RAWSON, P.F.
2007 Global relationships of Argentine (Neuquén Basin) Early Cretaceous ammonite faunas. Geological Journal. 42: 175-183.
RICCARDI, A.
2008 El Jurásico de la Argentina y sus Ammonites. Revista de la Asociación Geológica Argentina. 63: 625-643.
SALAZAR, C.
2012 The Jurassic-Cretaceous Boundary (Tithonian-Hauterivian) in the Andean Basin, Central Chile: Ammonite fauna, Bio- and Sequence Stratigraphy and Palaeobiogeography. Doctoral Thesis. Universität Heidelberg. Germany. 388 p.
SCHOLLE, P.A. and ULMER-SCHOLLE, D.S.
2003 A Color Guide to the Petrography of Carbonate Rocks: The American Association of Petroleum Geologist, Tulsa, Oklahoma, U.S.A. AAPG Memoir 77, 474 p.
STANLEY, S.M.
1977 Coadaptation in the Trigoniidae, a remarkable family of burrowing bivalves. Palaeontology. 20: 869-899
THIELE, R.
1980 Carta Geológica de Chile N° 39, Hoja Santiago, escala 1:250.000, Región Metropolitana. Instituto de Investigaciones Geológicas Chile. 51 p. Chile.
TUCKER, M.
2001 Sedimentary Petrology: An Introduction to the Origin of Sedimentary Rocks. Blackwell Science. 262 p.
WRIGHT, V.
1986 Facies sequences on a carbonate ramp: the Carboniferous Limestone of South Wales. Sedimentology, 33: 221-241.
WRIGHT, V. and BURCHETTE, T.
1996 Shallow-water carbonate environment, 325-394. In: Sedimentary Environments: Processes, Facies and Stratigraphy (ed. Reading H. G.). 3rd edition, Blackwell Sciences, Oxford. 688 p.

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