

**The Jurassic-Cretaceous Boundary (Tithonian - Hauterivian)  
in the Andean Basin of Central Chile: Ammonites, Bio- and  
Sequence Stratigraphy and Palaeobiogeography**

**INAUGURAL DISSERTATION**

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## Abstract

Five sections of the Baños del Flaco and Lo Valdés formations in the High Andean Cordillera of Central Chile have been analyzed with regard to sediment, bio- and sequence stratigraphy, ammonite assemblages and palaeobiogeography, in order to reveal the age and depositional facies of the sediment sequence, and to evaluate the age and important bioevents across the Jurassic-Cretaceous boundary.

The Baños del Flaco Formation was investigated at Rio Tinguiririca and in the Rio Maitenes valley, while sections of the Lo Valdés Formation were studied at Rio Volcán and in the Rio Maipo valley. The Baños del Flaco Formation is 369 m thick at Baños del Flaco section and 536 m thick at Rio Maitenes; lithologies consist of conglomerate, limestone, sandy limestone, calcareous sandstone, calcareous siltstone and siltstone. A lower and an upper member are distinguished by their lithological composition. The Lo Valdés Formation is here divided into two formations, based on the lithological composition. The lower part is assigned here as the Cathedral Formation, composed mainly of andesitic units and only restricted levels of sediment. This formation is 760 m thick and divided into two members (lower and upper); it is assigned to the Lower-Middle Tithonian. The Lo Valdés Formation as redefined here overlies the Cathedral Formation; it is 539 m thick in the type locality, 582 m thick at Cajón del Morado and 150 m thick at Cruz de Piedra. Three members are differentiated by their predominant lithological composition, from base to top a sandstone, siltstone and limestone member.

The ammonite assemblage of the Baños del Flaco Formation is referred to 12 species and 10 genera. *Aulacosphinctes proximus*, *Micracanthoceras spinulosum* and *Corongoceras evolutum* are new records for this formation. *Pseudolissoceras* cf. *zitteli*, *Euvirgalithacoceras malarguense*, *Choicensisphinctes windhauseni*, *Catutosphinctes* cf. *americanensis*, *Virgatosphinctes scythicus* and *Micracanthoceras microcanthum* are registered for the first time in Chile. *Micracanthoceras spinulosum* shows strong ontogenetic changes not recorded previously. *Virgatosphinctes scythicus* is here considered a morphologically variable species and considered synonymous with classical South American taxa such as *Virgatosphinctes andesensis*, *V. mendozanus*, *V. mexicanus* and *V. leñaensis*. *Virgatosphinctes* aff. *pseudolictor*, *V.* cf. *raja* and *V. guadalupensis* are considered synonymous with *E. malarguense*, while *V. tenuilineatus* is synonymous with *C. windhauseni* and *Aulacosphinctes chilensis* with *A. proximus*. Other synonymies include *Micracanthoceras lamberti* and *M. tapiai*, with *M. microcanthum*, and *Corongoceras rigali* with *C. alternans*. A detailed biozonation of the Baños del Flaco Formation is here presented for the first time. The following biozones were assigned, from bottom to top: *Virgatosphinctes scythicus* /

*Pseudolissoceras zitteli* zone, *Windhauseniceras internispinosum* zone, *Micracanthoceras microcanthum* / *Corongoceras alternans* zone and *Substeueroceras koeneni* zone. Here we suggest that the Baños del Flaco Formation reaches from the lower part of the Middle Tithonian to the lowermost part of the Lower Berriasian.

39 species of ammonoids were differentiated in the Lo Valdés Formation and were referred to 22 genera. *Frenguelliceras magister* is a new record for the Lo Valdés Formation and central Chile. *Pterolytoceras exoticum*, *Aspidoceras rogoznicense*, *Micracanthoceras microcanthum*, *Micracanthoceras vetustum*, *Corongoceras lotenoense*, *Corongoceras mendozanum*, *Spiticeras acutum*, *Spiticeras pricei*, *Spiticeras spitiense*, *Groebericeras rocardi*, *Berriasella (Berriasella) jacobi*, *Malbosiceras malbosi*, *Chigaroceras bardensis*, *Tirnovella kayseri*, *Thurmaniceras thurmanni*, *Crioceratites perditum* and *Bochianites* sp. are first registers for Chile. *Lytohoplites paredesi* n.sp., *Lytohoplites zambranoi* n.sp., *Lytohoplites varelae* n.sp. and *Lytohoplites rauloi* n.sp. are new taxa. The neotype of *Substeueroceras* is designated here and corresponds to the lectotype of *Substeueroceras koeneni*. *Parodontoceras* is here considered to be a junior synonym of *Substeueroceras*. We also designate lectotypes of *Micracanthoceras spinulosum*, *Micracanthoceras vetustum*, *Spiticeras acutum*, *Substeueroceras calistoide*, *Argentiniceras fasciculatum*, *Tirnovella kayseri*, *Crioceratites andinum*, *Crioceratites diamantense* and *Crioceratites perditum*. *Spiticeras acutum* is considered here a morphologically variable species. *Berriasella fraudans* is considered to be a junior synonym of *B. jacobi*. Six biozones are here differentiated for the Lo Valdés Formation, from bottom to top: *Micracanthoceras microcanthum* / *Corongoceras alternans*, *Substeueroceras koeneni* (*Berriasella jacobi* and *Groebericeras rocardi* sub-zones), *Thurmaniceras thurmanni* / *Argentiniceras fasciculatum*, and *Crioceratites diamantense*. In consequence, the Lo Valdés Formation reaches from the upper part of the Upper Tithonian to the Upper Hauterivian.

Biozonations of the Baños del Flaco and the Lo Valdés formations are integrated and correlated, leading to the identification of 9 biozones reaching from Middle Tithonian to Upper Hauterivian times. According to the ecological index, major bioevents are recognized for the Upper Tithonian, with peak relative abundances and diversity, and for the Lower Berriasian, which is characterized by highest species richness. The turn-over analysis indicates that similarity (Jaccard index) is low between the Upper Tithonian and the Lower Berriasian. Species abundances and richness decrease in the Valanginian and even further, during the Hauterivian.

Taxa endemic to Central Chile and Tethyan species are the dominant ammonites during the Tithonian. During the Berriasian, Cosmopolitan and Indo-Pacific influences increase and these

taxa form the dominant group, while Tethyan and Endemic ammonites dominate during the Valanginian. During the Tithonian, the dominance of endemic taxa suggests that Central Chile may not have been well connected with the Tethyan region via the Hispanic Corridor, but that Indo-Pacific affinities result from an open Indo-Austral seaway. During the Berriasian, the dominance of Cosmopolitans and abundance of Indo-Pacific taxa suggests that new pathways opened between Antarctica and South America–Africa. These connections were likely established via the Indo-Austral seaway and a new connection through the Hispanic Corridor. Subsequently, during the Lower Valanginian, Tethyan, Indo-Pacific (Indo-Austral) and Boreal taxa are present in the Central Chilean fauna and Endemic ammonites are equally abundant. This may correspond to a similar grade of influence from the Hispanic Corridor and the Indo-Austral seaway.

The base of the Baños del Flaco Formation represents transgressive facies (sequence 1) during the lowermost Middle Tithonian, with a maximum depth during the uppermost Middle Tithonian. Upsection, sequence 2 represents a second cycle with transgressive facies during the Upper Tithonian and a regression in the Lower Berriasian.

In the Lo Valdés Formation, sequence 3 represents a retrogradational and progradational pattern, which results in transgression during the Upper Tithonian to Lower Valanginian and a regression during the Upper Valanginian to Upper Hauterivian.



## Zusammenfassung

Im Rahmen der vorliegenden Dissertationsschrift wurden Sedimente, Bio- und Sequenzstratigraphie, Ammonitentaxonomie und Paläobiogeographie der Baños del Flaco und der Lo Valdés Formationen in den hohen Anden von Zentral-Chile untersucht, um das Alter und den Ablagerungsraum der Sedimenteinheiten zu dokumentieren und um wichtige Bioevents im Übergang zwischen Jura- und Kreidezeit abzuschätzen.

Die Baños del Flaco Formation wurde in Profilen an der Typuslokalität Baños del Flaco am Rio Tinguiririca und im Tal des Rio Maitenes untersucht. Profile der Lo Valdés Formation wurden am Rio Volcán und im Tal des Rio Maipo aufgenommen. Bei Baños del Flaco beträgt die Mächtigkeit der Baños del Flaco Formation 369 m und am Rio Maitenes 536 m. Die Einheit besteht aus Konglomerat, Kalkstein, Kalksandstein und Siltstein, wobei lithologisch ein unteres und ein oberes Member unterschieden werden. Die Lo Valdés Formation wurde neu definiert und dabei in zwei Formationen untergliedert. Die Catedral Formation bildet den unteren Teil der Abfolge und besteht vorrangig aus Andesit und nur untergeordnet aus geringmächtigen Sedimenteinheiten. Diese Einheit ist 760 m mächtig und wird dem unteren bis mittleren Tithonium zugeordnet. Die neu definierte Lo Valdés Formation überlagert die Catedral Formation. Die Mächtigkeit beträgt 539 m in der Typlokalität, 582 m im Cajón del Morado und 150 m bei Cruz de Piedra. Drei Member werden hinsichtlich ihrer lithologischen Zusammensetzung unterschieden, von der Basis zum Top das Sandstein-, Siltstein- und das Kalkstein-Member.

Die Ammoniten-Vergesellschaftung der Baños del Flaco Formation besteht aus 12 Arten, welche 10 Gattungen zugeordnet wurden. *Aulacosphinctes proximus*, *Micracanthoceras spinulosum* und *Corongoceras evolutum* sind Erstnachweise für diese Formation. *Pseudolissoceras* cf. *zitteli*, *Euvirgalithacoceras malarguense*, *Choicensisphinctes windhauseni*, *Catutosphinctes* cf. *americanensis*, *Virgatosphinctes scythicus* und *Micracanthoceras microcanthum* wurden erstmals in Chile registriert. *Micracanthoceras spinulosum* zeigt bisher nicht bekannte deutliche ontogenetische Veränderungen. *Virgatosphinctes scythicus* wird hier als eine morphologisch variable Art und als Homonym klassischer südamerikanischer Taxa wie *Virgatosphinctes andesensis*, *V. mendozanus*, *V. mexicanus* und *V. leñaensis* angesehen. *Virgatosphinctes* aff. *pseudolictor*, *V.* cf. *raja* und *V. guadalupensis* werden als Synonyme von *E. malarguense* betrachtet, wohingehend *V. tenuilineatus* ein Synonym zu *C. windhauseni* und *Aulacosphinctes*

*chilensis* ein Synonym zu *A. proximus* darstellt. Zusätzlich werden *Micracanthoceras lamberti* und *M. tapiai* als Synonyme von *M. microcanthum* und *Corongoceras rigali* als Synonym von *C. alternans* angesehen. Erstmals wird eine detaillierte Biozonierung der Baños del Flaco Formation vorgenommen. Die folgenden Biozonen werden vom Liegenden zum Hangenden untergliedert: *Virgatosphinctes scyticus* / *Pseudolissoceras zitteli* Zone, *Windhausenicerias internispinosum* Zone, *Micracanthoceras microcanthum* / *Corongoceras alternans* Zone und *Substeueroceras koeneni* Zone. Die Baños del Flaco Formation reicht damit vom unteren Mittel-Tithonium bis zum untersten Berriasium.

39 Ammonitenarten wurden in der Lo Valdés Formation 22 Gattungen zugeordnet. *Frenguellicerias magister* ist ein neuer Nachweis für die Lo Valdés Formation und für Zentral-Chile. *Pterolytoceras exoticum*, *Aspidoceras rogoznicense*, *Micracanthoceras microcanthum*, *Micracanthoceras vetustum*, *Corongoceras lotenoense*, *Corongoceras mendozanum*, *Spiticeras acutum*, *Spiticeras pricei*, *Spiticeras spitiense*, *Groebericerias rocardi*, *Berriasella (Berriasella) jacobi*, *Malbosicerias malbosi*, *Chigaroceras bardensis*, *Tirnovella kayseri*, *Thurmanicerias thurmanni*, *Crioceratites perditum* und *Bochianites* sp. sind Erst-Nachweise für Chile. *Lytroplites paredesi* n. sp., *Lytroplites zambranoi* n. sp., *Lytroplites varelae* n. sp. und *Lytroplites rauloi* n. sp. sind neue Arten. Der Neotypus der Gattung *Substeueroceras* wird definiert und entspricht dem Lectotypus von *Substeueroceras koeneni*. *Parodontoceras* wird hier als ein Synonym von *Substeueroceras* bezeichnet. Die Lectotypen von *Micracanthoceras spinulosum*, *Micracanthoceras vetustum*, *Spiticeras acutum*, *Substeueroceras calistoide*, *Argentinerias fasciculatum*, *Tirnovella kayseri*, *Crioceratites andinum*, *Crioceratites diamantense* und *Crioceratites perditum* werden festgelegt. *Spiticeras acutum* wird hier als eine morphologisch variable Spezies angesehen. *Berriasella fraudans* ist ein Synonym von *B. jacobi*. Die Lo Valdés Formation wird in sechs Biozonen untergliedert, vom Liegenden zum Hangenden: *Micracanthoceras microcanthum* / *Corongoceras alternans*, *Substeueroceras koeneni* (*Berriasella jacobi* und *Groebericerias rocardi* Sub-Zonen), *Thurmanicerias thurmanni* / *Argentinerias fasciculatum* und *Crioceratites diamantense*. Die Lo Valdés Formation reicht vom Oberen Tithonium bis zum Oberen Hauterivium.

Neun Biozonen der Baños del Flaco und der Lo Valdés Formation werden korreliert und reichen vom mittleren Tithonium bis zum oberen Hauterivium. Wichtige Bioevents werden an Hand der maximalen relativen Häufigkeit und Diversität abgeschätzt, wobei sich das untere Berriasium gefolgt vom Ober-Tithon durch besonderen Artenreichtum auszeichnet. Trotzdem zeigt die Turn-

over-Analyse, dass die Ähnlichkeit der Faunen-Vergesellschaftung (Jaccard-Index) zwischen diesen beiden Stufen nur gering sind. Während des Valanginium und im Hauterivium nimmt die Diversität weiter ab.

Endemiten sowie Tethys-Arten sind die dominierenden Ammoniten zur Zeit des Tithonium. Während des Berriasium nehmen kosmopolitische und indo-pazifische Einflüsse zu. Im Valanginium dominieren dagegen tethyale und endemische Ammoniten. Die Dominanz endemischer Taxa im Tithonium belegt, womöglich dass Zentral Chile schlecht mit der Tethys verbunden und dass der hispanische Korridor noch geschlossen war. Demgegenüber indizieren die deutlichen indo-pazifischen Affinitäten vermutlich einen offenen indo-australischen Seeweg. Während des Berriasium bedeutet die Dominanz der Kosmopoliten und der Reichtum an indo-pazifischen Taxa, dass sich neue Verbindungswege zwischen der Antarktis und Südamerika und Afrika öffneten. Diese Verbindungen belegen einen indo-australischen Seeweg und eine neue Verbindung über den hispanischen Korridor. Danach treten während des unteren Valanginium tethyale, indo-pazifische (indo-australische) und boreale Taxa in der zentralchilenischen Fauna auf und auch endemische Ammoniten sind divers. Der hispanische Korridor und der indo-australische Seeweg scheinen in diesem Zeitraum einen ähnlichen bedeutenden Einfluss gehabt zu haben.

Die Basis der Baños del Flaco Formation belegt transgressive Fazies (Sequenz 1) während des untersten Mittel-Tithonium und maximale Wassertiefen im obersten Mittel-Tithonium. Darüber repräsentiert Sequenz 2 einen zweiten Zyklus mit transgressiver Fazies im oberen Tithonium gefolgt von einer Regression im unteren Berriasium.

In der Lo Valdés Formation belegt Sequenz 3 ein retrogradierendes und progradierendes Muster, welches im oberen Tithonium bis unterem Valanginium in einer Transgression und im oberen Valanginium bis oberen Hauterivianium in einer Regression resultiert.



## Resumen

Cinco secciones de las formaciones Baños del Flaco y Lo Valdés de la Cordillera de los Andes en Chile Central, han sido analizadas, considerando su sedimentología, bio-estratigrafía secuencial, paleontología de ammonites y paleobiogeografía, con el fin de precisar la edad y facies de depositación de la secuencia sedimentaria, y para evaluar la edad e importantes bioeventos a través del límite Jurásico-Cretácico.

La Formación Baños del Flaco fue analizada en las secciones del Río Tinguiririca y en el valle del Río Maitenes, mientras que las secciones de la Formación Lo Valdés fueron estudiadas en el Río Volcán y en el valle del Río Maipo. La Formación Baños del Flaco tiene 369 m de espesor en la sección Baños del Flaco y 536 m de espesor en la sección de Río Maitenes, que consiste en conglomerados, calizas, calizas arenosas, areniscas calcáreas, lutitas y lutitas calcárea. Se diferencian dos miembros por su composición litológica, Superior e Inferior. La Formación Lo Valdés es dividida aquí en dos formaciones, basado en la composición litológica. La parte inferior se asigna aquí como la Formación Catedral, compuesta principalmente por unidades andesíticas y restringidos niveles sedimentarios. Esta formación tiene 760 m de espesor, y se divide en dos miembros (inferior y superior), asignada al Tithoniano Inferior-Medio. La Formación Lo Valdés aquí redefinida se superpone a la Formación Catedral, con 539 m de espesor en su localidad tipo; 582 m de espesor en la sección Cajón del Morado y 150 m de espesor en la sección Cruz de Piedra. Tres miembros se diferencian de acuerdo a su composición litológica, desde base a techo el miembro arenoso, lutítico y calcáreo.

La Formación Baños del Flaco contiene 12 especies de amonoides agrupados en 10 géneros. *Aulacosphinctes proximus*, *Micracanthoceras spinulosum* y *Corongoceras evolutum* son nuevos registros para esta formación. *Pseudolissoceras* cf. *zitteli*, *Euvirgalithacoceras malarguense*, *Choicensisphinctes windhauseni*, *Catutosphinctes* cf. *americanensis*, *Virgatosphinctes scythicus* y *Micracanthoceras microcanthum* son registrados por primera vez para Chile. *Micracanthoceras spinulosum* presenta fuertes cambios ontogenéticos, no registrados previamente. *Virgatosphinctes scythicus* es aquí considerado una especie morfológicamente variable y considerado sinonima con especies clásicas de Sur America, tales como *Virgatosphinctes andesensis*, *V. mendozanus*, *V. mexicanus* y *V. leñaensis*. *Virgatosphinctes* aff. *pseudolictor*, *V.* cf. *raja* y *V. guadalupensis*, son consideradas sinonimias con *E. malarguense*, mientras que *V. tenuilineatus* es sinonima con *C. windhauseni* y *Aulacosphinctes chilensis* con *A. proximus*. Otras sinonimias incluyen

*Micracanthoceras lamberti* y *M. tapiai*, con *M. microcanthum*, y *Corongoceras rigali* con *C. alternans*. Una detallada biozonación de la Formación Baños del Flaco es aquí presentada por primera vez. Las siguientes biozonas fueron asignadas, de base a techo: zona *Virgatosphinctes scyticus* / *Pseudolissoceras zitteli*, zona *Windhauseniceras internispinosum*, zona *Micracanthoceras microcanthum* / *Corongoceras alternans* y zona *Substeueroceras koeneni*. Aquí se sugiere que la Formación Baños del Flaco alcanza desde la parte baja del Titoniano Medio a la parte más baja del Berriasiano temprano.

39 especies de ammonoideos fueron diferenciados en la Formación Lo Valdés y referidos a 22 géneros. *Frenguelliceras magister* es un nuevo registro para la Formación Lo Valdés y para Chile Central. *Pterolytoceras exoticum*, *Aspidoceras rogoznicense*, *Micracanthoceras microcanthum*, *Micracanthoceras vetustum*, *Corongoceras lotenoense*, *Corongoceras mendozanum*, *Spiticeras acutum*, *Spiticeras pricei*, *Spiticeras spitiense*, *Groebericeras rocardi*, *Berriasella* (*Berriasella*) *jacobi*, *Malbosiceras malbosi*, *Chigaroceras bardensis*, *Tirnovella kayseri*, *Thurmaniceras thurmanni*, *Crioceratites perditum* y *Bochianites* sp. son primeros registrados en Chile. *Lytohoplites paredesi* n. sp., *Lytohoplites zambranoi* n. sp., *Lytohoplites varelae* n. sp. y *Lytohoplites rauloi* n. sp. son nuevas especies. El Neotipo de *Substeueroceras* es aquí designado y corresponde al lectotipo de *Substeueroceras koeneni*. *Parodontoceras* es aquí considerado un sinónimo menor de *Substeueroceras*. También se designan los lectotipos de *Micracanthoceras spinulosum*, *Micracanthoceras vetustum*, *Spiticeras acutum*, *Substeueroceras calistoide*, *Argentiniceras fasciculatum*, *Tirnovella kayseri*, *Crioceratites andinum*, *Crioceratites diamantense* y *Crioceratites perditum*. *Spiticeras acutum* es aquí considerado una especie morfológicamente variable. *Berriasella fraudans* es considerado un sinónimo menor de *B. jacobi*. Seis biozonas son aquí diferenciadas para la Formación Lo Valdés, de base a techo: *Micracanthoceras microcanthum* / *Corongoceras alternans*, *Substeueroceras koeneni* (sub-zonas *Berriasella jacobi* y *Groebericeras rocardi*), *Thurmaniceras thurmanni* / *Argentiniceras fasciculatum*, y *Crioceratites diamantense*. En consecuencia, la Formación Lo Valdés representa la parte alta del Titoniano Superior al Hauteriviano Superior.

Las biozonaciones de las formaciones Baños del Flaco y Lo Valdés están integradas y correlacionadas, lo que lleva a la identificación de 9 biozonas que van desde el Titoniano Medio al Hauteriviano Superior. De acuerdo con los índices ecológicos, importantes bioeventos son reconocidos en el Tithoniano Superior, con máximos de abundancia relativa y diversidad, y para el Berriasiano Inferior, que se caracteriza por la más alta riqueza de especies. El análisis Turn-

over indica que la similitud (índice de Jaccard) es bajo entre el Titoniano Superior y el Berriasiano Inferior. La abundancia y riqueza de especies disminuye en el Valanginiano y más aún, durante el Hauteriviano.

Las especies endémicas de Chile Central y del Tethys son los amonoideos dominantes durante el Tithoniano. Durante el Berriasiano, la influencia aumenta de las especies con afinidades Cosmopolita e Indo-Pacífica, mientras que las especies endémicas y del Tethys dominan nuevamente durante el Valanginiano. Durante el Titoniano, el predominio de especies endémicas sugiere que la zona central de Chile no estaba bien conectada con la región del Tethys a través del Corredor Hispanico, mientras que las afinidades Indo-Pacíficas son el resultado de la apertura de una ruta Indo-Austral. Durante el Berriasiano, el predominio de especies Cosmopolitas y la abundancia de especies del Indo-Pacífico sugiere que nuevas rutas se abrieron entre la Antártida y América del Sur y África. Estas conexiones se establecieron probablemente a través de la vía marítima Indo-Austral y una nueva conexión a través del Corredor Hispánico. Posteriormente, durante el Valanginiano Inferior, las especies con afinidades del Tethys, Indo-Pacífico (Indo-Austral) y Boreal están presentes en la fauna de Chile Central y amonites endémicos son igualmente abundantes. Esto puede corresponder a un grado similar de influencia del Corredor Hispánico y la vía marítima Indo-Austral.

La base de la Formación Baños del Flaco esta representada por facies transgresivas (secuencia 1) durante la parte baja del Titoniano Medio, con su máxima profundidad durante la parte alta del Titoniano Medio. Sobre yaciendo, la secuencia 2 representa un segundo ciclo con facies transgresivas durante el Titoniano Superior y una regresión en el Berriasiano Inferior.

En la Formación Lo Valdés, la secuencia 3 representa un patrón retrogradacional y progradacional, lo que resulta de la transgresión durante el Titoniano Superior al Valanginiano Inferior, y una regresión durante el Valanginiano superior al Hauteriviano Superior.



## 1. Introduction

### 1.1 Jurassic-Cretaceous (J/K) boundary

The Jurassic-Cretaceous (J/K) transition is characterized by a sea-level lowstand (Haq et al. 1987, 1988, Ziegler 1990, Hardenbol et al. 1998, Hallam 2001), resulting in a diversification and separation of depocenters and faunal provinces. The climatic history during this interval of time is well documented, suggesting an increase in humidity (Price 1999) and cooling during the Late Jurassic, followed by moderate warming into the Lower Cretaceous (Ruffell et al. 2002). Both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  stable isotopic curves pass the J/K boundary without major excursions (Wiessert & Channell 1989, Weissert & Mohr 1996; Bartolini et al. 1999, Gröcke et al. 2003) and coeval Sr87/86 values only present a minor increase (Jones 1992, Howart & McArthur 1997, Gröcke et al. 2003). This absence in the J/K transition of characteristic isotopic events and other geochemical criteria hampers intercontinental correlation. New biostratigraphic approaches are needed to resolve the existing difficulties to correlate between faunal realms of the Pacific, the Atlantic Hispanic corridor and the Tethys.

Even though the position of the J/K boundary has been discussed over more than a century, no internationally valid definition has been agreed upon about its position or Global Stratotype Section and Point (GSSP) (Remane 1991). This complex situation results from the absence of a significant faunal change at the end of the Jurassic period, extreme faunal provincialism and endemism, and from the worldwide sea level regression during the “Purbeckian” (Upper Berriasian - early Lower Valanginian). Even today, the combination of these factors still complicates intercontinental correlation between Tethyan and Boreal sections of Tithonian and Berriasian age. It has been recommended during the “Colloque International sur la limite Jurassique-Cretacé, Lyon-Neuchâtel, 1973, that the boundary should best be placed at the base of the combined ammonite zone *Jacobi-Grandis* which is approximately equivalent to the base of the *Calpionella* Zone in terms of microfossils, but the base of the *Tirnovella occitanica* - Zone (lower *Calpionella* Zone near base of calpionellid Zone C) has also been proposed (Hoedemaker 1987, 1991). However, this classification has only been applied for the European Tethys whereas correlation with the western Atlantic Hispanic Corridor (e.g., Mexico), or even with the classical Pacific southern high latitude localities in Chile and Argentina, remained tentative, at most. Until a few years ago, no calpionellids were known from South America and ammonites were considered to be endemic on both sides of the Atlantic. In consequence, the stratigraphical ranges

of many South and North American ammonite genera have long been controversially discussed in terms of European zones (e.g., Zeiss, 1983, 1984, 1986; Jeletzky, 1984, Cantu-Chapa, 1989, 1999, 2006) and it appeared likely that no direct oceanic connection existed then between Europe and America. Data on the J/K interval in Mexico, however, suggest that biostratigraphic correlation is possible between faunal realms of the western Pacific, the Hispanic Corridor and the western Tethys and that classical biostratigraphical research may bear the key to resolve decades of confusion in the calibration of faunal and environmental changes in the J/K interval of the western hemisphere (Adatte et al. 1994, Adatte et al. 1996).

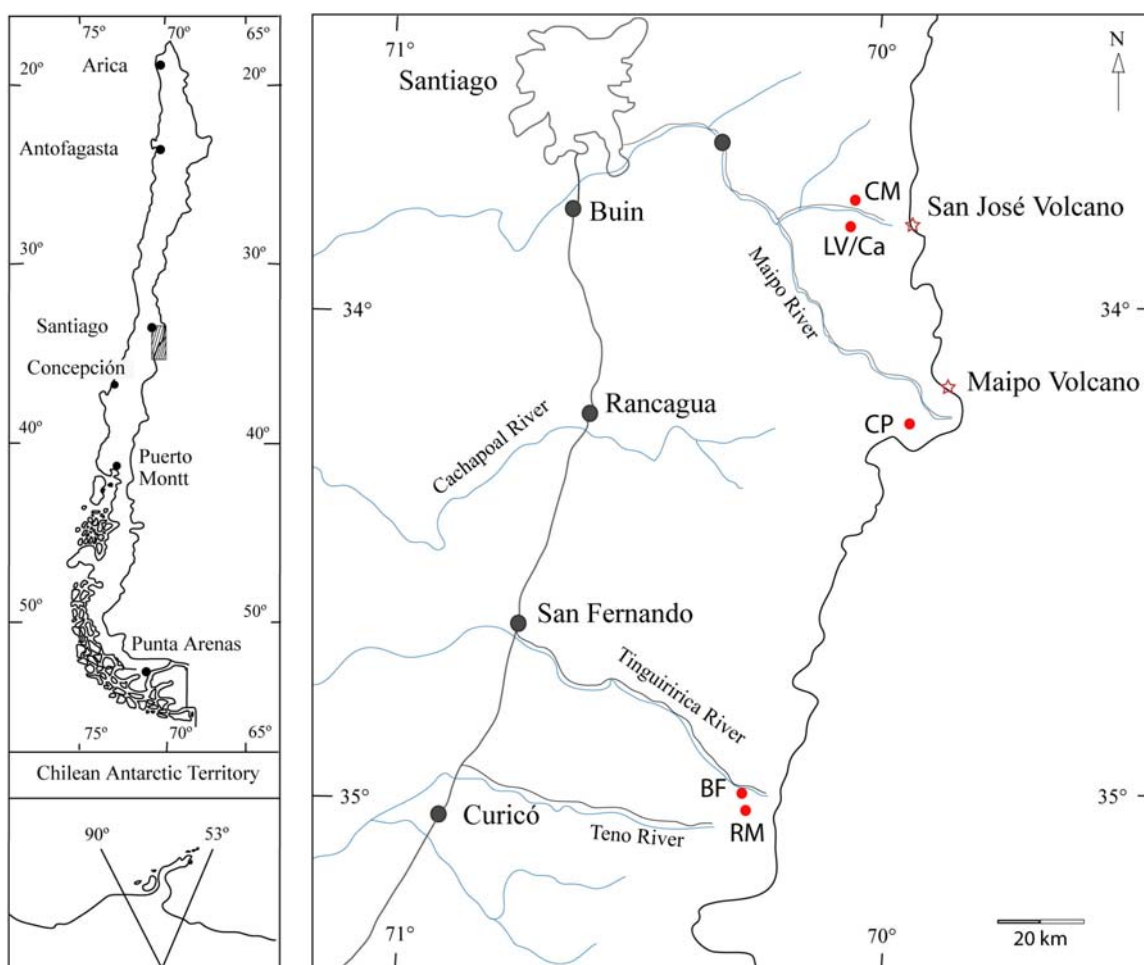
### **1.2 The Jurassic/Cretaceous (J/K) boundary in southern South America (Chile and Argentina)**

The Jurassic/Cretaceous (J/K) boundary in Chile and adjacent west central Argentina has been the subject of considerable attention since the turn of the XIXth century, beginning with the classic works made by German speaking scientists, such as Behrendsen (1891-92, 1922), Steuer (1897-1921), Bodenbender (1892), Burckhardt (1900a, 1900b, 1903), Haupt (1907), Krantz (1926-1928) and Gerth (1921-1925). It was A. F. Leanza (1945) who proposed the first modern zonation based on ammonites in the southern Mendoza province while Biro (1964) and Corvalán (1956, 1959) worked on the faunas in Central Chile. H. Leanza (1973, 1980, 1981a, 1981b) was also devoted to the J/K boundary, but in this case in the Neuquén province in Argentina. The author demonstrated the diachronic nature of the formational units in this region, independent of the J/K boundary. A similar diachrony likely occurs in Chile but has never been documented in detail. Nearly 40 years have passed since the original publications by Leanza and Biro, and the general and rapid improvement of knowledge as well as the development of new techniques (e.g., sequence stratigraphy), makes a revision quite necessary. Recently, Rawson (2007) discussed the global relationships of Argentinian Early Cretaceous ammonites and documented striking similarities between taxa from the Neuquén basin and species of the Boreal faunal realm. These new data therefore suggest that a faunal link and possibly a direct marine connection existed between the two regions.

The position of the J-K boundary, as defined in Europe, has not been convincingly located in the Eastern Pacific Province. Recent improvements by Rawson (2007) and Aguirre-Urreta et al. (2007) focus on the Early Cretaceous (Valanginian-Barremian) sequence and do not include the Jurassic-Cretaceous transition.

### 1.3. Location

The working area is located the central high Andes of Chile, between the Metropolitan and Maule regions (Figure 1.1). In this area three sections of the Lo Valdés Formation and two sections of the Baños del Flaco Formations were measured and sampled. Sections of the Lo Valdés Formation are located in the Cajón del Morado (CM), near Lo Valdés (LV) and at Cruz de Piedra (CP) (Figure 1.1). Sections covering Baños del Flaco Formations were measured at Baños del Flaco (BF) and at Rio Maitenes (RM) (figure 1.1). For details of each section see chapter 3.



**Figure 1.1.** Map of Chile showing the location of outcrops of the Baños del Flaco and Lo Valdés Formations. CM: Cajón del Morado; LV: Lo Valdés; CP: Cruz de Piedra; Baños del Flaco and RM: Rio Maitenes.

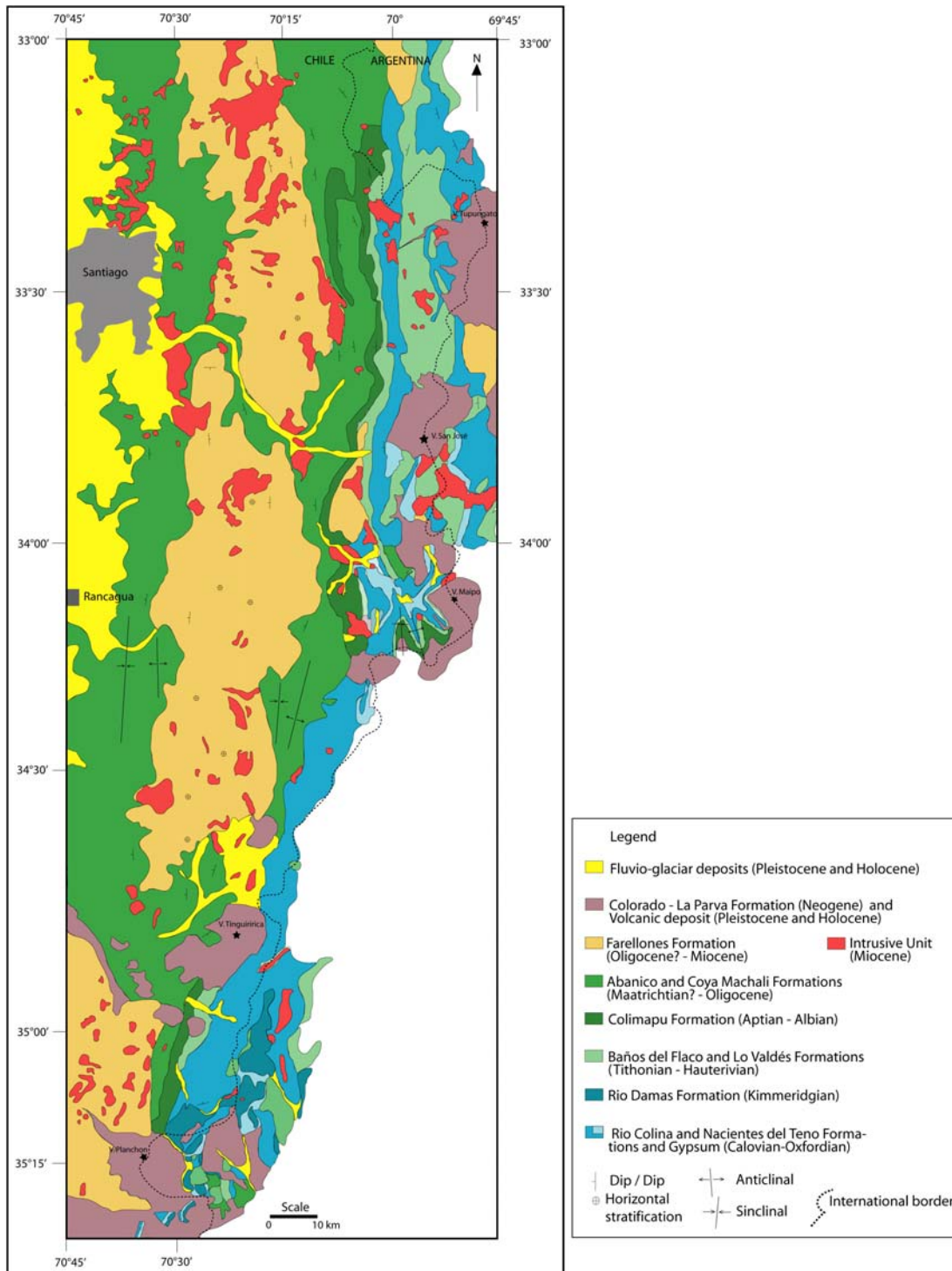
## 1.4. Geological Setting

The geology of Central Chile is characterized by the ongoing subduction of the oceanic plate under continental South American plate, a process which continues since early Jurassic times. As a consequence of these processes, geological settings in the region include a dynamic volcanic arc as well as fore arc, intra arc and back arc basin (Mpodozis & Ramos 1989).

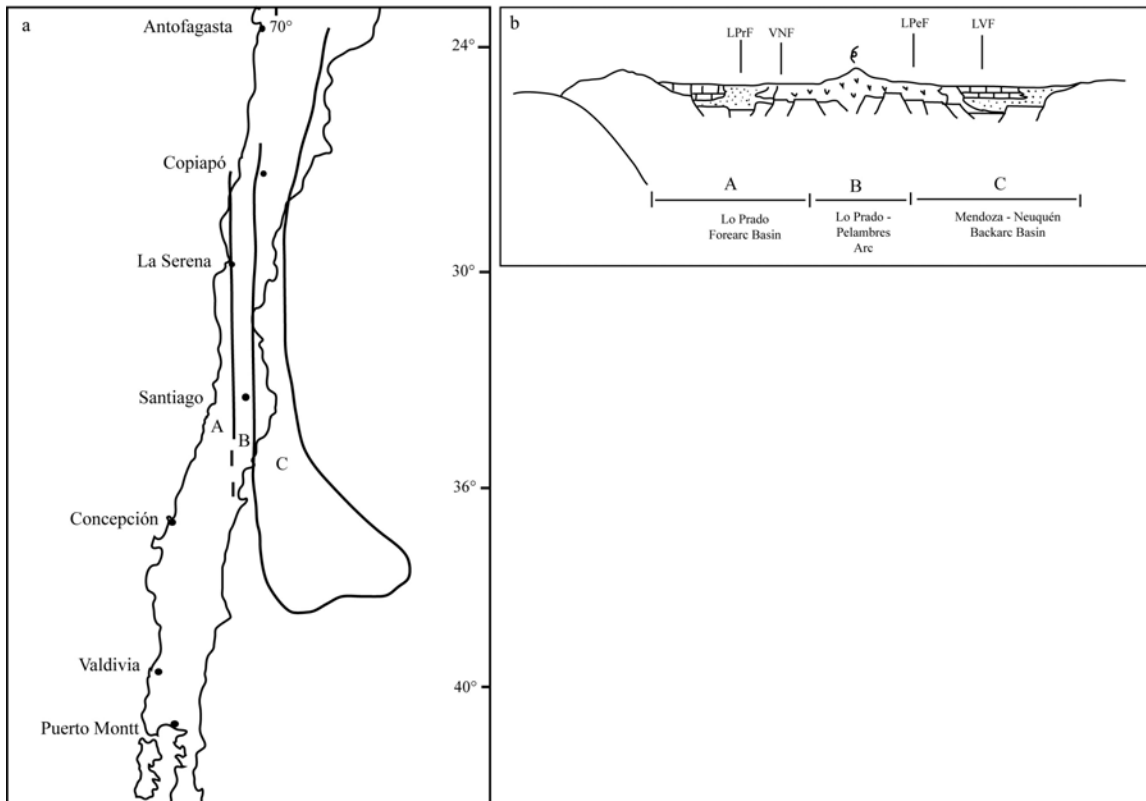
In Chile, the backarc basin related to this subduction system is traceable without interruption along the eastern side of the magmatic arc from at least southern Perú to southern Chile (Charrier et al. 2007). The Central Chilean segment (30°S to 39°S) is considerably wider than further to the north and is known as the Mendoza-Neuquén Basin. It extends eastwards into Argentina and shows a general southeastward bend (Charrier et al. 2007).

The area of research forms part of the central Chilean subduction system (figure 1.1 - 1.2) and thus presents a sequence of volcanic rocks and intercalated sediments from Jurassic to present ages. The sequence was folded from the Upper Cretaceous to present as part of the Andean orogeny. Tectonic orientations are North-South (figure 1.2) and thus follow the regional trend. In addition, laccoliths and batholiths of granitic composition intruded during the Miocene (Klohn 1960, Thiele 1980, Charrier 1981a).

Two depositional areas are recognized in the for the marine deposits accumulated during the Late Jurassic to Early Cretaceous time, one in the Coastal Cordillera and the second in the High Cordillera, and mostly on its eastern side (A and C, figure 1.3) (Charrier et al. 2007). The two basins are separated from each other by a volcanic Arc. It is therefore possible to identify three palaeogeographic domains, from west to east: the Lo Prado Forearc Basin, the Lo Prado-Pelambres Volcanic arc, and the Mendoza-Neuquén Backarc Basin (figure 1.3) (Charrier et al. 2007).



**Figure 1.2.** Geological map of Central Andes of Chile. This figure is based on the Geological maps “Hoja Santiago” (Thiele 1980) and “Geología de la Cordillera de los Andes de Chile Central” (Klohn 1960). The geological map correlated the formations and unites present in both areas. Lo Valdés and Baños del Flaco Formations are show as the same color. Lo Valdés Formation is distributed to the north of latitude 34°30' S, and Baños del Flaco Formation is distributed to the south of latitude 34°30' S.



**Figure 1.3.** Late Jurassic-Early Cretaceous palaeogeographic distribution in central Chile.

a) The forearc and backarc basin separated from each other by the Pelambres arc in central Chile. A, Lo Prado Forearc Basin; B, Lo Prado-Pelambres Volcanic Arc; C, Mendoza-Neuquén Basin.

b) Schematic palaeogeographic cross section of Andean evolution in central Chile between 32°S and 33°S. A, Lo Prado Forearc Basin; B, Lo Prado-Pelambres Volcanic Arc; C, Mendoza-Neuquén Basin. LPrF, Lo Prado Formation; VNF, Veta Negra Formation; LPeF, Los Pelambres Formation; LVF, Lo Valdés Formation (Charrier et al. 2007).

#### 1.4.1. Andean Basin: The Late Jurassic-Early Cretaceous sequence

East of Santiago, in the western part of Andean Basin, the Late Jurassic-Early Cretaceous (Neocomian) transgression-regression cycle resulted in the deposition of a thick succession of neritic to shallow marine (external platform) and predominantly calcareous sediments, known as the San José (Aguirre 1960), Lo Valdés (González 1963; Hallam et al 1986) and Baños del Flaco formations (Klohn 1960; González & Vergara 1962; Covacevich et al. 1976; Charrier 1981a, b; Arcos 1987, and Charrier et al. 2007).

In the segment of Santiago-Curicó (figure 1.1 - 1.2), the upper Jurassic and lower Cretaceous sediment sequence is differentiated in the Río Colina, Nacientes del Teno, Río Damas, Leñas-

Espinoza, Baños del Flaco and Lo Valdés formations. Río Colina Formation consists of limestone, calcareous siltstone, siltstone and gypsum and was deposited in a shallow marine setting during the Upper Oxfordian (Thiele 1980) or Callovian-Oxfordian (Alvarez et al. 1997). The Nacientes del Teno Formation is a penecontemporaneous equivalent (Bajocian? to Oxfordian; Klohn 1960) of the Río Colina Formation and composed of conglomerate, sandstone, siltstone, limestone, marl, gypsum and pyroclastic rocks. These units underlie the Río Damas Formation, a continental unit of Kimmeridgian age, composed by siliciclastic sediments and andesite (Klohn 1960, Thiele 1980). The Leñas-Espinoza Formation encompasses sandstone and limestone which were deposited during the Tithonian under shallow marine conditions. Originally this unit was thought to represent the Tithonian (Klohn 1960), while Charrier (1982) assigned this formation to the lower part of the Baños del Flaco Formation. The Lo Valdés Formation is composed of andesite, sandstone, siltstone and limestone, assigned to the Tithonian-Hauterivian or Barremian? Age (González 1963; Biro 1964; see chapter 3).

### **1.4.2. Baños del Flaco Formation**

This unit was defined by Klohn (1960) as a sequence of marine fossil-bearing grey limestone, sandy limestone and calcareous sandstones, and minor conglomerate, glauconitic sandstone and siltstone (e.g., Corvalán 1956, Klohn 1960, Covacevich et al., 1976). The unit is well developed in the area of Baños del Flaco, located in the valley of the Río Tinguiririca, O'Higgins Region of Chile; and along the Río Maitenes, tributary of Río Teno, Curicó, Maule Region of Chile (figure 1.1, 1.2).

Ammonites collected in the Baños del Flaco Formation by Corvalán (1956 and 1959) and Klohn (1960) on the southern side of Tinguiririca River y and along the Maitenes river in the Curicó province have been assigned to the late Tithonian, the Berriasian, early and late Valanginian, and to the Hauterivian. In addition to ammonites, sediments also contain sponges, corals, bivalves, gastropods, nautiloids and echinoids.

### **1.4.3. Lo Valdés Formation**

This unit is located east of the Chilean capital of Santiago in the high Andes (figure 1.1, 1.2). The Lo Valdés Formation was defined by González (1963) and the type locality placed at Lo Valdés, a village located to 5 km (figure 1.1). The only detailed study on the biostratigraphy and lithology of the section was by Biro (1964). At Lo Valdés, the Lo Valdés Formation consists of a 750 m

thick sequence of limestone, calcareous siltstone and calcareous sandstones, conglomerates and breccias as well as >600 m of andesite in the lower part of the section. Biro (1964) divided the formation in three members which are predominantly volcanic (spilite member, at base unit), siliciclastic (sandstone member, middle part of unit) and calcareous (calcareous member, at top of unit). The faunal assemblage was determined by Biro (1964) and consists of abundant ammonites as well as nautiloids, bivalves and gastropods. Biro (1964 and 1980a) and Hallam et al. (1986) assigned the Lo Valdés Formation to the early? Tithonian to Hauterivian based on ammonites. The latter authors also presented a biostratigraphic profile in which they differentiated 8 faunal associations.

## 2. Objectives and Methods

### 2.1 Objectives

The main objective of this dissertation is to re-evaluate the Jurassic/Cretaceous (J/K) boundary in the classical localities of central Chile using new techniques and data, to clarify the paleogeographic setting of this region, and to improve the stratigraphic correlation of these sections with localities of the Tethys and elsewhere. The present research includes sequence stratigraphical, micro- and macrofacies and faunal analyses, principally of ammonites and bivalves. Biostratigraphical and palaeobiogeographical analyses will be based on ammonites. This multistratigraphical approach will allow us to verify sea level fluctuations across the J/K boundary, including main flooding episodes, as well as the identification of systems tracts. Biostratigraphy is based on ammonite assemblages and will lead to a high resolution of events across this transition. This new data set will allow us to manage modern fine stratigraphic correlation at a global perspective, thus allowing to correlate the Chilean J/K boundary sequences with those of the other regions within South America and the Northern Hemisphere Tethyan Realm, including the Boreal and European Mediterranean region.

### 2.2 Methods

The Geological maps “Hoja Santiago” (sheet N°39, scale 1:250 000, Thiele 1980) and “Geología de la Cordillera de los Andes de Chile Central” (boletín N°8, scale 1:150 000, Klohn) of the “Servicio Nacional de Geología y Minería” (SERNAGEOMIN) were used for orientation in search the outcrops (figure 1.2).

Field work campaigns to the region were executed in 2006, 2007 and 2008, usually during the summer months of January and February. A total of five months were spent in the field searching and measuring and drawing sections as well as collecting fossils and rocks samples.

Five sections were measured and sampled at Cajón del Morado, Lo Valdés, Cruz de Piedra, Baños del Flaco and Rio Maitenes. Samples were taken every 10 m of section and in 1 m distances across the Jurassic-Cretaceous boundary transition.

**Lithology:** The description of carbonate microfacies is based on the classification of Wright (1992), who revised the classification of Dunham (1962) and Embry & Klovan (1971) and expanded it to diagenetically of Dunham. Siliciclastic sediments are subdivided by grain size.

Differentiation of conglomerate, sandstone and siltstone followed rules according to British Geological Survey (BGS) grain size scheme proposed by Wentworth (1922) and Folk (1968).

**Thin sections:** The microfacies of siliciclastic and carbonate rocks were analyzed with a petrographical microscope, based on small-sized thin sections (4.5 cm x 4.5 cm).

**Facies and sequence stratigraphy:** The terminology used here was proposed by Coe (2003) and Nichols (2009), who summarized the vast numbers of articles on facies and sequences stratigraphy published within the past years. The terminology on facies and sequence stratigraphy terms used in the present research is presented in the chapters 4 and 6.

**Fossils and Taxonomy:** Fossils samples were collected during field campaigns in every section. The fossils from Rio Maitenes section were collected by Lajos Biró Bagoszky from the Universidad de Concepción in the early 1960ies. He only published a single article on an echinoid of this assemblage (Larraín & Biro 1985). His field book, rock samples and his collection of ammonites is available for this research.

Fossils were prepared in the Palaeontological laboratory of the Institut für Geowissenschaften (Heidelberg University, Germany), with the “air pen” methodology.

The taxonomic citations are only used in the faunal lists. Taxa described in open nomenclature are assumed to represent indeed the species given in the systematic part of this research. The paleontological systematic terms and abbreviations used in this research are given in the chapter 4.

Explanation and abbreviations to symbols used in the figures are given in figure 2.1. Unless figures contain separate explanations, this legend is valid for all figure of the present research.

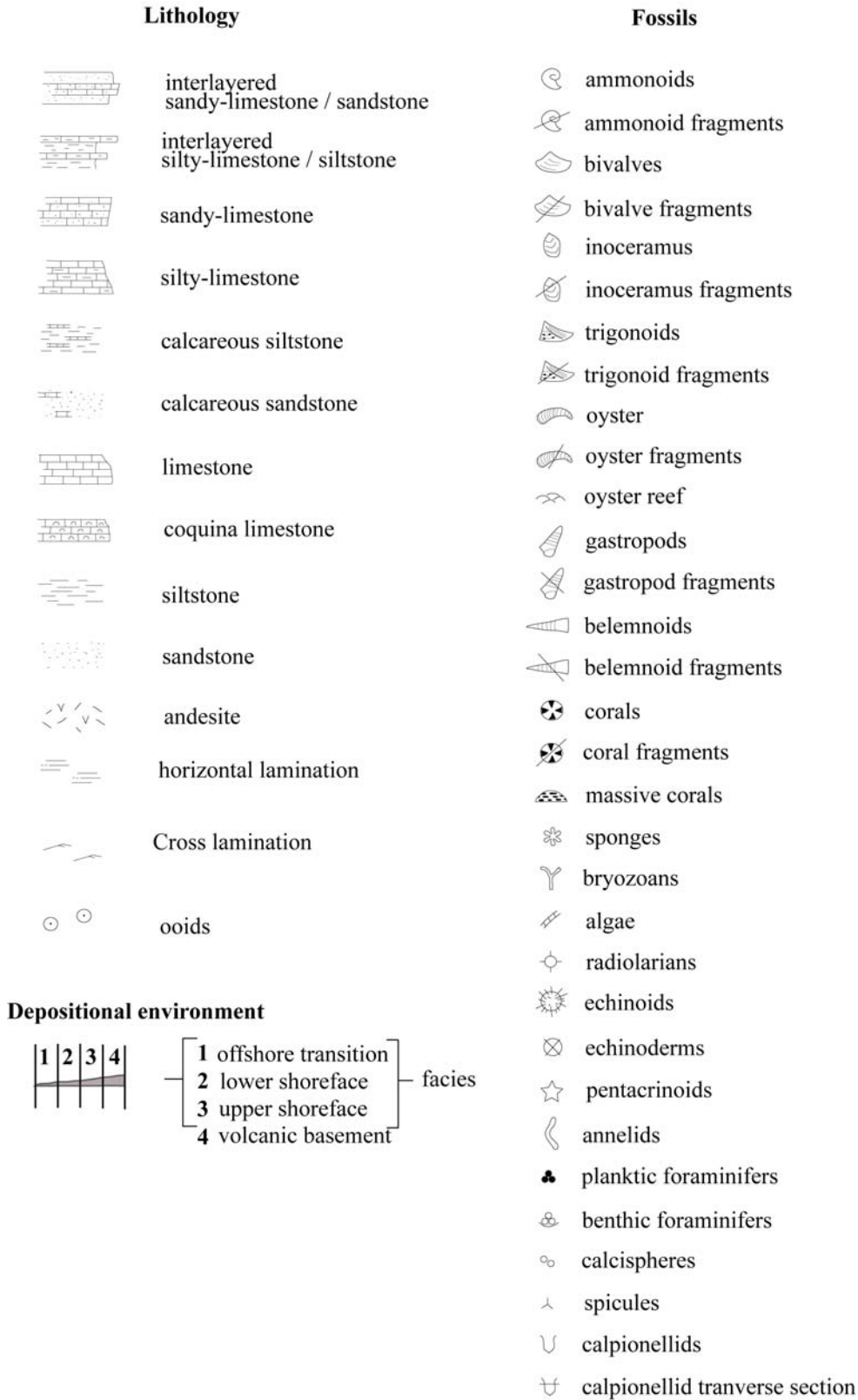


Figure 2.1. Key to symbols and abbreviations used in the stratigraphic columns.

