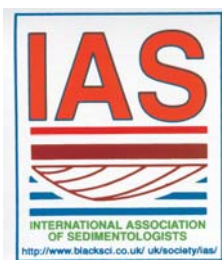


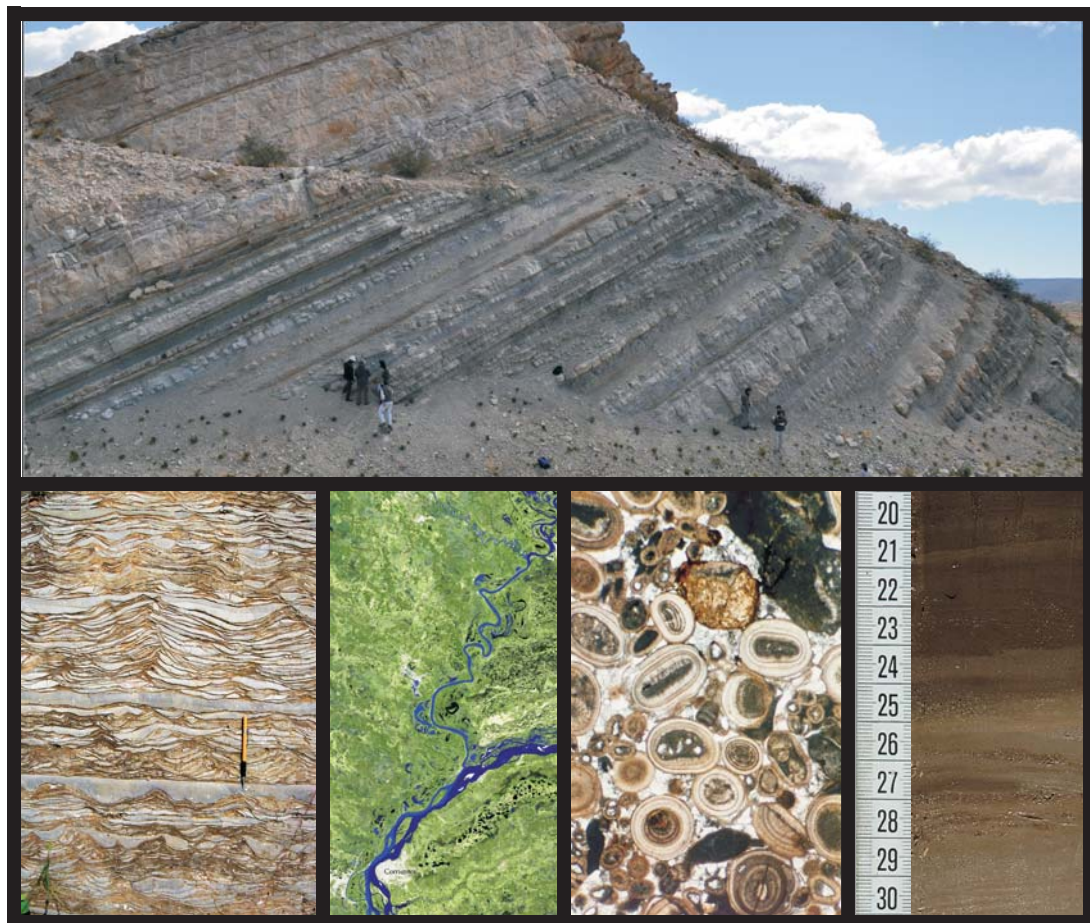


18th International Sedimentological Congress

“Sedimentology at the Foot of the Andes”



PETROBRAS



FE-C3: FACIES AND STRATIGRAPHIC SEQUENCES OF THE MESOZOIC NEUQUÉN BASIN (WESTERN ARGENTINA): CONTINENTAL TO DEEP MARINE SETTINGS

Luis Spalletti, Gonzalo Veiga and Ernesto Schwarz

Mendoza, Argentina
26th September - 1st October 2010

Field Excursion Guide

Front cover. Central: Marine deposits of the Picún Leufú Formation, Neuquén Basin, Argentina. From left to right: teppee structures, Salitre Formation, Brazil. Satellite imagen from the Paraná and Paraguay rivers, Argentina. Lacustrine grainstones, Maíz Gordo Formation, Argentina. Lacustrine organic matter-rich facies, Laguna Mar Chiquita, Argentina

FACIES AND STRATIGRAPHIC SEQUENCES OF THE MESOZOIC NEUQUÉN BASIN (WESTERN ARGENTINA): CONTINENTAL TO DEEP MARINE SETTINGS

3rd - 6th October 2010, Neuquén, Argentina

Luis Spalletti,
Gonzalo Veiga,
Ernesto Schwarz

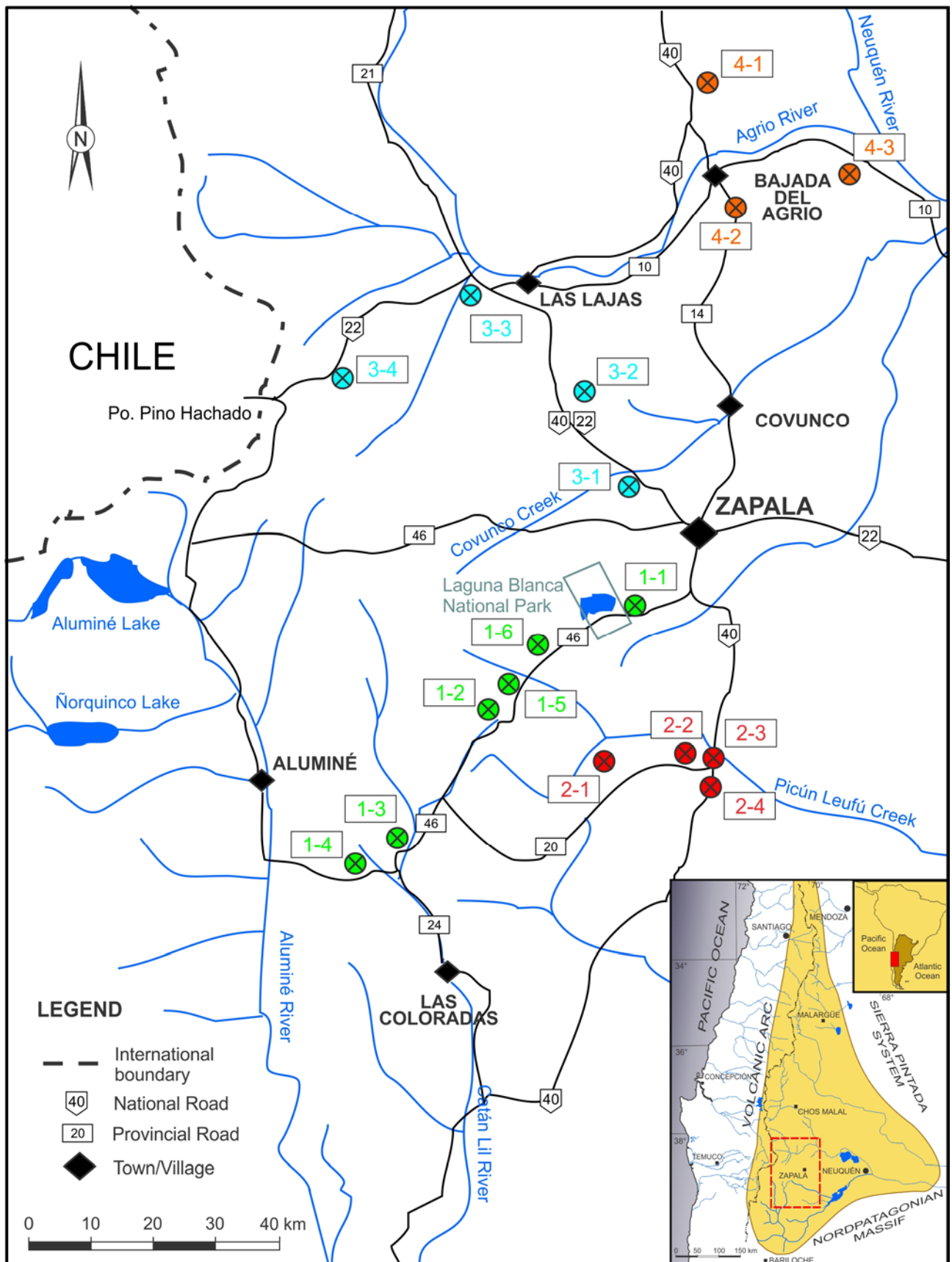
Centro de Investigaciones Geológicas, CONICET- University of La Plata, Argentina

Field Excursion Guide

PUBLISHER 'S NOTE

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Map for the central part of the Neuquén province and location of stops during the field course.

ITINERARY

DAY 1 – October 3rd

Departure from Neuquén Airport (10:15) and drive to Zapala.

Arrival at Zapala at midday. Luggage drop at the Hue Melén Hotel.

The Syn-rift Stage and the Initial Flooding of the Neuquén Basin

STOP 1.1. Overview and Holocene Volcanic Landscape at Laguna Blanca

STOP 1.2. General View of the early Syn-Rift deposits of the Neuquén Basin

STOP 1.3. to 1-5. The Deep-marine Deposits of the Los Molles Fm: The First Marine Flooding of the Neuquén Basin.

STOP 1.6. Overview of the Shallow-Marine deposits of the Lajas Fm at Lohan Mahuida.

DAY 2 – October 4th

Sedimentology and Stratigraphy of the Middle to Upper Jurassic

STOP 2.1. The Lajas Fm at Bajada de Los Molles

STOP 2.2. Fluvial Highstand deposits: The Challacó Fm.

STOP 2.3. The Kimmeridgian Lowstand Wedge: the Quebrada del Sapo (Tordillo) Fm.

STOP 2.4. The Tithonian Transgression: The Vaca Muerta and Picún Leufú Fm.

DAY 3 – October 5th

From the Jurassic Deposits to the Andean Magmatic Arc

STOP 3.1. The Jurassic Succession at Arroyo Covunco.

STOP 3.2. The Upper Jurassic Succession at the Western Vaca Muerta Range.

STOP 3.3. The Cainozoic Volcaniclastic Record of Western Neuquén.

STOP 3.4. The Cainozoic Volcanic and Pyroclastic Record of Western Neuquén.

DAY 4 – October 6th

Transgressive-Regressive cycles in the Lower Cretaceous and the Transition to the Foreland Stage

STOP 4.1. The Lower Cretaceous Succession at the Salado River. The Mulichinco and Agrio Formations.

STOP 4.2. The Lower Cretaceous Succession at Bajada del Agrio. The Agrio Fm.

STOP 4.3. The Foreland Stage: The Neuquén Group (Candeleros Member, Río Limay Formation) at Agrio del Medio

Luggage pick-up at the hotel and drive to Neuquén.

Arrival at 18:00 at Neuquén Airport. End of the Field Excursion.

Facies and stratigraphic sequences of the Mesozoic Neuquén basin (western Argentina): continental to deep marine settings

Luis Spalletti, Gonzalo Veiga and Ernesto Schwarz

Centro de Investigaciones Geológicas, CONICET- University of La Plata, Argentina

INTRODUCTION

Aims

This four-day field trip to the Neuquén Basin provides an excellent opportunity to observe the geology and to enjoy the superb outcrops of the most extensively studied petroleum basin of Argentina. Numerous outcrops along the Andean Fold and Thrust Belt will be visited in order to show the participants the stratigraphy, sedimentology and facies associations of Mesozoic siliciclastic, carbonate and evaporite units. The field trip will highlight the stratigraphic architecture of fluvial, aeolian, shallow marine and deep marine sequences and reservoir rocks.

Fieldwork Safety and Conservation Notice

There is risk inherent in all geological field excursions so this notice and the hazard assessment at the start of each day's itinerary should be read carefully and acted upon. The leaders will take all care in conducting the trip but safety is everyone's responsibility.

- Be prepared for conditions ranging from warm (35°C) to cold and windy.

- Always use a hat and strong walking boots and carry sunblock cream.
- Do not step on bushes, dislodge rocks or disturb any form of wildlife.
- Do not litter and refrain from making permanent marks on rock surfaces.
- Always be aware of people above or below you with respect to falling rocks.
- Never take risks over climbing in sections where you do not have confidence.
- Always be guided by the leaders over the safest routes up the rocky sections.

The organizers can not anticipate and are not responsible for the actions or circumstances created and controlled by others, including but not limited to the weather, the conditions of the routes and program destinations, the behavior of other road users, the skill and judgment of participants, and the negligent or criminal actions of other individuals. Health insurance is not included in any excursion. Personal health insurance, travel and baggage insurance is strongly recommended.

GEOLOGICAL SETTING

Introduction to the Neuquén Basin (from Howell et al. 2005)

The Neuquén Basin is located on the eastern side of the Andes in Argentina and central Chile, between 32° and 40° south latitude. It covers an area of over 120,000 km² and comprises a continuous record of up to 4,000 m of stratigraphy. This Late Triassic to Early Cretaceous succession includes continental and marine siliciclastics, carbonates and evaporites that accumulated under a variety of basin styles.

The basin has a broadly triangular shape and two main regions are commonly recognised: the Neuquén Andes to the west and the Neuquén Embayment to the east and southeast. The majority of the hydrocarbon fields are located in the Neuquén Embayment where most of the Mesozoic sedimentary record is in the subsurface and the strata are relatively undeformed. This is in contrast to the Andean region where Late Cretaceous to Cretaceous deformation has resulted in the development of a series of north-south-oriented fold and thrust belts (Aconcagua, Marlargüe and Agrio Fold and Thrust Belts) which provide excellent outcrops of the Mesozoic successions.

During present times and throughout much of its history the triangular Neuquén Basin has been limited on its northeastern and southern margins by wide cratonic areas of the Sierra Pintada Massif and North Patagonian Massif, respectively. The western margin of the basin is the Andean magmatic arc on the active western margin of the Gondwanan-South American Plate.

This geotectonic framework and the highly complex history of the basin are largely controlled by changes in the tectonics on the western margin of Gondwana. The evolution and development of the basin can be considered in three stages:

1- Late Triassic to Early Jurassic: prior to the onset of subduction on its western margin, this part of Gondwana was characterised by large transcurrent fault systems. This led to extensional tectonics within the Neuquén Basin and the evolution of a series of narrow, isolated

depocentres (Maceda & Figueroa 1995, Vergani et al. 1995, Franzese & Spalletti 2001).

2- Early Jurassic to Early Cretaceous: development of a steeply dipping, active subduction zone and the associated evolution of a magmatic arc along the western margin of Gondwana led to back-arc subsidence within the Neuquén Basin. This post-rift stage of basin development accounts for more than 4,000 m of the basin fill (Vergani et al. 1995).

3- Late Cretaceous to Cretaceous: transition to a shallowly dipping subduction zone resulting in compression and flexural subsidence, associated with 45 to 57 km of crustal shortening (Introcaso et al. 1992, Ramos 1999b) and uplift of the foreland thrust belt.

The final phase of Andean tectonism produced the uplift of the tightly folded outcrops in the western part of the area. These outcrops expose a complete Mesozoic succession that includes a very wide variety of depositional settings. The lateral extent and spatial distribution of the deposits facilitates stratigraphic correlation and the tracing of regional unconformities. These outcrops have been used to understand hydrocarbon reservoir systems both in the adjacent subsurface systems (Vergani et al. 2002) and also World-wide (Brandsæter et al. 2005).

The palaeontology of the Neuquén Basin is central to its global significance. The Basin contains one of the most complete records of Jurassic and Cretaceous marine invertebrates. The completeness of this record has allowed the construction of accurate biostratigraphic charts for western Gondwana (Riccardi et al. 1999, Aguirre-Urreta et al. 1999). These charts allow excellent correlation and dating within the basin and comparative correlation to faunas and successions from other parts of the world, e.g. North America and Thethys. The Mesozoic continental and marine reptile record of the Neuquén Basin is one of the most complete, varied and well preserved in the entire world. New theories with global implications on taxonomy, palaeobiogeography, palaeoecology and taphonomy merged from the study of these herpetofaunas (Gasparini et al. 2005).

The Neuquén Basin has been the subject of numerous studies since the beginning of the

twentieth century. Prior to the 1960's early work included regional studies on the stratigraphy, palaeontology, biostratigraphy and structural geology (e.g. Weaver 1931, Herrero Duicloud 1946, Groeber 1946, Groeber et al. 1953, DeFerrariis 1947). From the 1960's to the 1990's a concerted hydrocarbon exploration effort by YPF (the Argentinian National Oil Company) coupled with numerous academic studies led to significant advances in the understanding of the basin. During this period the different structural styles were defined (Ramos 1978, Ploszkiewicz et al. 1984), the biostratigraphic charts for the Jurassic and the Cretaceous were refined and updated (Riccardi

et al. 1971, Leanza 1973, 1981, Leanza et al. 1977, Riccardi 1983) and the early schemes for the regional sequence and seismic stratigraphy were developed (Gulisano et al. 1984, Mitchum & Uliana 1985, Legarreta & Gulisano 1989, Legarreta & Uliana 1991, 1999, Legarreta et al. 1993). Since the early 1990's studies within the basin (including those presented in this special publication) have utilised the regional frameworks to address specific issues such as high resolution sequence stratigraphic problems, detailed palaeogeographic and sedimentological studies of specific intervals, improved biostratigraphic charts and geochemical studies.

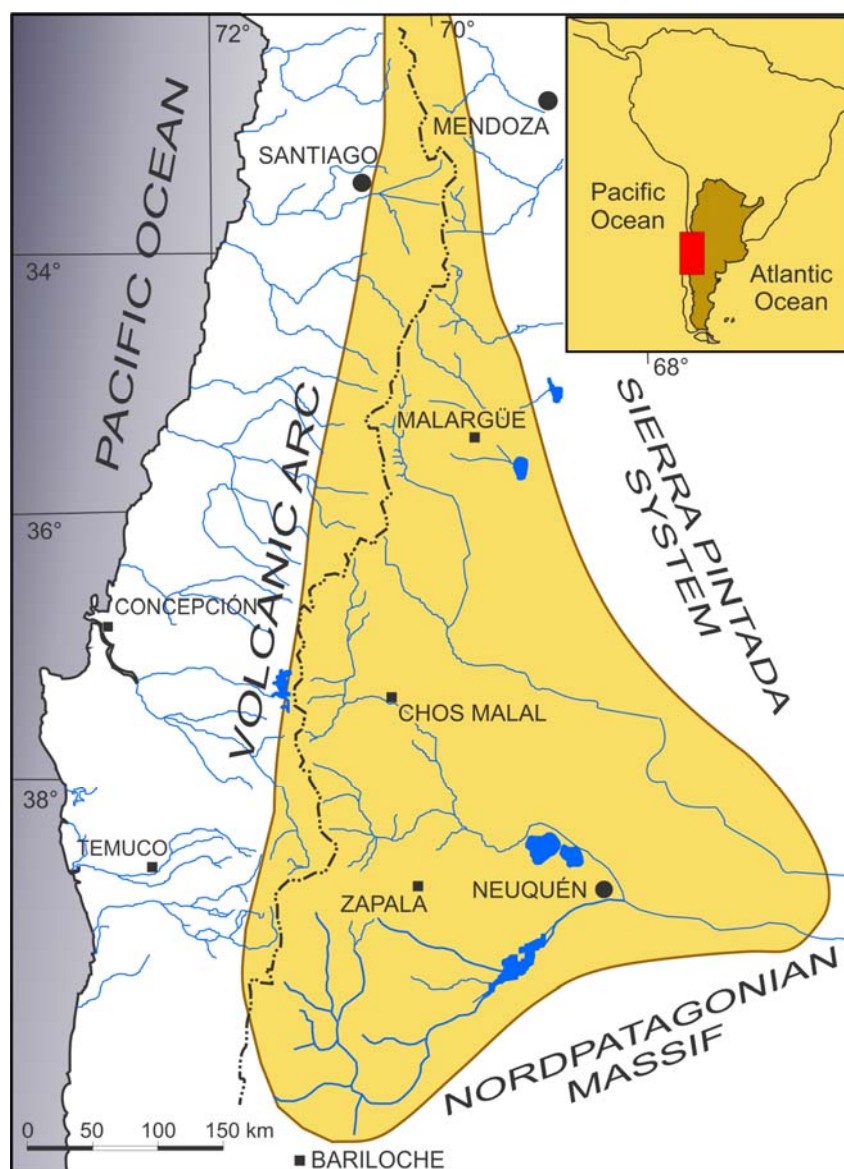


Figure 1. Location map of the Neuquén Basin and adjacent areas.

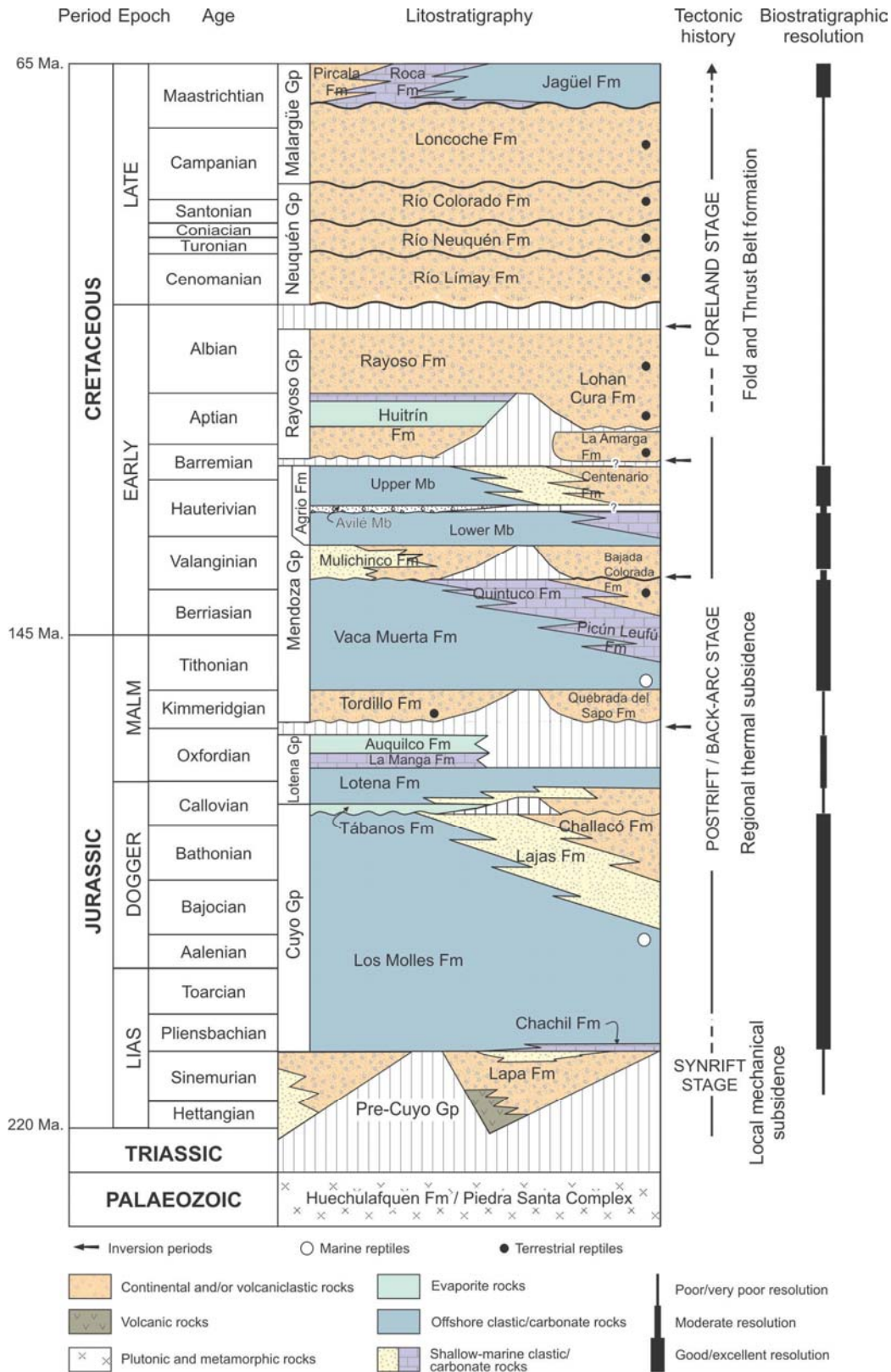


Figure 2. Chronostratigraphy, tectonic history and biostratigraphy of the Neuquén Basin. Lithostratigraphy is mostly after Legarreta & Gulisano (1989) and Legarreta & Uliana (1991). Only nomenclature of the Neuquén sector of the Basin is depicted. Tectonic history after Vergani et al. (1995) and Franzese et al. (2003). Biostratigraphic resolution after Riccardi et al. (1999) (Jurassic), Aguirre-Urreta & Rawson (1997), Aguirre-Urreta et al. (1999) (Early Cretaceous) and Casadio et al. (2004) (Late Cretaceous). From Howell, Schwarz, Spalletti & Veiga (2005).

Geodynamic Evolution

The Neuquén Basin originated in the Late Triassic as a result of continental intraplate extension. During this period a series of extensional troughs were filled with volcanoclastic and continental deposits. During the subsequent growth of the Andean magmatic arc the basin became a back-arc system with widespread marine sedimentation. Acceleration of plate convergence during the Late Cretaceous produced partial inversion and the development of a retro-arc flexural system. This was associated with a progressive change from marine to continental sedimentation. The evolution of the Neuquén Basin is intimately linked to the development of the Neuquén Andes and the geometry of the subducting slab (Ramos & Folguera 2005).

Late Triassic - Early Jurassic synrift phase

The Late Triassic to Early Jurassic margin of Gondwana in the vicinity of the Neuquén Basin lacks evidence for slab subduction. The tectonic system was dominated by a strike-slip regime subparallel to the western continental margin (Franzese & Spalletti 2001). In the area of the Neuquén Basin extension related to the collapse of the Gondwana orogen produced a series of long, narrow half-grabens which were filled by a complex array of clastic and volcanoclastic deposits associated with extensive lava flows (Franzese et al. 2006) (Lapa Formation, and equivalent units). Clastic deposits include alluvial, fluvial, shallow-marine, deltaic and lacustrine deposits (Franzese & Spalletti 2001). Fault growth, interaction and a transition to more regional subsidence during Early Jurassic times resulted in a more widespread lacustrine and shallow marine facies distribution.

Early Jurassic to Early Cretaceous postrift phase

During the Early to Middle Jurassic the subduction regime along the western Gondwana margin was initiated (Franzese et al. 2003) and by the Late Jurassic the Andean magmatic arc was almost fully developed. Back-arc subsidence led to an expansion of the marine realm and flooding of the basin which was

connected to the proto-Pacific through gaps in the arc (Spalletti et al. 2000, Macdonald et al. 2003). Initially sedimentation was strongly influenced by the topography inherited from the underlying synrift systems (Burgess et al. 2000, McIlroy et al. 2005). After this initial period the most important evolutionary phase of the Neuquén Basin started. Thick and widespread successions were deposited during this long period of protracted thermal subsidence and regional back-arc extension. They include a complex series of transgressive-regressive cycles of different magnitude, controlled by the combined effects of changes in subsidence rates, localised uplift and eustatic sea-level oscillations (Cuyo, Lotena and Mendoza Groups).

Late Cretaceous to Cainozoic - compression and foreland basin phase

Towards the end of the Early Cretaceous changes in the rates of South Atlantic spreading and a reorganisation of the Pacific plates, including a decrease in the angle of slab subduction, resulted in the development of a compressional tectonic regime which caused inversion of previous extensional structures (Vergani et al. 1995). At this stage the Neuquén region became a retroarc foreland basin, and significant variations in the size and shape of the basin (Legarreta & Uliana 1991) together with an eastwards migration of the depocentres occurred (Franzese et al. 2003).

The active depositional systems within the Neuquén Basin were strongly controlled by the compressive regime. Uplift and tectonic inversion in the mountain chain to the west led to the deposition of more than 2,000 m of continental deposits in the main depocentres (Rayoso and Neuquén Groups) (Legarreta & Uliana 1991, 1999, Vergani et al. 1995). Towards the end of the Cretaceous continental sedimentation was widespread and the Neuquén Basin merged with other basins to the south (e.g. the San Jorge Basin) to produce a unique giant depocentre (Franzese et al. 2003). In the latest Cretaceous very high global sea-levels resulted in the first marine transgression from the Atlantic with shallow-marine deposits

occurring over wide areas of the Basin (Barrio 1990).

Several thin- and thick-skinned fold and thrust belts developed as a result of the foreland basin phase (Ramos 1999b) and their position constitutes a major control on the present day physiography of the Neuquén region. However, the compressional regime was not a continuous, simple process through time. Zapata & Folguera (2005) have identified several different stages of tectonic compression and relaxation in the evolution of the Andean Fold and Thrust Belt between the Late Cretaceous and Cainozoic. Moreover, these authors propose that flexural subsidence during tectonic compression was occasionally coeval with the generation of small depocentres associated with intense (arc and retroarc) volcanic activity. Ramos & Folguera (2005) provide a detailed analysis of the main characteristics and evolution of these magmatic related depocentres.

Jurassic to Cretaceous Sedimentology and Sequence Stratigraphy

The majority of the succession that outcrops in the Neuquén region was deposited in the Jurassic to Cretaceous postrift basin. During this period steep subduction of the Pacific plates resulted in negative roll back and a broad, generally extensional regime in both the arc and back-arc settings (Ramos 1999b). Within the Neuquén Basin this extension was gentle and was expressed as broad scale, regional subsidence rather than rifting with active extensional faults at the surface. The depositional systems were marine-dominated and show well defined records of cyclic sea-level change at different scales. These cycles were a product of the complex interaction of eustatic oscillations, minor extension and thermal subsidence with localised uplift and inversion and form the focus of sequence stratigraphic studies of the sedimentary record in the basin.

In his pioneering study of the stratigraphy in the basin, Groeber (1946) identified two major cycles (Jurásico and Ándico) each composed of several transgressive-regressive subcycles. Building on this work several authors (Gulisano et al. 1984, Mitchum & Uliana 1985, Legarreta

& Gulisano 1989, Legarreta & Uliana 1991, 1996, 1999, Legarreta et al. 1993) produced a more detailed breakdown of these cycles and attributed them primarily to eustatic sea-level changes under a regime of thermal subsidence. The dramatic sea-level falls that occurred during the Cretaceous (>100 m), such as the sequence boundaries at the base of the Avilé and Troncoso Members in which aeolian deposits overlie offshore marine shales (Veiga, G. et al. 2002, Veiga et al. 2005) were attributed to sea-level in the Pacific falling below a sill in the Andean arc that separated the Neuquén Basin from the open ocean. Whilst appealing and an excellent starting point, this interpretation appears to have underrated the importance of intra-basinal and intra-arc tectonics. According to Vergani et al. (1995), Tankard et al. (1995), Veiga, R. et al. (2002) and Pángaro et al. (2002), the sag phase of subsidence was frequently disturbed by tectonic reactivations associated with changes in the subduction regime and intraplate reorganisation.

There are a number of aspects of the basin that make it an excellent case study in sequence stratigraphy. The high resolution biostratigraphic record provides a framework for study; the high quality outcrops and the proximity to an abundance of subsurface information provide good data to develop and constrain models and the geodynamic setting outlined above produced well developed cycles of relative sea-level change. In the early Jurassic the Basin had a topography that was inherited from the late Triassic rift phase (Burgess et al. 2000). During the remainder of the Jurassic and early Cretaceous history the Basin had a ramp style geometry, similar to other retro-arc basins (e.g. the Western Interior Basin of the USA; Edwards et al. 2005).

The Early Jurassic of the Neuquén Basin provides an excellent study in the significance of basin geometry on sequence and facies architecture. The deep water turbidite systems of the Los Molles Formation (Burgess et al. 2000) and the shallow marine tidal deposits of the Lajas Formation (McIlroy et al. 2005) were strongly influenced by the relict topography inherited from the early rift phase. This topography controlled the distribution of

depositional lows and in the Lajas Formation resulted in the localised amplification of the tidal wave and a thick, highly aggradational succession of tidal deposits.

Deposition in the late postrift ramp setting was characterised by well-developed cycles showing a complete record of lowstand, transgressive and highstand systems tracts. Surfaces that bound these sequences are marked by a sharp basinward shifting of continental-dominated facies. Falling-stage deposits are present in some cases (Veiga et al. 2005), but are typically poorly developed. The transgressive systems tracts are mainly composed of thick offshore deposits (Doyle et al. 2005, Sagasti 2005), even near the basin margins. These deposits commonly show features of restricted marine circulation. The highstand systems tracts are mainly composed of mixed offshore siliciclastics and carbonates that pass upward into progradational shoreface, deltaic and fluvial deposits. The Lower Cretaceous succession of the Neuquén Basin includes a number of such examples of ramp margin sequences.

The extreme facies shifts that are associated with the sequence boundaries are attributed to the effects of relative sea-level fall, enhanced and locally overprinted by phases of localised tectonic inversions. Although the basinward shift in facies is commonly major, the sequence boundaries are typically planar and incised valleys are rare (Schwarz et al. 2006, Schwarz & Howell 2005). The nature of the facies that overlie the sequence boundaries is partially controlled by the degree of connection that was maintained to the proto-Pacific Ocean. In some cases a complete desiccation of the basin occurred as the connection was severed (e.g. the aeolian deposits of the Troncoso Member, Veiga et al. 2005), in others a limited connection was maintained and the lowstand deposits show evidence of open or restricted marine circulation. Schwarz & Howell (2005) examine one of these long-term lowstand wedges and highlight how tectonic activity and basin physiography conditioned the internal sequence architecture and the relationship between contemporary marine and non-marine depositional systems.

The low angle of the ramp margin also favoured rapid landward migration of shorelines during the transgressions that followed the lowstands. In many cases shallow marine and offshore deposits directly overlie fluvial and aeolian facies. Strömback et al. (2005) analyse one of these transgressive events that occurred across the top of a lowstand aeolian sand sea. In this case the transgression was fast enough to preserve at least some of the dune topography with soft sediment deformation and slumping into the interdune lows and only localised reworking of the dune tops.

Transgressive systems tracts within the postrift fill of the Basin are characterised by thick successions of offshore marine deposits that commonly show evidence for restricted water circulation. Within these cyclically stacked black shale and marl successions Doyle et al. (2005) examine how systematic variation in the Jurassic to Lower Cretaceous ichnologic and faunal record may be employed to interpret the firmness of the marine substrate and different levels of oxygenation at the water-sediment interface. Besides, a detailed study of organic facies within transgressive intervals by Tyson et al. (2005) reveals that Cretaceous anoxic events do not exactly correlate with previously documented global anoxic events. They are interpreted as the result of the combination of a long term rise in sea level and the development of locally restricted conditions.

Within low-frequency transgressive cycles, high-frequency subdivisions may be recognised in the Neuquén Basin record. Scasso et al. (2005) analyse the rhythmic succession of limestones and marls that characterise one of the high-frequency Tithonian highstands, concluding that these offshore cycles are the result of systematic changes in productivity on the sea surface, and supply of terrigenous and non-terrigenous material in suspended plumes. Sagasti 2005) analyses high-frequency cycles developed during two low-order Valanginian-Barremian transgressive successions. These outer ramp rhythms are interpreted as dilution cycles triggered by orbital climatic changes within the Milankovitch range.

Towards the end of the Early Cretaceous the Neuquén Basin started to experience one of its

major tectonic changes, passing from the back-arc sag phase to the early part of the foreland phase. Veiga et al. (2005) analyse the sequence stratigraphic architecture and the evolution of the depositional systems through this transition. Some striking differences are depicted from the

previous sequence stratigraphic framework, with well developed falling stage systems tract followed by a lowstand episode characterised by complete disconnection from the ocean and without re-establishment of “normal” marine conditions during the subsequent transgression.

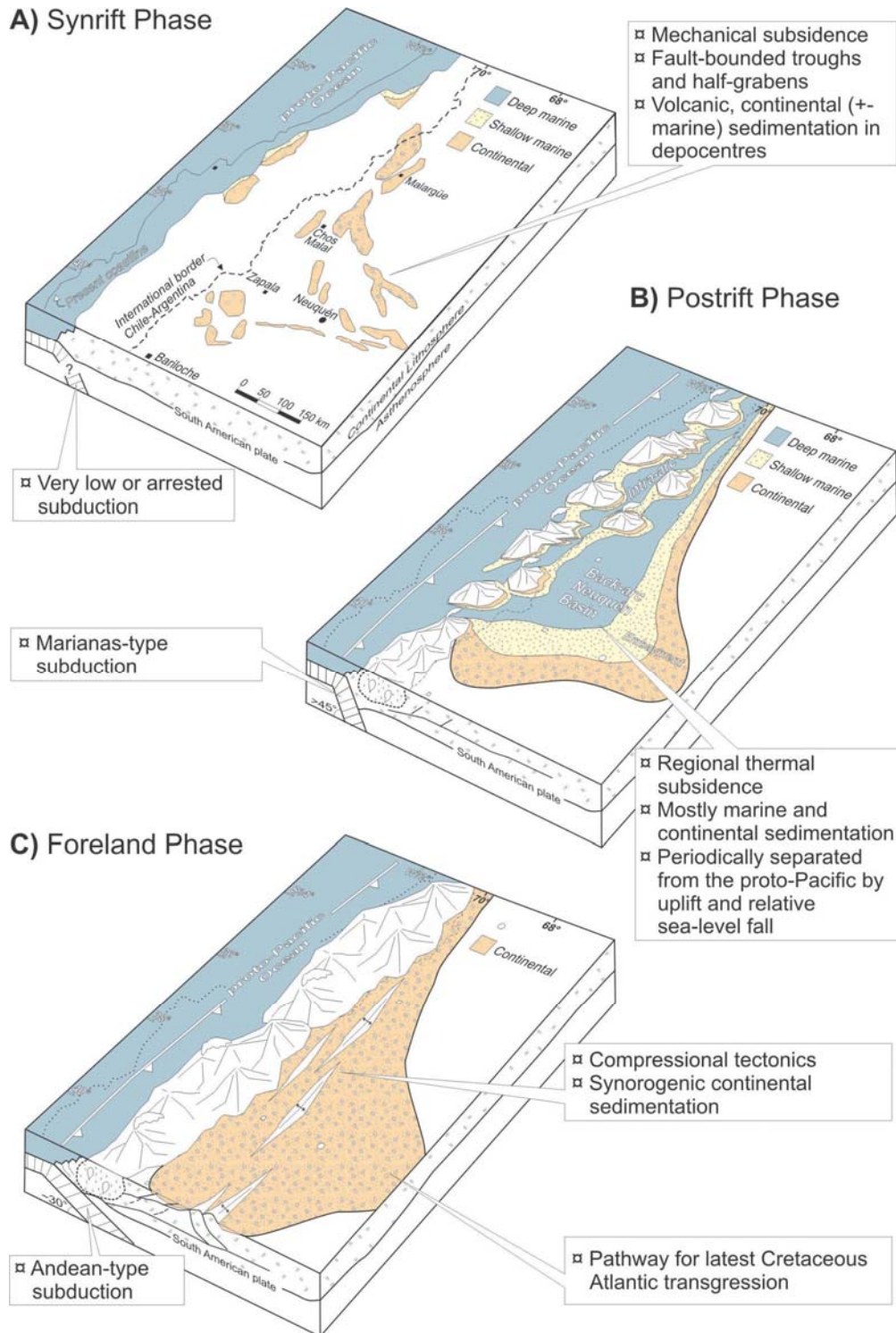


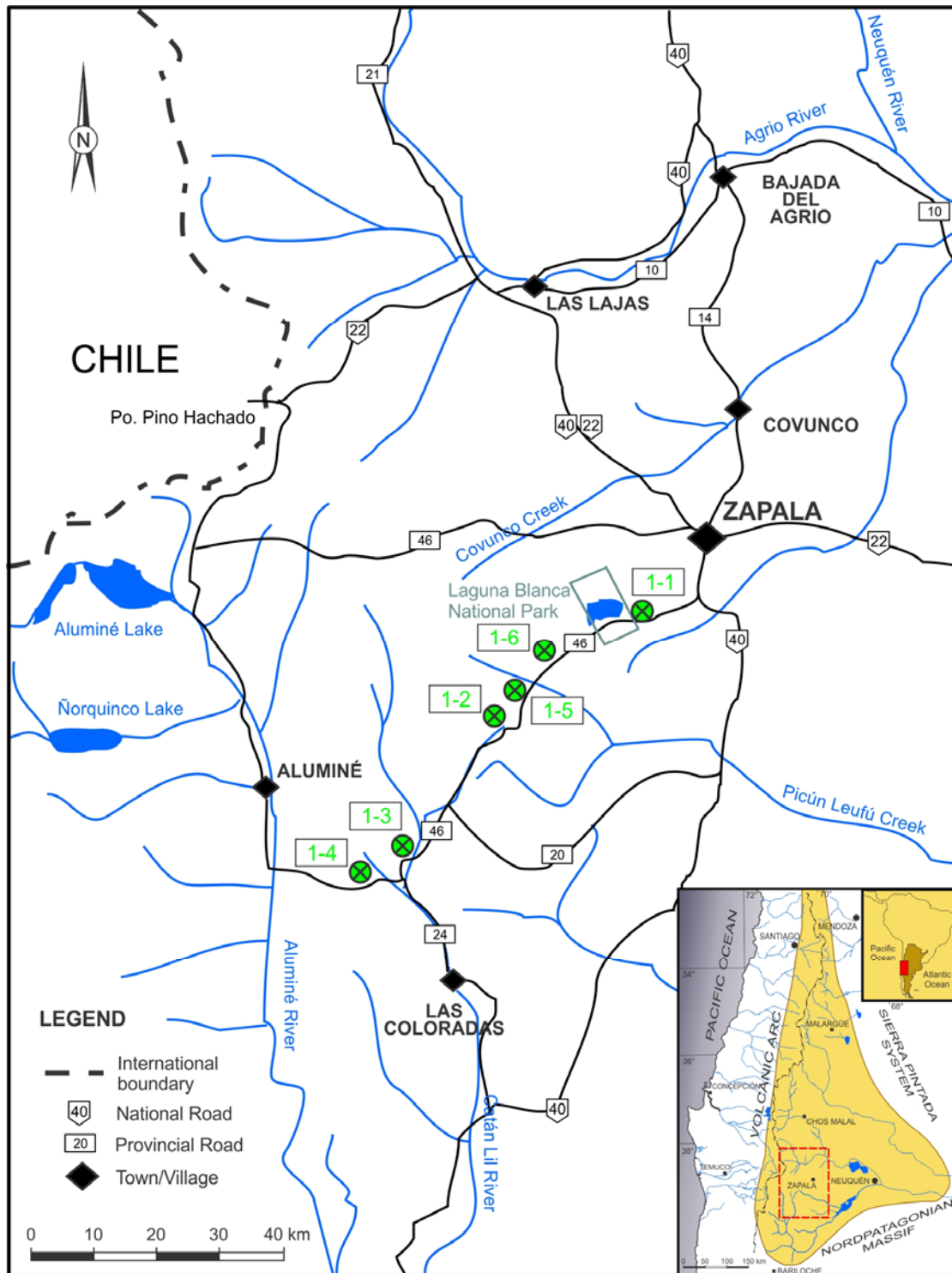
Figure 3. Schematic evolution of the Neuquén Basin from the Late Triassic to the Cretaceous. A) Late Triassic Early Jurassic, characterised by pre-subduction rifting in a series of narrow grabens. B) Jurassic Early Cretaceous, onset of subduction on the western margin of Gondwana and the early development of the Andean chain. The Basin is a large triangular embayment periodically separated from the proto-Pacific by uplift and relative sea-level fall. C) Late Cretaceous Andean uplift, development of a foreland thrust belt and basin. Much of the Basin fill is non-marine although periodic transgression from the Atlantic results in some marine intervals. Based on Vergani et al. (1995), Ramos (1999b), Franzese & Spalletti (2001), Folguera & Ramos (2002) and Franzese et al. (2003). Original drafts courtesy of Dr. Juan Franzese. From Howell, Schwarz, Spalletti & Veiga (2005).

DAY 1 – October 3rd

Travel along the Provincial Road 46 to Rahue

THE SYN-RIFT STAGE AND THE INITIAL FLOODING OF THE NEUQUÉN BASIN

The aims of this day are to observe the large-scale characteristics of the initial syn-rift deposits and to examine the basinal deposits of the Pliensbachian - Aalenian Los Molles Formation that represent the first widespread marine incursion in the Neuquén Basin.



Cumulative distance from ZAPALA (km)	Geographic – Geologic Reference
0	Zapala. National Road 40
11.6	Junction National Road 40 and Provincial Road 46 to Rahue.
25.8	Provincial Road 46. Holocene dark ashes and basaltic lava flows (El Puente and Tromen volcanics). View of the Mellizos Sur Hill
29.2	Laguna Blanca National Park
31.8	STOP 1-1. General view of the Laguna Blanca, cinder cone (Tromen Formation) and volcanic landscape
43.5	Ñireco School and Creek
49.7	STOP 1-6. Lohan Mahuida: general view of the Lajas Formation
52.1	Picún Leufú Creek (Bridge)
60	STOP 1-5. Los Molles Formation. Amalgamated sandy turbidites
60.9	STOP 1-2. Morro del Águila. General view of the syn-rift deposits (Precuyano)
66	Contact Gondwanan granites (Permian) and Chachil Limestone (Base of the Cuyo Group)
68.8	Pesqueira Creek
74	Espinazo del Zorro
84.6	Contact basement (Colohuincul Formation) – Los Molles Formation
86.3	Catán Lil River (bridge)
89.3	Belisle Creek
92.4	STOP 1-3. Huge turbiditic palaeochannel Los Molles Formation (Fortín Primero de Mayo)
97.6	STOP 1-4. Los Molles turbidites, examples of different primary structures. Coarse-grained turbidites and slump deposits
98.2	La Jardinera Creek
103.8	Araucaria forest
106	Rahue slope

STOP 1-1. General View of the Laguna Blanca National Park. Overview of the Field Trip and Holocene Volcanic Landscape

The National Park was created in 1940 in order to protect one of the most important places where the black-necked swan (*Cygnus melancoryphus*) lives. It is located in the northwest of Neuquén province and houses –in a volcanic landscape- a lot of different forms of aquatic and terrestrial life. The particular characteristic of the region is the small lake,

located between gentle slope hills. The Laguna Blanca is located 1.270 meters above sea level; it has a 30-kilometer-long shore and a 1.700 hectare surface. It has a 10 meter depth and receives water from two brooks: Llano Blanco and Pichi-Ñireco but the main water supply comes from subsurficial flow. This place has been included in the important Wetlands List (Ramsar Convention) due its importance as an aquatic bird's habitat.

Notes:



Figure 1.1. Satellite image of the Laguna Blanca National Park and surrounding areas.



Figure 1.2. General view of the Laguna Blanca from the east with a cinder cone in the background.

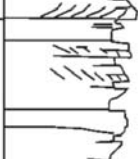
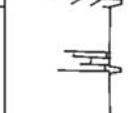
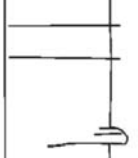
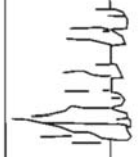
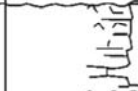
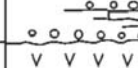
Berriasian	Bajada Colorada Fm		Fluvial conglomerates, sandstones and claystones
	Picún Leufú Fm		Inner shelf clastics and carbonates. Coastal plain and fluvial sandstones, mudstones and conglomerates
Tithonian		Vaca Muerta Fm	
	Kimmeridgian	Qda. del Sapo Fm	
Bathonian	Challacó Fm		Fluvial conglomerates, sandstones and red mudstones
Bajocian	Lajas Fm		Estuarine, deltaic and inner shelf sandstones and mudstones
			Prodeltaic and outer shelf shales and micritic limestones
Aalenian	Los Molles Fm		Marginal marine sandstones and conglomerates
Toarcian			Outer shelf to basinal shales and thin sandstones
Pliensbachian			Turbiditic sandstones and deep marine shales
		Basinal shales	
Hettangian	Lapa Fm		Basal conglomerate
Late Triassic			Volcaniclastic conglomerates and sandstones. Pyroclastic deposits.
Permian	Choiyoi Group		Volcanic rocks, pyroclastic breccias, tuffs and volcaniclastic deposits
Carboniferous - Permian	Huechulafquen Fm		Granites
Devonian ?	Piedra Santa - Colohuincul Fm		Low grade metamorphics

Figure 1.3. Stratigraphic column for the southwestern area of the Neuquen Basin. Modified after Gulisano and Gutiérrez Pleimling (1994).

STOP 1-2. General View of the Syn-Rift deposits of the Neuquén Basin

From Late Triassic to Early Jurassic, part of the protopacific margin of Gondwana was affected by continental extension driven by the thermo-mechanical collapse of an Upper Palaeozoic thickened crust (Franzese & Spalletti 2001). This led to the creation of an ensialic back-arc basin (Neuquén Basin) that was active during the Mesozoic and Cenozoic between 30°SL and 40°SL. The initial (syn-rift) configuration of the basin was characterised by the development of isolated deep depressions bounded by normal faults and filled with volcano-sedimentary successions (Vergani et al. 1995). Mesozoic and Cenozoic inversion in the central and southern Neuquén Basin produced uplift and exposure of the fault-bounded margins of the depocentres providing good exposures of the syn-rift succession. Subsurface studies also show them as a series of half-grabens with variable polarity, intersected by “en echelon” transfer faults (Vergani et al. 1995).

The syn-rift fill (Rhaetian – Lower Pliensbachian) is composed of volcanic,

pyroclastic and siliciclastic rocks collectively termed the Precuyano Cycle (Gulisano 1981). In this area these deposits constitute the Lapa Formation. Although there are no absolute indicators of the age of the syn-rift sequence, ignimbrites of the Lapa Formation in neighbouring areas have been dated as Late Triassic (219 Ma) to Early Jurassic (182 Ma) (Pángaro et al. 2002a). Plant remains collected in the Lapa Formation towards the south were also identified as Late Triassic in age (Spalletti et al. 1999).

Carbonate deposits of the Chachil Formation represent the early post-rift accumulation in this part of the basin. They overlie both the syn-rift succession and the pre-rift basement and are related to a widespread marine transgression of the Neuquén Basin. The Chachil Formation is comprised of shallow-marine siliciclastic deposits that pass upward into spiculitic limestones deposited in a low-energy carbonate ramp (Gómez Pérez & Franzese 1999a). This unit grades upward into a thick succession of deep-marine black shales and turbidites of the Los Molles Formation.

Notes:

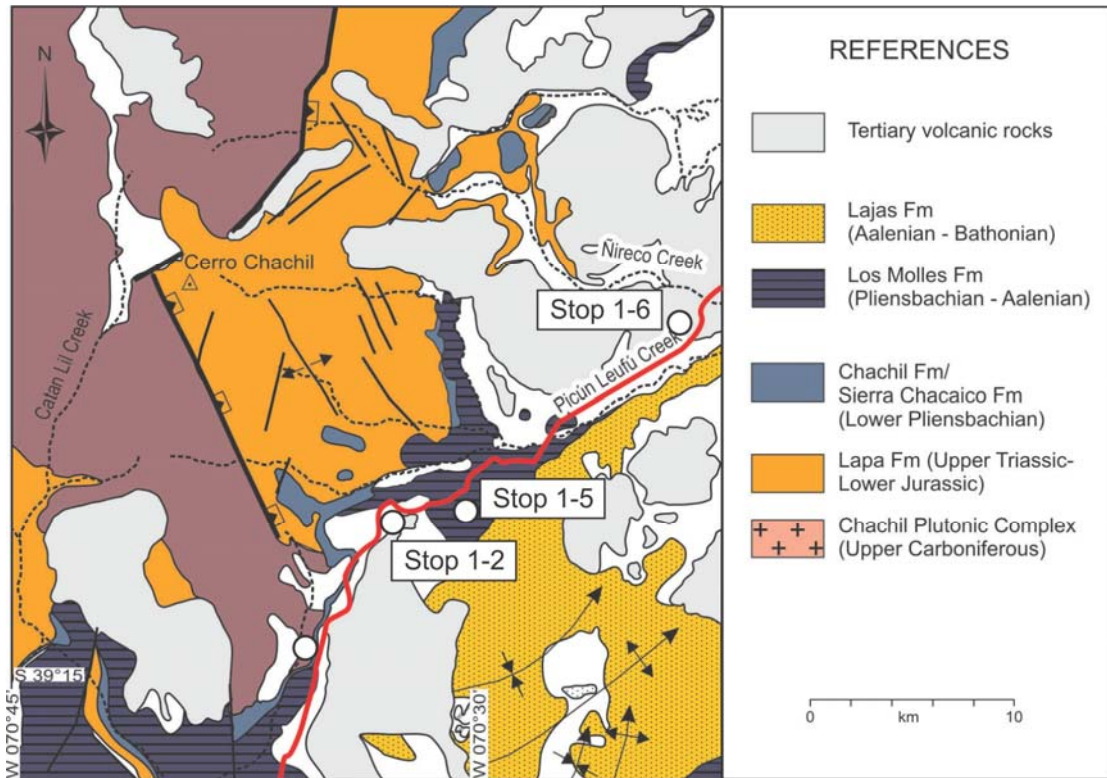


Figure 1.4. Geological map of the Cerro Chachil/Lohan Mahuida sector and location of some of the stops during Day 1. Modified after Franzese et al. (2006).

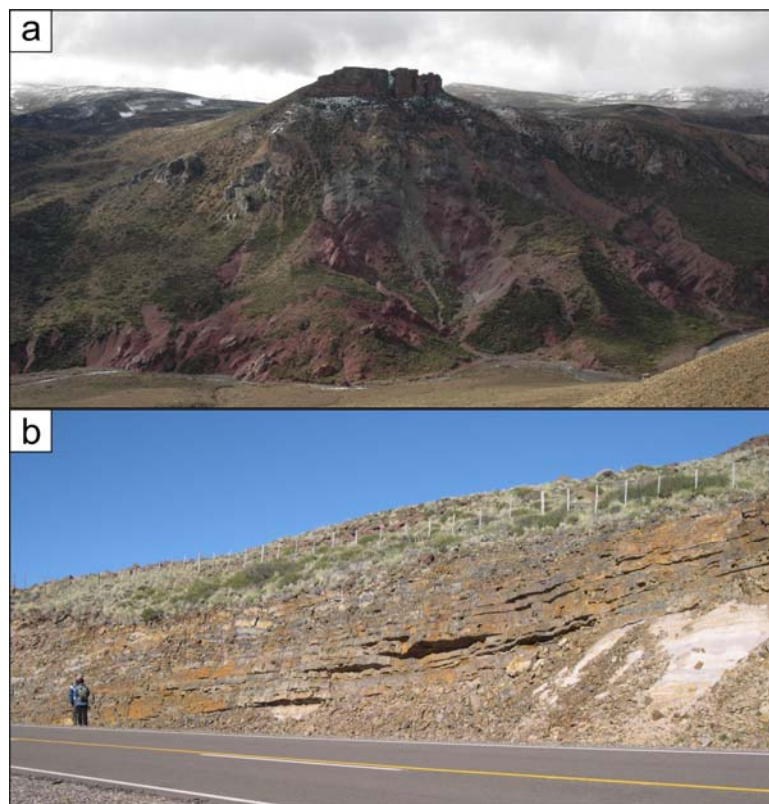


Figure 1.5. a) Morro del Águila. General view of the syn-rift deposits of the Neuquén Basin (Precuyano–Lapa Formation) covered by the Pliensbachian Chachil Limestone. b) Contact between the Huechulafquen Granitoid (= Chachil Plutonic Complex, Permian) and the Chachil Limestone (Lower Pliensbachian).

STOP 1-3 to 1-5. The Deep-marine Deposits of the Los Molles Fm: The First Marine Flooding of the Neuquén Basin.

This is a more than 500 m-thick unit composed of black and dark grey shales, accompanied by grey sandstones and fine-grained conglomerates. Several facies associations are recognised in the Los Molles Formation, being the most common: 1) thick intervals dominated by black shales, 2) heterolithic intervals composed of rhythmic and thin tabular interstratifications of black shales and fine- to medium-grained massive, laminated or rippled-laminated sandstones, and 3) amalgamated beds of sandstones, fine-grained conglomerates, pebbly sandstones and mud clast intraconglomerates. The sandstone and pebbly sandstone beds are tabular to lenticular, and internally graded, thinning upwards into finer-grained deposits. Some beds show a faint internal planar lamination, ripple cross-lamination, and larger hummocks. The base of these beds is sharp and erosional, although records a discrete degree of incision.

Primary current marks and deformational structures (such as flute, groove, bounce, prod, load and flamigerous casts) are commonly preserved at the base of the sandstone beds. The coarser and thicker the sandstone beds, the larger the sole marks. Internal deformational features (dish structures, large liquefaction folds, slump structures) and injection structures (clastic dikes and sills) are also identified in the Los Molles succession. These deposits have been assigned to an inner basin, deep marine environment (Gulisano & Gutiérrez Pleimling, 1994; Smith & Spalletti, 1995, Burgess et al., 2000). The thin sandstone intervals are interpreted as very diluted and non-channelised turbiditic deposits. The amalgamated sandstone beds are the deposits of low-density to high density sandy and gravelly turbidity currents associated with occasional slumps and debris flows. The architecture and vertical stacking of these deposits suggest the development of turbidite channels and lobes (Gulisano & Gutiérrez Pleimling, 1994; Smith & Spalletti, 1995, Burgess et al., 2000).

Notes to Stops 1-3 to 1-5:

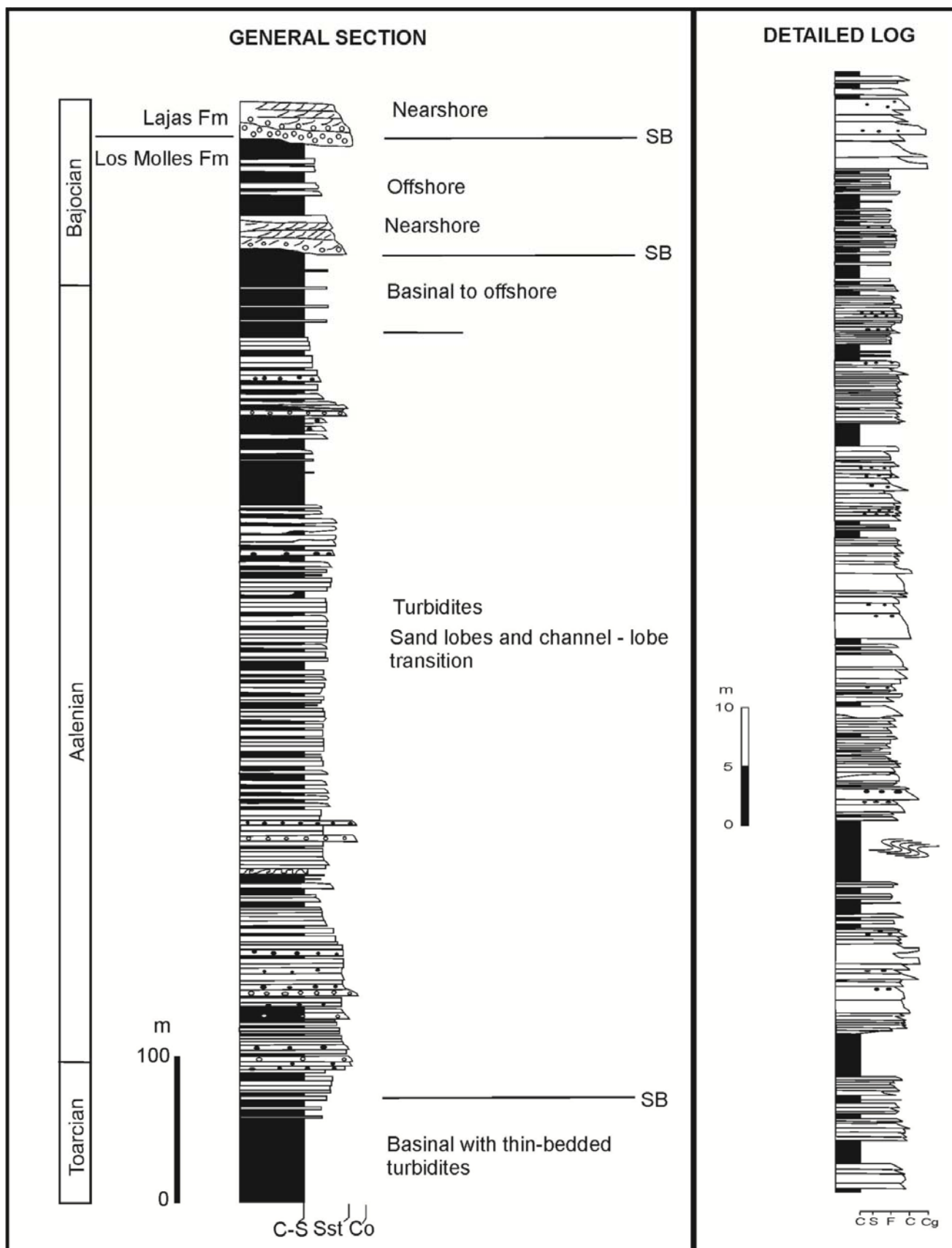


Figure 1.6. Schematic section of the Los Molles Formation and detailed log at La Jardinera Creek (Stop 1-4). Modified after Gulisano and Gutiérrez Pleimling (1994).

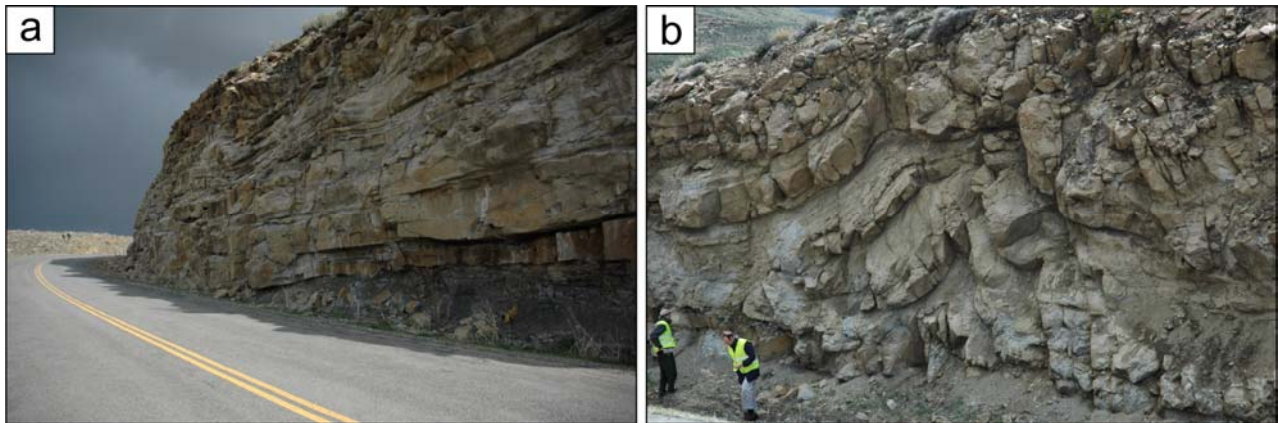


Figure 1.7. General features of the Los Molles Fm. at Fortín Primero de Mayo (Stop 1-3). a) Turbidite channel fill (sandstones, pebbly sandstones and mud-clast conglomerates) in basinal facies. b) Large-scale, soft-sediment deformation features (large-amplitude liquefaction folds associated with sandstone dikes and sills)



Figure 1.8. General features of the Los Molles Formation at Arroyo La Jardinera (Stop 1-4). a) Graded bedding. b) Graded bedding in coarse-grained turbidites. c) Slump fold. d) Thickening-upward stacking of the Los Molles turbidites.



Figure 1.9. Flute monument west of La Jardinera Creek. Los Molles Formation

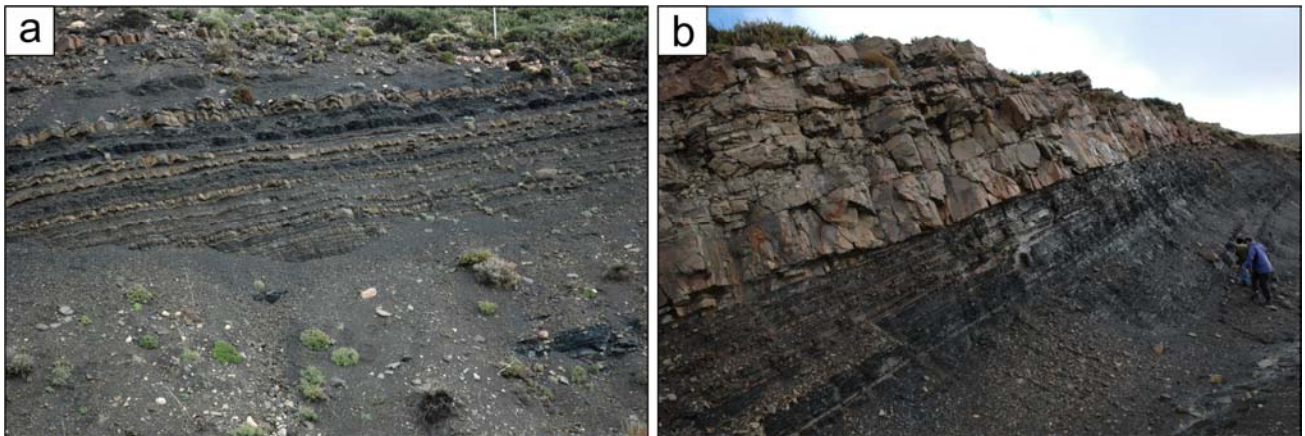


Figure 1.10. General features of the Los Molles Formation at Lohan Mahuida (Stop 1-5). a) General view of the fine-grained turbidites. b) Amalgamated sandy turbidites.



Figure 1.11. General view of the Lajas Formation at the Lohan Mahuida Hill (Stop 1-6).

STOP 1-6. Overview of the Shallow-Marine deposits of the Lajas Fm.

The deep-marine deposits of the Los Molles Formation are gradually replaced by more than 600 m of mostly sandstone-dominated siliciclastics sediments called the Lajas Formation. This unit, also included in the Cuyo Group, represents a wide range of tide-

dominated shallow-marine and marginal-marine systems.

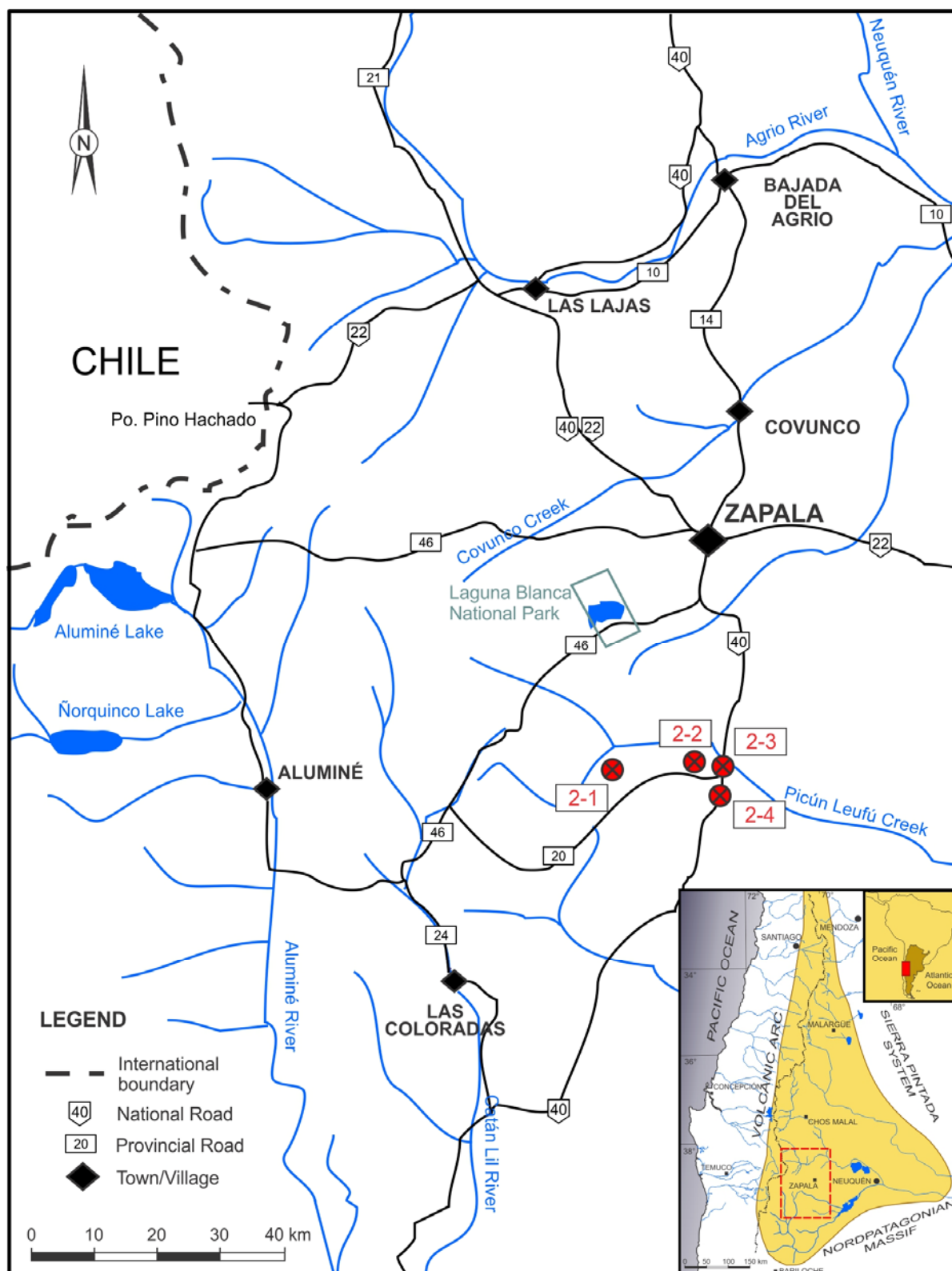
In this stop we will look at the large-scale architecture and stratigraphy of the unit at the base of the Lohan Mahuida Hill, a classical locality. The Lajas Formation deposits will be visited during the second day of the excursion in the Picún Leufú area (see Stop 2-1)

Notes:

DAY 2 – October 4th

The Picún Leufú Anticline

**SEDIMENTOLOGY AND STRATIGRAPHY
OF THE MIDDLE TO UPPER JURASSIC SUCCESSION**



Cumulative distance from ZAPALA (km)	Geographic – Geologic Reference
0	Zapala. National Road 40
11.3	Junction Provincial Road 46. Stay on road 40
11.8	Santo Domingo Creek. El Manzano place. View of basaltic lava flows and slumps
12.2	Section of the basaltic lava flows
14.9 - 21.4	Basaltic lava plain
23	Base El Sauce slope
32.2	View of aligned vegetated places along the cliff slope
38.1	Northern flank of the Picún Leufú anticline
43.3	General view of the clinoforms at the upper section of the Vaca Muerta Formation. Southern flank of the Picún Leufú anticline
44.6	Junction with old National road 40
44.7	Bridge on the Picún Leufú Creek
44.9	STOP 2-3. Aeolian/Fluvial deposits of the Tordillo Formation.
45.8	Deviation to Barda de Los Molles
47.4	STOP 2-2. Outcrops of the Challacó Formation (Callovian). Fluvial red beds of the topmost Middle Jurassic highstand
53.5	Detailed view of the Lajas Formation
58.9	Large palaeochannel of the Lajas Formation
62.0	Highly deformed area due to regional flexure of the Picún Leufú – Chacaico anticline
63.7	General view of the Jurassic succession (Los Molles, Lajas and far beyond Vaca Muerta and Picún Leufú formations)
64.6	STOP 2-1. General view of the outcrops of the Lajas Formation (Bajocian – Callovian) at Barda de los Molles
84.4	Return to National Road 40.
84.9	STOP 2-4. Outcrops of the basal section of the Picún Leufú Formation.

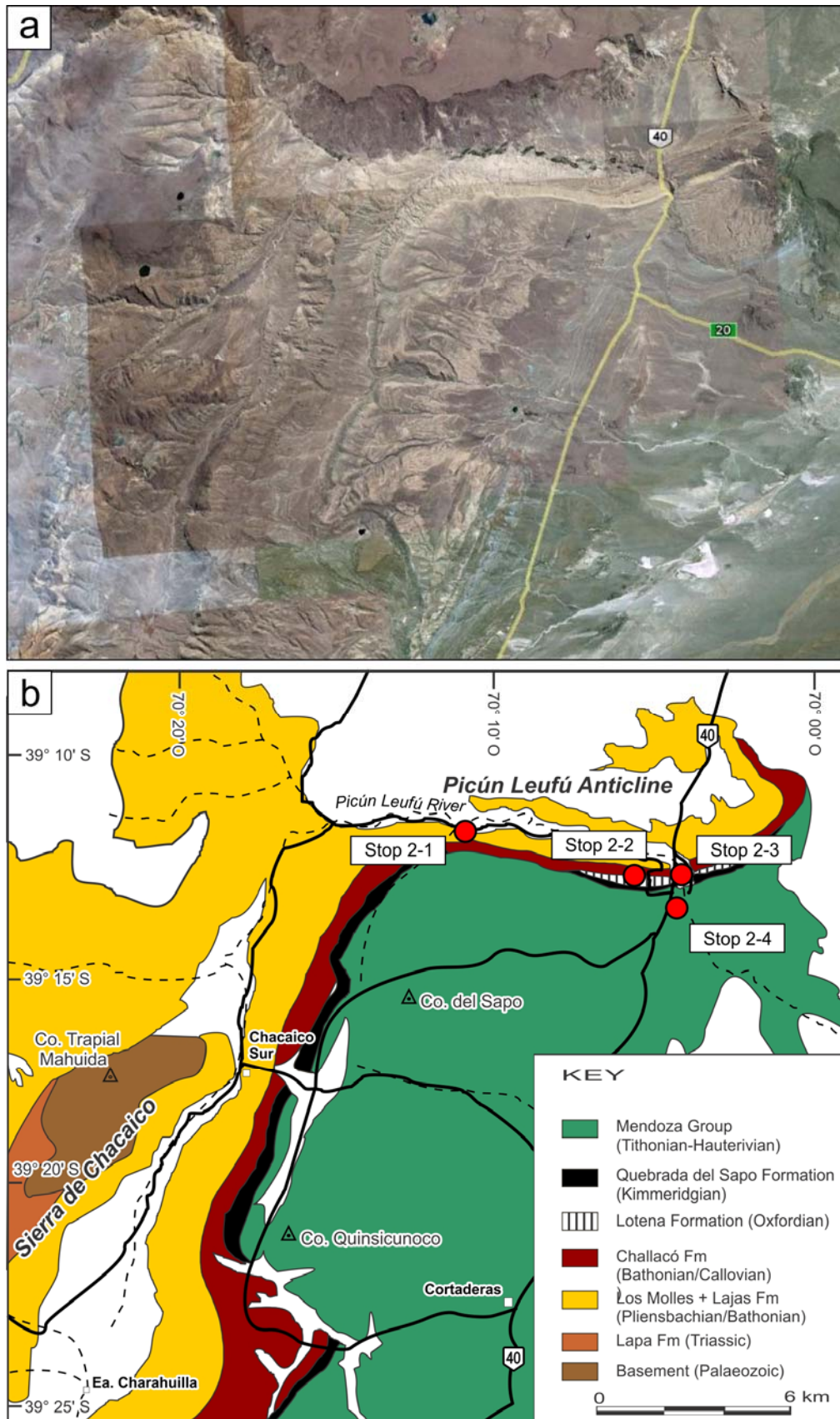


Figure 2.1. a) Satellite image of the Picún Leufú/Chacaico sector in southern Neuquén Basin. b) Geological map of the Picún Leufú/Chacaico area, distribution of outcrops of the Middle/Upper Jurassic succession and location of the stops during Day 2.

STOP 2-1. The Lajas Fm at Bajada de Los Molles

The 600-m-thick Lajas Formation (Middle Jurassic) is composed of a wide variety of tide-dominated shallow-marine and marginal-marine deposits and represents a long-term progradation over the deep-marine Los Molles Formation. Facies associations of the Lajas Formation include tide-dominated deltas, sandy-heterolithic tidal channel fills, tidal-flat successions and minor fluvial channel-fill and overbank deposits. According to McIlroy et al. (2005), much of the Lajas depositional environment is inferred to have been dominated by prograding tidal flats, with tidal channel meander belts rarely wide enough to destroy all of the intervening tidal-coastline deposits. They interfingered with an open marine setting

towards the basin and with a coastal plain dominated by tidally-influenced fluvial channels towards the continent.

The Lajas Formation facies are arranged in different types of parasequences (coarsening-upwards, fining-upwards and coarsening- to fining-upwards cycles). Sequence boundaries are marked by shallow incision and the juxtaposition of stacked fluvial and tidal channel fills on subtidal and intertidal facies associations (McIlroy et al., 2005). Noteworthy, the Lajas Formation constitutes a very rare example of accumulation in a tidally-dominated environment, which is not only important during transgressive periods but also during regressive intervals with the development of tidally-influenced deltas.

Notes:



Figure 2.2. General view of the Lajas Formation at Bajada de Los Molles (Stop 2-1).

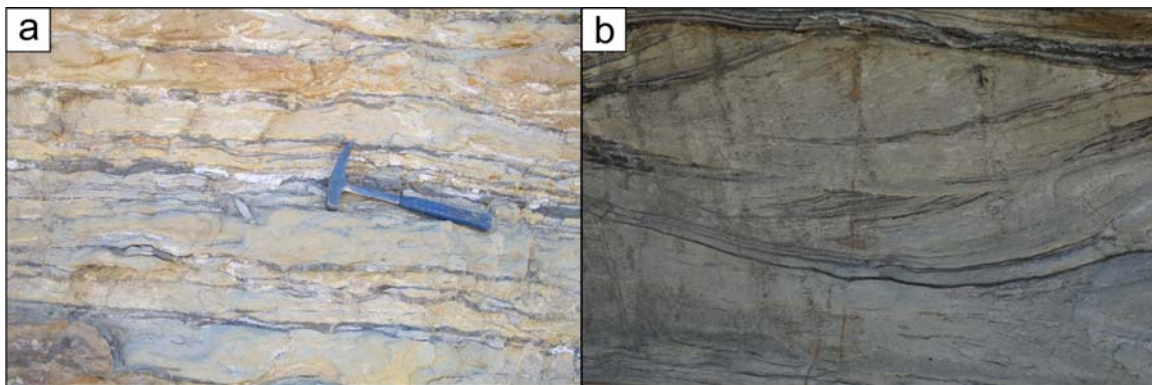


Figure 2.3. a) Detailed view of a heterolithic interval. Lajas Formation. b) Detailed view of a cross-bedded set with coal drapes.

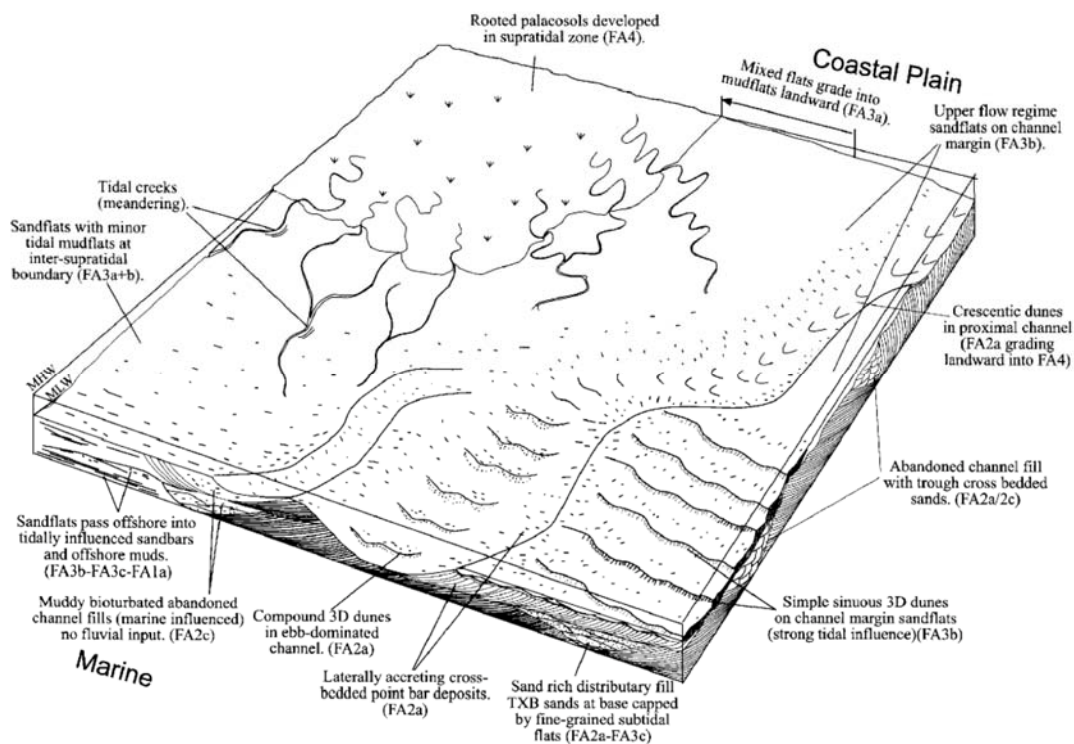


Figure 2.4. Conceptual facies model based on the facies distributions showing the relationship between tidal flat and tidal channel environments. Note that tidal flats are commonly developed on top of tidal channel meander-belt facies. From McIlroy et al. (2005).

Palaeoenvironment of deposition	Lithology	Graphic log Grain size	Facies association (FA)	Facies Interpretation	Biogenic sedimentary structures	Bioturbation Index	Comments
Floodplain			Multi-storey fluvial channels (FA4)	Multi-storey meandering fluvial channels	<i>Teredolites</i> borings in wood	0-1	The channels commonly have lags of silicified wood. Rare organic-rich drapes demonstrate an extensive tidal reach.
			Flood plain with minor fluvial/distributary channels (FA4)	Rooted floodplain	Rootlets	6	Rootlets completely bioturbate the floodplain mudstones.
				Isolated fluvial channels	Unbioturbated	0	Isolated channels up to 400m wide cut the floodplain mudstones.
				Rooted floodplain	Rootlets	6	The floodplain mudstones are commonly red/green.
Tidal Plain and Coastline			Bayfill (FA 1c)	Mouthbar	<i>Didy., Planol.</i>	1-2	Delta sands are muddy, relatively unbioturbated and micaceous.
				Bayfill	Not determinable	6	Muds are burrow-mottled and may have thick oyster beds.
			Tidal flats (FA3)	(FA3a) Mudflats	<i>Planol.</i>	0-1	Mostly unbioturbated and laminated.
				(FA2b) Tidal creek	<i>Planol., Crab</i>	0-2	Unbioturbated inclined heteroliths.
				(FA3a) Mixed tidal flats	<i>Teich., Planol.</i>	0-3	Low (?seasonal) bioturbation.
				(FA3b) Sandy inter-subtidal flats	<i>Dacty., Arenic., Planol., Ophio., Didy.</i>	0-3	Tidal flats have variable proportions of wave and tide influence depending on geomorphic setting. Typified by small dunes which grade into channel fill facies.
				(FA3c) Subtidal flats/shoals	<i>Ross., Astero., Teich., Planol. Pphy., Skol.</i>	3-5	Bioturbated subtidal facies with abundant flaser bedding, bedsets are commonly convex up in nature.
				(FA1a) Offshore muds	Not determinable	5-6	Burrow mottled offshore muds.
			Tidal channels (FA2)	(FA2a) Compound tidal bars	<i>Dacty., Ophio.</i>	0-2	Barforms may be either trough or planar cross-bedded
				(FA2c) Abandoned tidal channels (sandy)	<i>Ophio.</i>	4-5	Tidal channels with low sediment supply.
				(FA2c) Abandoned tidal channels (muddy)	<i>Thal., Ophio., Pphy., Tereb., Astero.</i>	4-6	Tidal channels without fluvial input, essentially marine in character.
				(FA2a) Meandering tidal channels	<i>Dacty., Planol., Didy.</i>	0-3	Lateral accretion bedsets with superimposed, axis parallel dunes.
Tidal Delta			Distributary channels (FA2a)	Distributary channels	<i>Dacty., Ophio</i>	0-2	Delta top distributary channels with ebb-dominated palaeocurrents. Channel-fills may be structureless.
			Mouth bars (FA1b)	Delta front and subtidal mouth bars	<i>Ophio., Teich., Thal., Astero., Siphon., Planol., Tereb., Pphy., Crab, Diplo.</i>	2-4	Steeply inclined bedsets composed of parallel/ planarcross-bedded sandstone arranged in coarsening upward packages. Bioturbation also gradually decreases upward.
			Pro-delta (FA1a)	Subtidal distal mouth bars	<i>Teich., Ophio., Tere., Parah., Chond., Rhiz.</i>	4-6	Thin prodelta heteroliths with intense bioturbation.
Offshore Shelf			Offshore shelf and shelfal turbidites (FA 1a)	Offshore muds with turbiditic event beds	<i>Chond., Protov.</i>	1 or 6	The turbiditic sands are generally clean, well-sorted and lithologically similar to those of the tidal delta. Turbidite sands are in excess of 2km in length but rarely more than 4m thick.

Figure 2.5. Summary diagram showing the range of sedimentary facies for the Lajas Fm. The facies are diagrammatically represented in a broadly progradational succession that is not intended to represent any realistic succession. From McIlroy et al. (2005).

STOP 2-2. Fluvial Highstand deposits: The Challacó Fm.

The final stage of the Lower-Middle Jurassic Cycle on the SW margin of the Neuquén Basin (Cuyo Group) is represented by continental deposits of the Challacó Formation. The accumulation in the Picún Leufú area is characterised by the development of a mixed-load river system, dominated by high sinuosity sandy channels (coarse member) and floodplain fine-grained facies (fine member).

Based on the coarse member/fine member ratio and the architecture of channel deposits, this unit was further divide in two sections.

The lower section is dominated by fine-grained facies and single storey channel deposits are isolated on floodplain deposits. The upper section shows the development of multistorey channel deposits with thin floodplain intercalations (Veiga, 1998, 2002). The change in fluvial channel style record a gradual decrease in the rate at which accommodation was created that could be related to a decrease in the rate at which the system base level raised

Notes:



Figure 2.6. General view of the Challacó Formation at Picún Leufú (Stop 2-2).

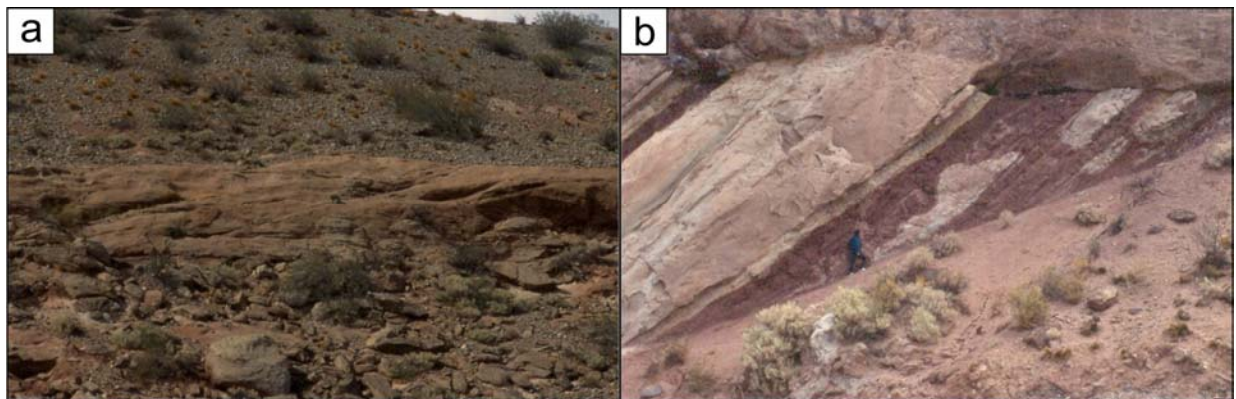


Figure 2.7. a) Lateral-accretion deposits developed in the upper portion of the Challacó Formation as the gradient of the system decrease and channel started migrating laterally. b) Fine-grained floodplain facies of the Challacó Formation in the Picun Leufú area.

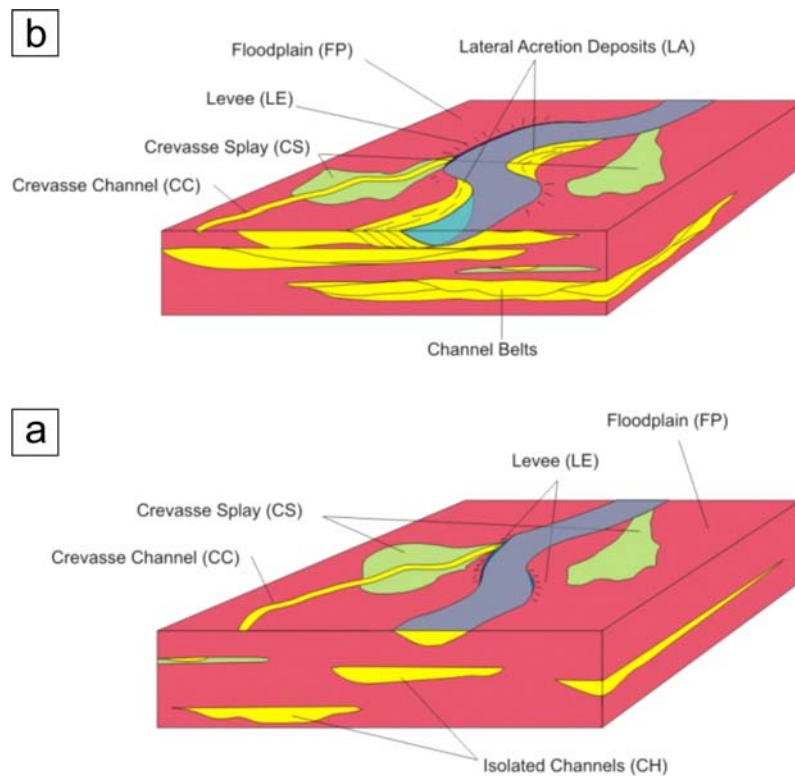


Figure 2.8: Conceptual model for the accumulation of the Challacó Formation in the Picún Leufú area. a) with isolated channels. b) with amalgamated channel belts. From Veiga (2000).

STOP 2-3. The Kimmeridgian Lowstand Wedge: the Quebrada del Sapo (Tordillo) Fm.

The Quebrada del Sapo Formation is a 40 m-thick succession of coarse- to fine-grained fluvial deposits overlain by aeolian deposits. These deposits are related to a major, tectonically enhanced, relative sea-level fall and therefore interpreted as a lowstand wedge. The fluvial section is dominated by braided-channel, fine-grained ephemeral, and sheetflood deposits. Aeolian facies are dominated by dune deposits, with minor sandsheet and wet interdune units.

Notes:

Regional changes in the nature of both fluvial and aeolian sedimentation suggest a marked variability of accommodation/sediment supply conditions. The vertical transition from fluvial to aeolian deposits may be the result of a local climatic change to drier conditions due to the development of a climatic barrier imposed by growth of a magmatic arc to the west. Alternatively, the vertical transition could be related to a lowering of the water table associated with the compartmentalisation of the basin during a period of low sea-level (Veiga & Spalletti, 2007).



Figure 2.9. General view of the Quebrada del Sapo Formation at Picún Leufú (Stop 2-3).

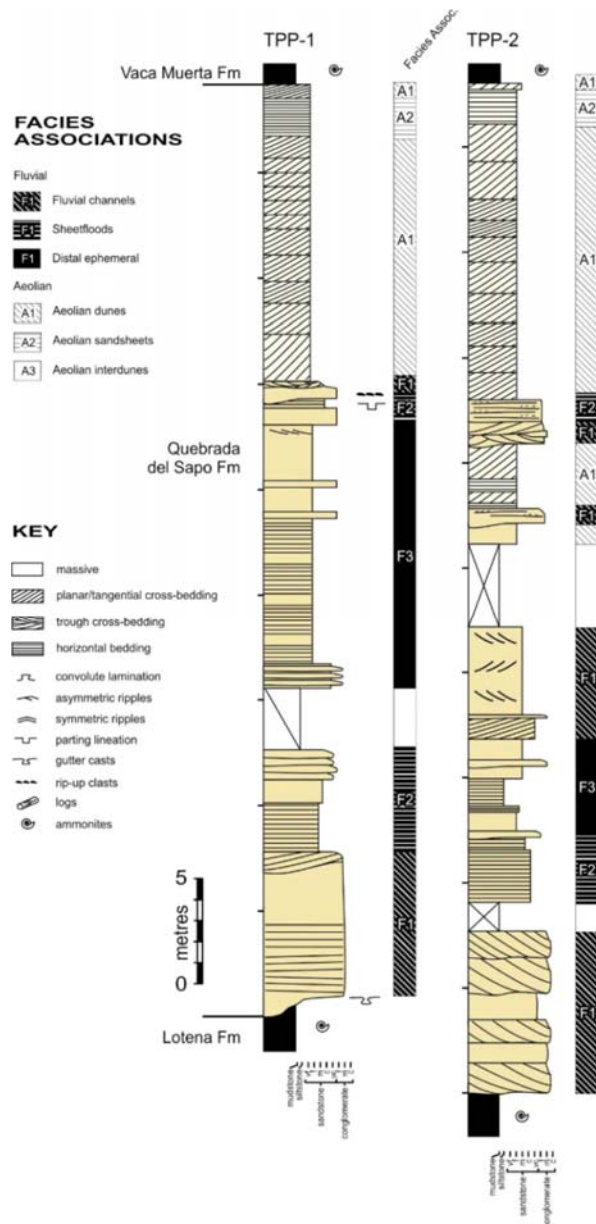


Figure 2.10. Sedimentary logs of the Quebrada del Sapo Fm in the Picún Leufú area. From Veiga & Spalletti (2007).

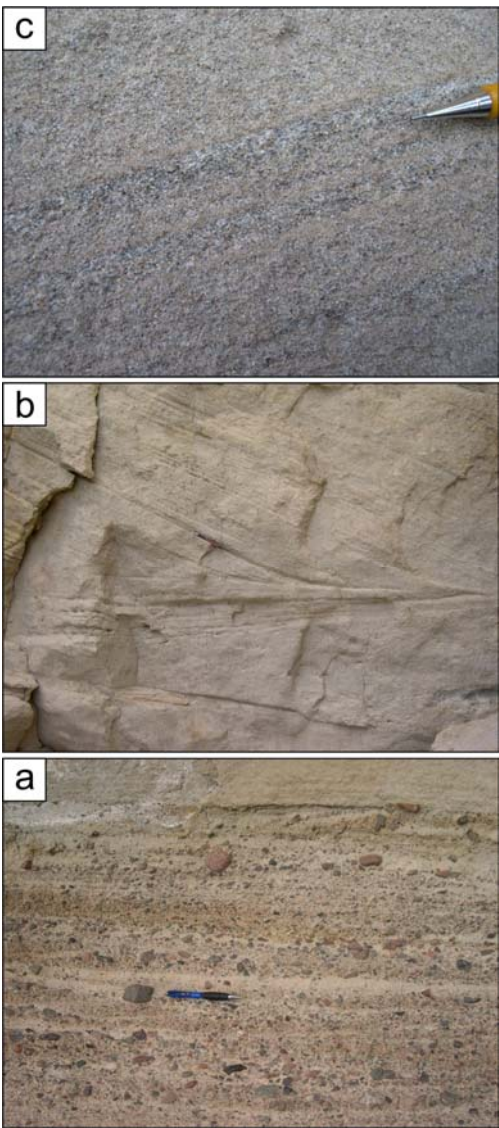


Figure 2.11. a) Horizontally laminated conglomerates and sandstones associated with sheetfloods. Lower fluvial section. b) Large-scale aeolian dune sets. c) Grainfall and grainflow deposits in the foresets of aeolian dunes.

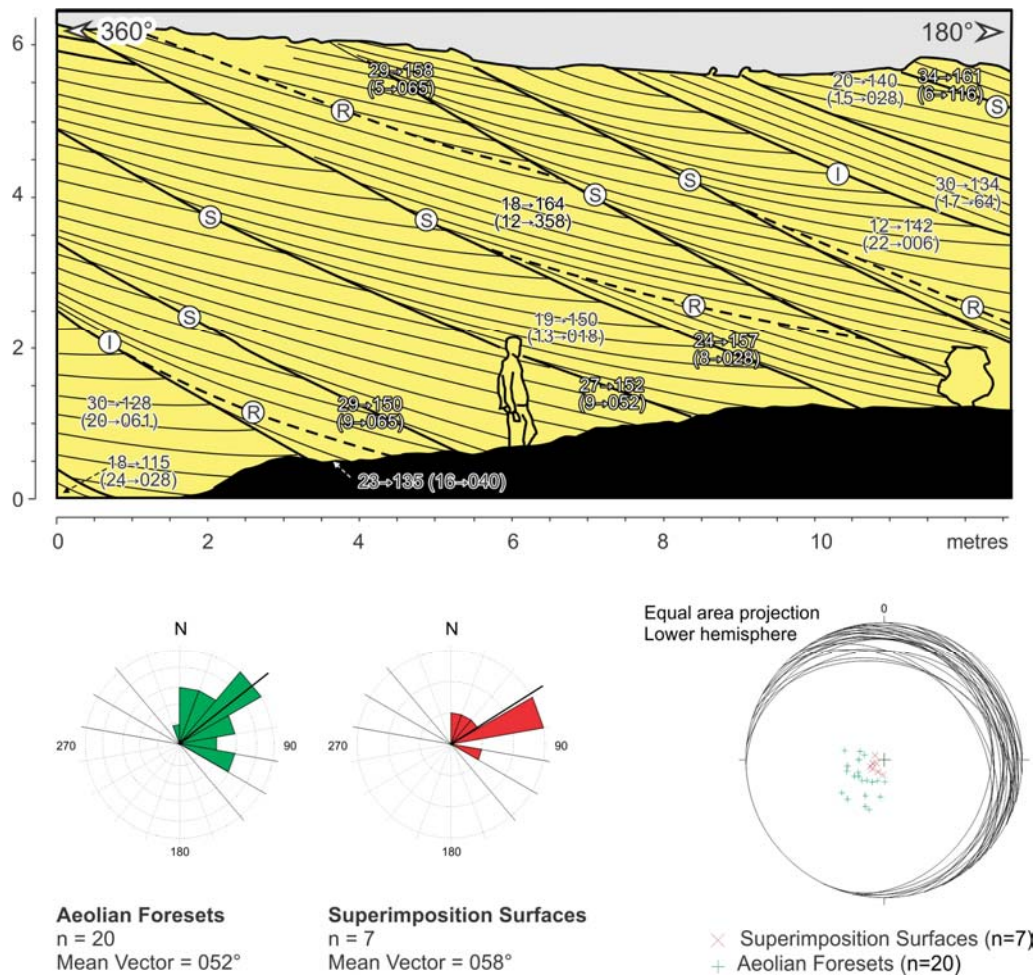


Figure 2.12. Architectural Element Analysis of aeolian deposits of the Quebrada del Sapo Formation in the Picún Leufú area. I: interdune surface, S: superimposition surface, R: reactivation surface. Black labels show amount and direction of dip of cross strata. White labels show amount and direction of dip of bounding surfaces. Values in brackets represent rotated values considering the tectonic tilt of the outcrop. From Veiga & Spalletti (2007).

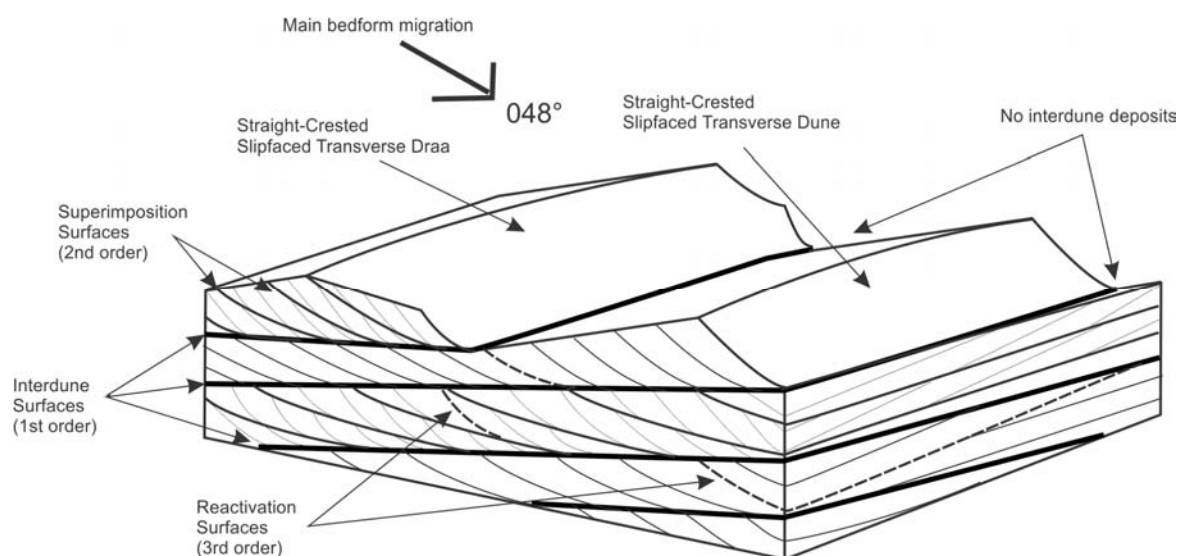


Figure 2.13. Reconstruction of the aeolian systems of the Quebrada del Sapo Formation in the Picún Leufú area. From Veiga & Spalletti (2007).

**STOP 2-4. The Tithonian Transgression:
The Vaca Muerta and Picún Leufú Fm.**

Following the Kimmeridgian lowstand, a major transgression occurred during the Early Tithonian, which triggered deposition of basinal black shales as far as the present day position of Neuquén city. While in distal areas (northward of Zapala) black shale deposition continued during the entire Tithonian and even Berriasian times, in the proximal Southern Neuquén sector the system evolved into a shallow-marine system by Middle Tithonian. Here the complete succession is about 300 m thick, of which the lower one third is dominated by black shales and minor marls and mudstones (the Vaca Muerta Formation) and the upper two thirds are composed of siliciclastic and carbonate deposits (the Picún Leufú Formation).

The Vaca Muerta and Picún Leufú formations in the area have been interpreted as a tidally-dominated, mixed carbonate-siliciclastic ramp (Spalletti et al., 2000). The transition from the anoxic basinal conditions to shallower ramp settings is evidenced by seismic-scale progradational clinoforms in the lower part of the Vaca Muerta - Picún Leufú system. The clinoform package is up to 80 m thick, deepens 1-2 degrees toward northwest and it extends about 15 km in an updip-downdip cross section in the Picún Leufú area. This clinoform package is interpreted to represent highstand conditions, and is clearly truncated by an erosive surface assigned to a regional sequence boundary.

Notes:

The rest of the Picún Leufú formation is composed of siliciclastic and carbonate sediments in which outer, middle, shallow and back ramp facies associations are recognised. Outer and middle ramp environments were apparently dominated by storm processes, whereas tidal effect increases in the inner ramp. Carbonate and mixed beds (quartz-oid grainstones or oyster floatstones) occasionally occur at the top of siliciclastic intervals. Abundant tidal deposits in the shallow marine settings, showing sigmoidal cross-bedding, herringbone cross-bedding, reactivation surfaces, rapid changes in palaeoflow pattern, and heterolithic intervals, suggest the development of widespread sand wave fields. In turn, low-energy lagoonal to peritidal deposits appear in the most landward (back ramp) part of the ramp profile.

Although the unit mostly represents a siliciclastic to mixed system, a significant change in sedimentation is recorded in the middle Picún Leufú Formation. A less than 30-m thick pure carbonate package occurs. It is mostly composed of skeletal packstones, with minor ooid-skeletal grainstones and coral floatstones. The carbonate package is capped by chertified sponges probably representing a subaqueous hardground. This unique event represents a minimum in siliciclastic flux to the basin likely coupled with an increase in carbonate production.

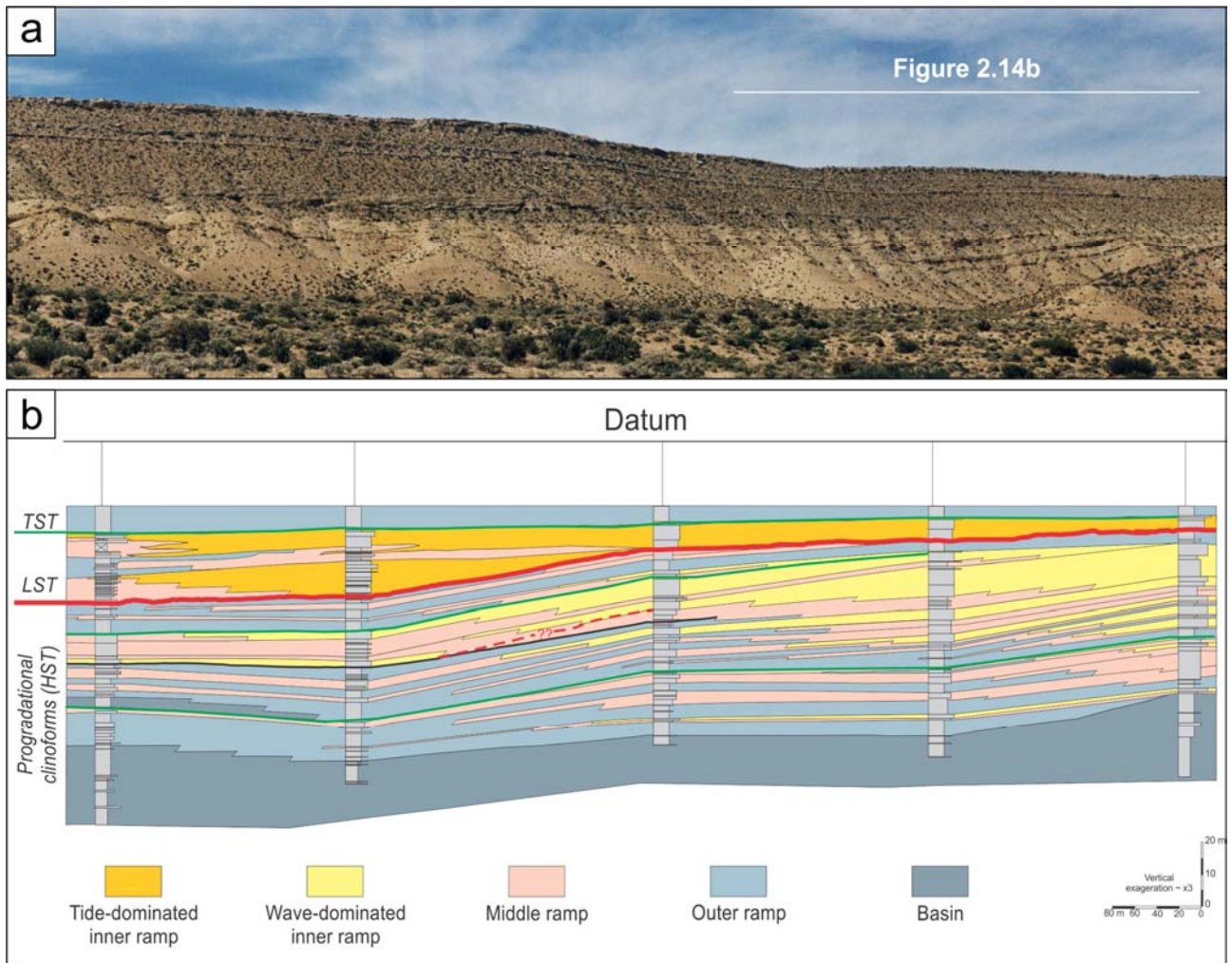


Figure 2.14. General view (a) and interpretation (b) of the Tithonian depositional clinoforms. Note the progradational and retrogradational stacking of the clinoforms. Southern flank of the Picún Leufú anticline (Spalletti et al., unpublished).



Figure 2.15. General view of the Picún Leufú Fm at Puente Picún Leufú (Stop 2-4).

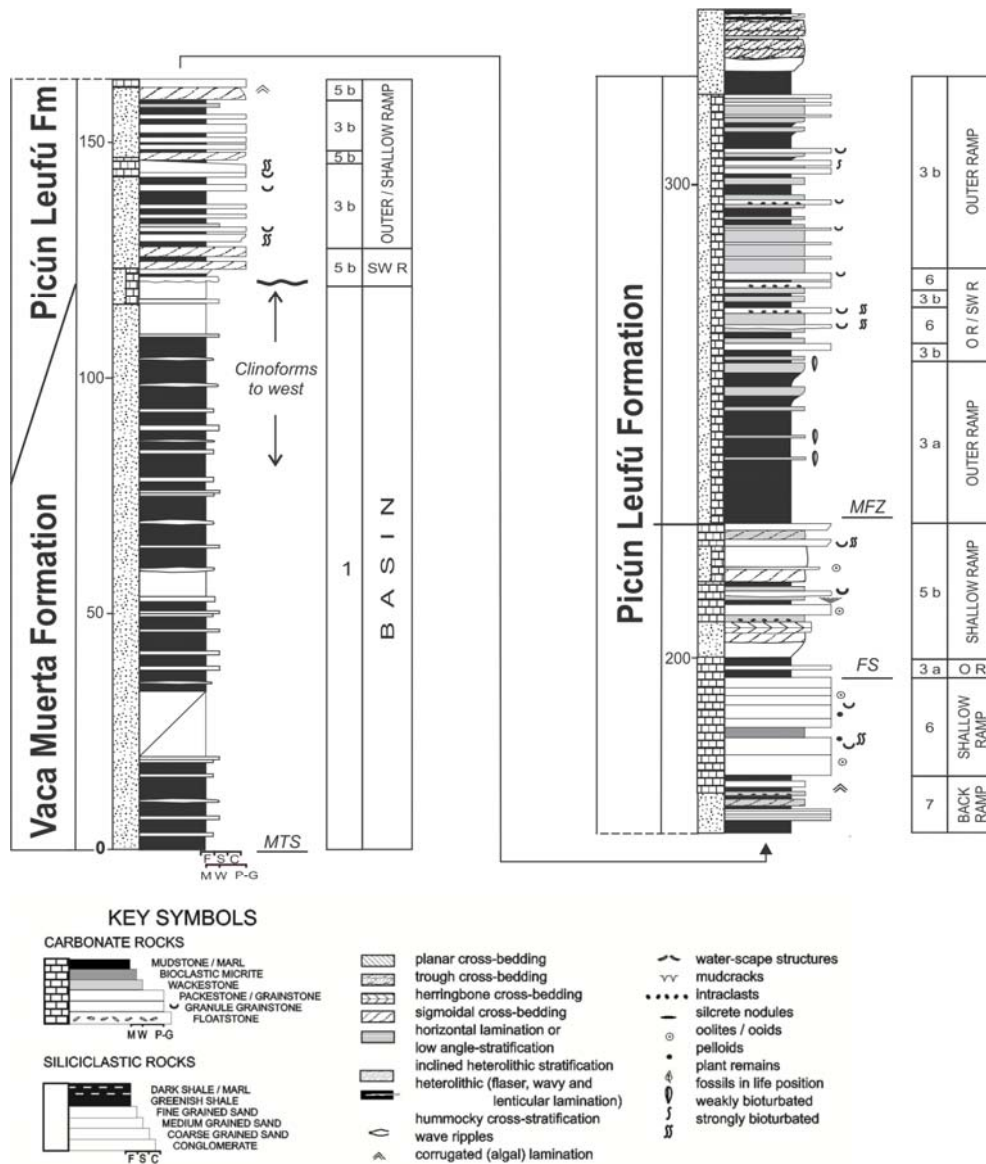


Figure 2.16. General log and sequence stratigraphic scheme of the Vaca Muerta – Lower Picún Leufú formations at the southern flank of the Picún Leufú anticline (Spalletti et al., 2000).

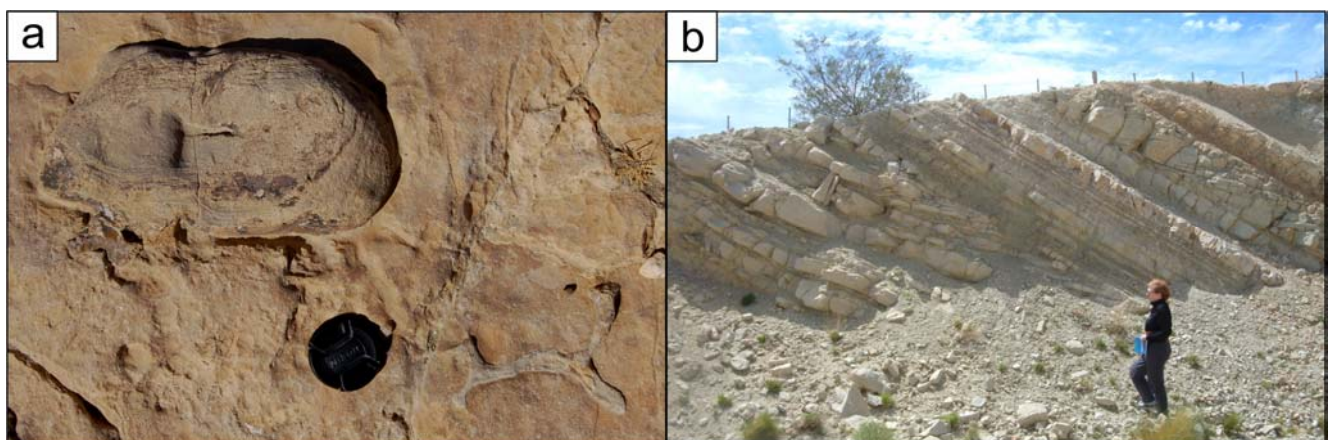


Figure 2.17. a) *Thalassinoides* and silicified sponges at the top of the pure carbonate interval of the Picún Leufú Formation. This contact might represent a subaqueous hardground. b) Sigmoidal sets of the Picún Leufú Formation interpreted as subtidal bars.

ASSOCIATION	FACIES	INTERPRETATION	
1	DF (Lm-Sm)	Suspension fall out, anoxic-suboxic floor	BASIN
2	Mf (DF)	Bioclastics micrites (blooms), anoxic to suboxic floor	
3 a	GF (Lm)	Suspension fall out, oxic to suboxic Bivalves in life position	OUTER RAMP
3 b	GF ; Lm	Suspension fall out, oxic to suboxic	
4	Lf	Biogenic framework	
5 a	Lwr-Swr ; Shcs ; Sm ; Sh (Gf, H)	Oscillatory waves	MID RAMP
5 b	Lsg-Ssg ; Shb ; Hihs ; Sm ; Sh (Gf, H)	Medium to high energy tidal currents	INNER (SHALLOW) RAMP
5 c	Lt-St ; Lp-Sp ; Sm ; Sh (Gf, H)	Wave-induced currents	
6	Lm (GF) ; Lm (Lwr) ; Lm ; Lh	Carbonate shoals	INNER (BACK) RAMP
7	H ; La ; Lsg-Ssg ; Lwr ; Lh ; GF (Lm-Sm)	Alternating fall-out and current deposition Low-regime tidal currents and wave action	
8	GF (Hihs, Lwr-Swr)	Suspension fall-out associated with weak tidal currents and wave action	

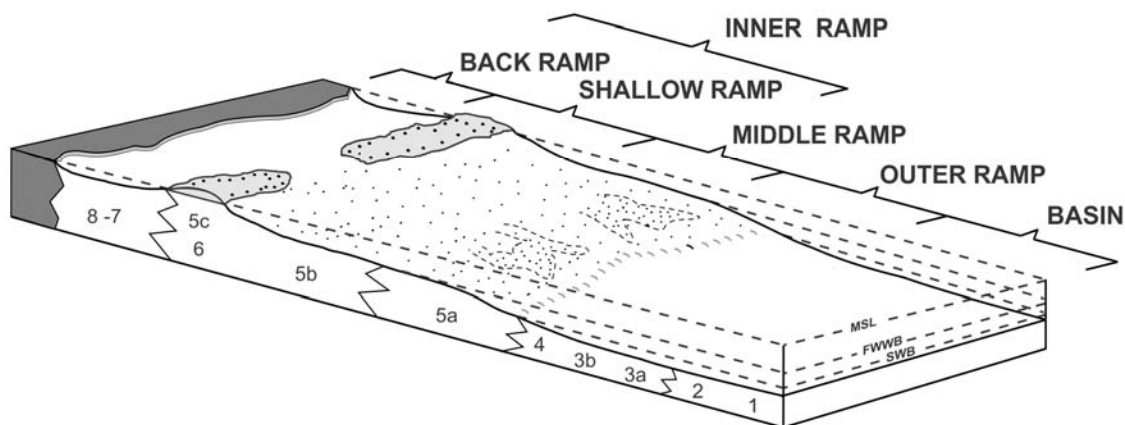
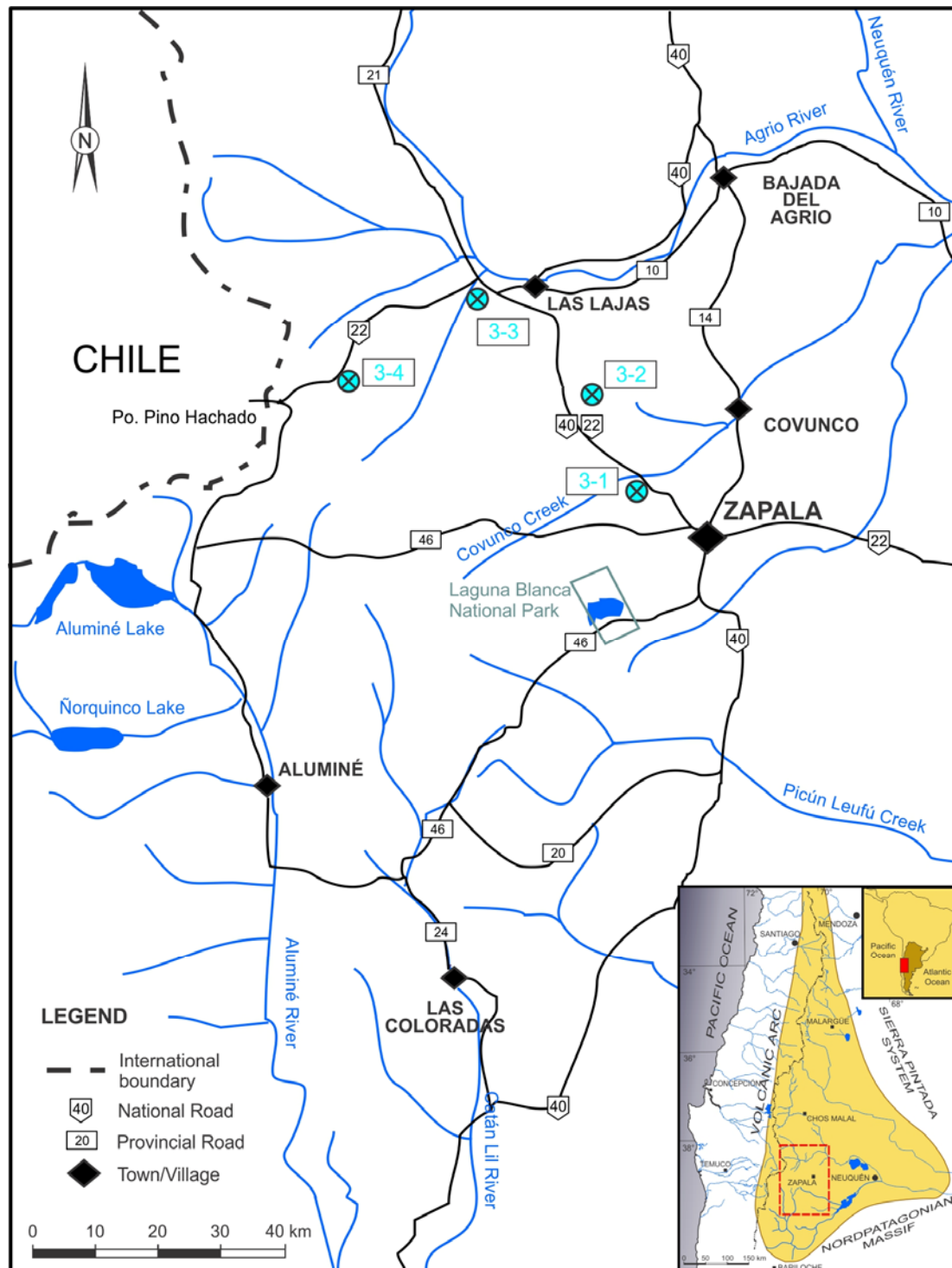


Figure 2.18. Facies associations and the basin-ramp depositional model proposed for the Vaca Muerta - Picún Leufú system, from Spalletti et al. (2000). MSL: maximum sea-level; FWWB: fair-weather wave-base; SWB: storm wave-base.

DAY 3 – October 5th

**FROM THE JURASSIC DEPOSITS TO THE
ANDEAN MAGMATIC ARC**

This day has two main objectives. The first one is to examine the well-exposed Middle and Upper Jurassic sequences north of Zapala, at the Covunco creek and the western side of the Vaca Muerta Range. The second objective is to inspect the Cainozoic pyroclastic and volcanoclastic deposits of the western Neuquén Basin related to the Andean magmatic arc.



Cumulative distance from ZAPALA (km)	Geographic – Geologic Reference
0	Zapala. National Roads 40/22 north
11	Outcrops of the Picún Leufú Formation
11.8	Entrance to Los Catutos Quarry
17.6	STOP 3-1. Outcrops of the Lajas, La Manga Limestone, Tordillo Formation and Vaca Muerta Fm at the Covunco Creek
21.1	Junction to Mallín de Los Caballos
30.0	STOP 3-2. Entrance to the Ambar Quarry: the Lotena, La Manga and Tordillo Fms. in the western Vaca Muerta Range
55.0	Access to Las Lajas town. National Road 22.
58.1	Las Lajitas Creek (bridge)
59.1	STOP 3-3. Huarenchenque Formation (Pliocene). Gravelly bedload, volcanoclastic fluvial system
63.7	Liu Cuyín River (bridge)
65.2	Joint National road 22 (or 242) and Provincial road 21
76.5	End of the Fosa de Loncopué and first volcanoes
84.6	General view of dissected volcano to the north of the road
87.8	Pliocene ignimbritic deposits (pumiceous lapillites).
93.8	Welded ignimbrites
96.3	Contractional joints in welded ignimbritic deposits
99.6	Panoramic view of the volcanic landscape
101.1	Beautiful araucarias and curved contractional joints in welded ignimbrites
102.5	STOP 3-4. Pyroclastic and Volcanic deposits of the Pino Hachado Volcanic Complex.
105.7	Basalt – basaltic andesite. Joint with Provincial Road 23 to Aluminé



Figure 3.1. Satellite Image of the Covunco Creek/Vaca Muerta Hill region.

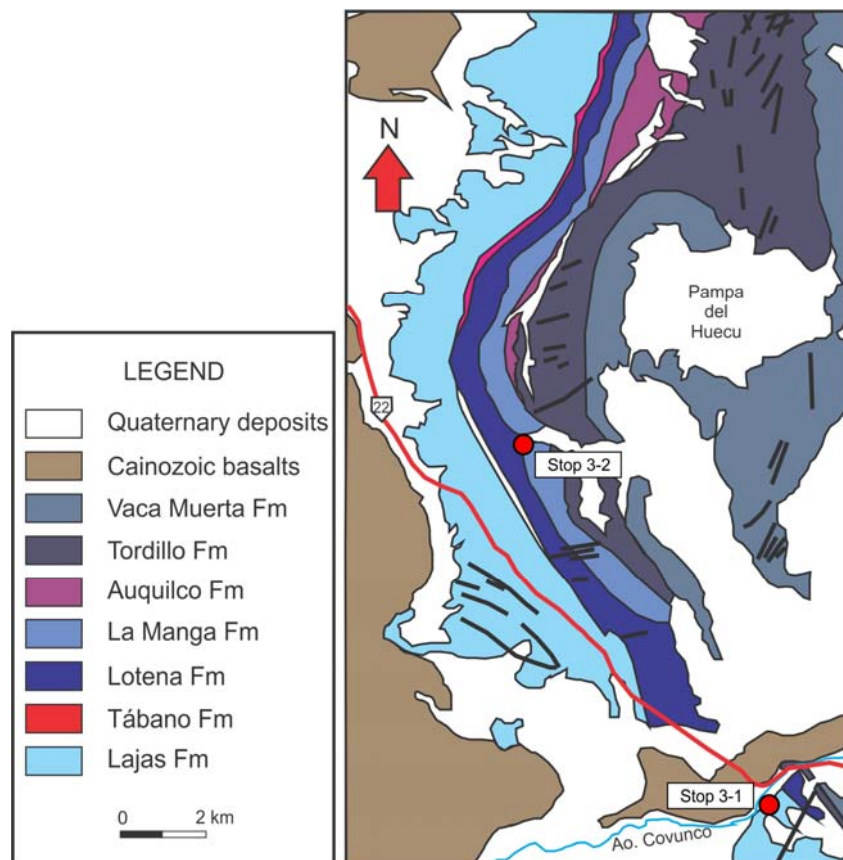


Figure 3.2. Geologic map of the Vaca Muerta Hill (modified after Gulisano & Gutiérrez Pleimling 1994).

STOP 3-1. The Jurassic Succession at Arroyo Covunco: The Lajas Fm

The Lajas Fm. in the Arroyo Covunco constitutes a thick succession in which three sections have been recognized by Veiga (1998). The lower section is characterized by the typical facies associations of the Lajas Formation: thick (1.5 m to 7 m) subtidal sandbodies with abundant sigmoidal cross-bedding, associated with heterolithic intervals showing features of both storm and fair weather wave action. The middle section is dominated by a heterolithic succession in which the sand couplets were

deposited by storm events. Tabular (up to 5 m thick) bodies of coarse-grained sandstones and fine-grained conglomerates with erosional bases intercalate. These deposits are the result of unidirectional frictional flows entering the shallow marine platform. The upper section is composed of a series of thickening- and coarsening- upward parasequences. These shallowing cycles are composed of heterolithic intervals grading upwards into bioturbated sigmoidal sand waves and shell rich conglomerates.

Notes:

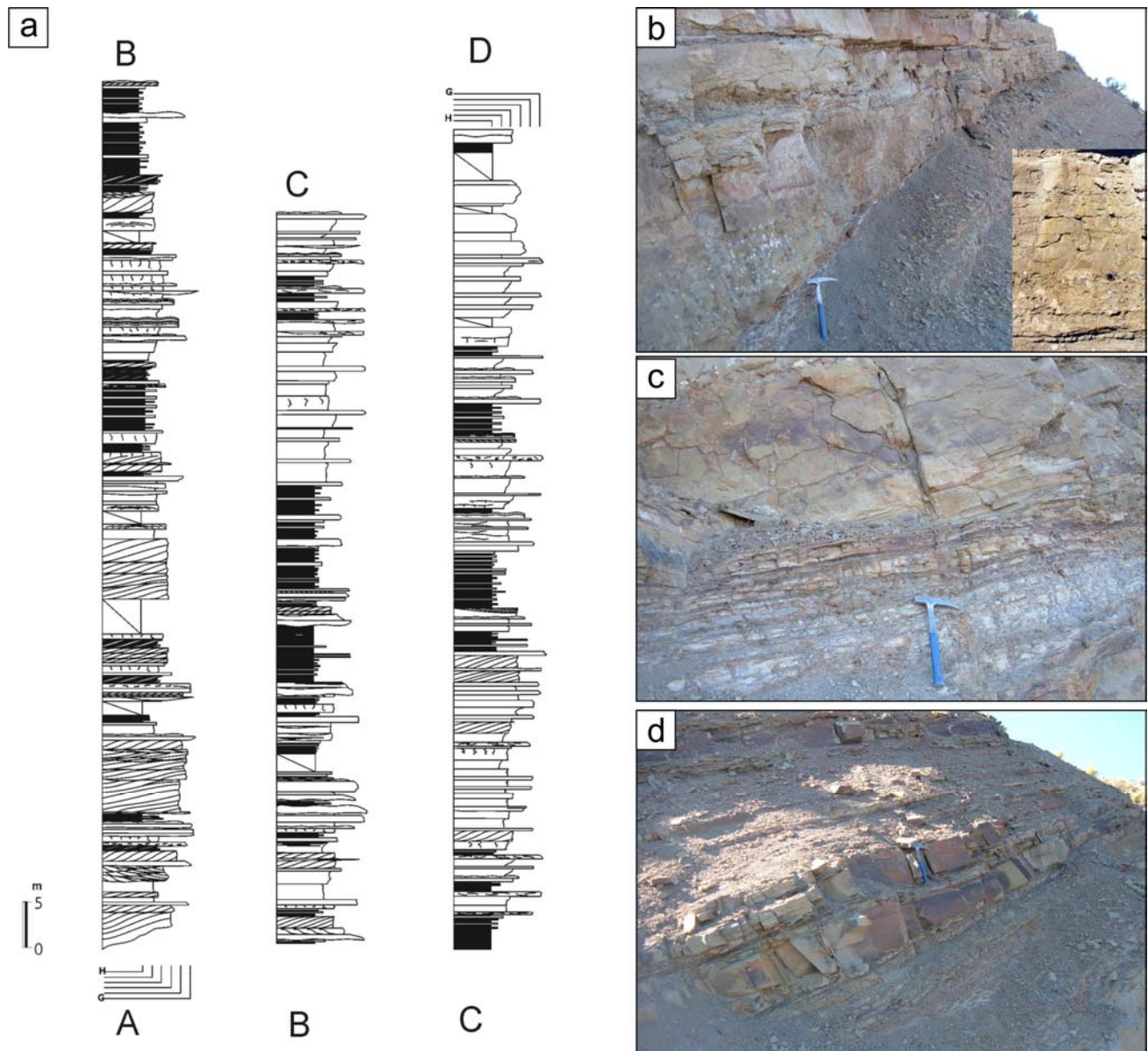


Figure 3.3. General features of the Lajas Fm at the Covunco Creek (Stop 3-1). a) Stratigraphic log of the Lajas Formation at Covunco Creek (Veiga, unpublished). b) Incised frictional deposits (conglomerates). Inset: detail of the coarse-grained texture and the inverse grading at the base. c) Heterolithic interval covered by coarse-grained sand wave. d) Storm beds with HCS.



Figure 3.4. General view of the upper section of the Lajas Fm in the Covunco Creek (Stop 3-1).

STOP 3-2. The Jurassic Succession at the Vaca Muerta Range

The Callovian - Kimmeridgian sedimentary record at this locality shows marked changes in the facies patterns and in sequence architecture. The Middle – Upper Callovian deposits (Lotena Formation) show three main shallowing upwards cycles within a general shallowing upward trend from outer ramp to inner ramp deposits. The Oxfordian records a drastic facies change to shallow ramp carbonates (boundstones, wackestones, packstones and grainstones, La Manga Formation) and marine-lagoonal evaporite facies (anhydrite-gypsum and micritic mudmounds, Auquilco Formation). Towards the top of this non-terrigenous succession a major (2nd order) unconformity was developed as a result of the Araucanian (Inter-Malm) tectonic inversion. On top, the upstream gravelly and sandy bedload fluvial deposits of the

Tordillo Formation (Kimmeridgian) represent the lowstand wedge of a new (2nd order) Kimmeridgian - Valanginian cycle.

The stratigraphic architecture of the Tordillo Formation in this area is characterised by reduced thickness and coarse grain size. These features suggest a steep gradient, excess of bedload supply and a low subsidence rate that resulted in diminished accommodation space. The sandy and gravelly deposits of this proximal fluvial system were accumulated as downstream accreting bars in very unstable channels. Vertical and lateral alternation of gravels, sandy gravels and sands is indicative of highly unsteady and non-uniform flows. This cyclic pattern of sedimentation seems to be the result of a combination between vertical pulses of uplift in the source area and long-term variations in sediment and/or water discharge (Spalletti & Colombo, 2005).

Notes:

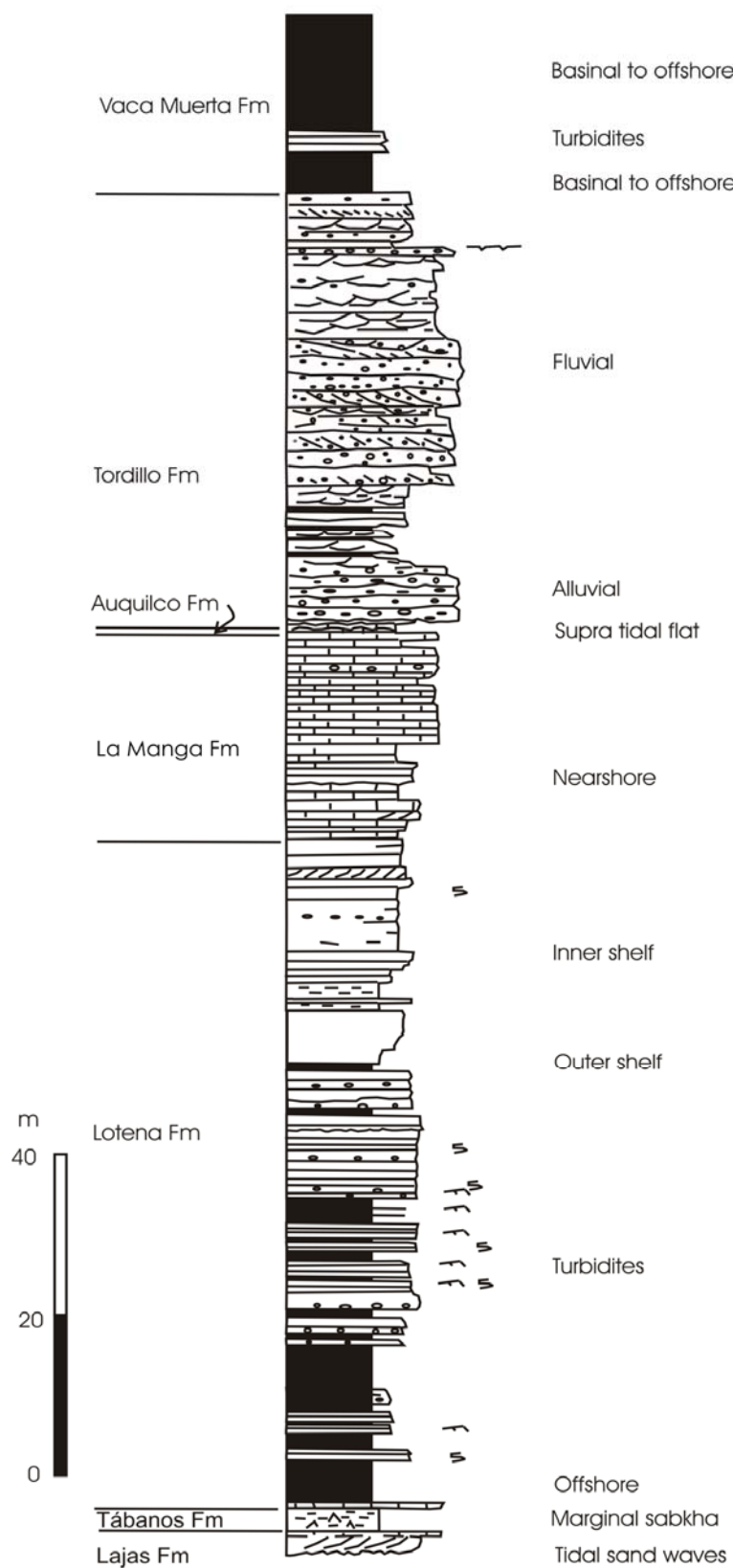


Figure 3.5. Generalized stratigraphic column of the Jurassic succession at Manzano Guacho (Ambar Quarry), Vaca Muerta Hill (modified after Gulisano & Gutiérrez Pleimling, 1994) (Stop 3-2).

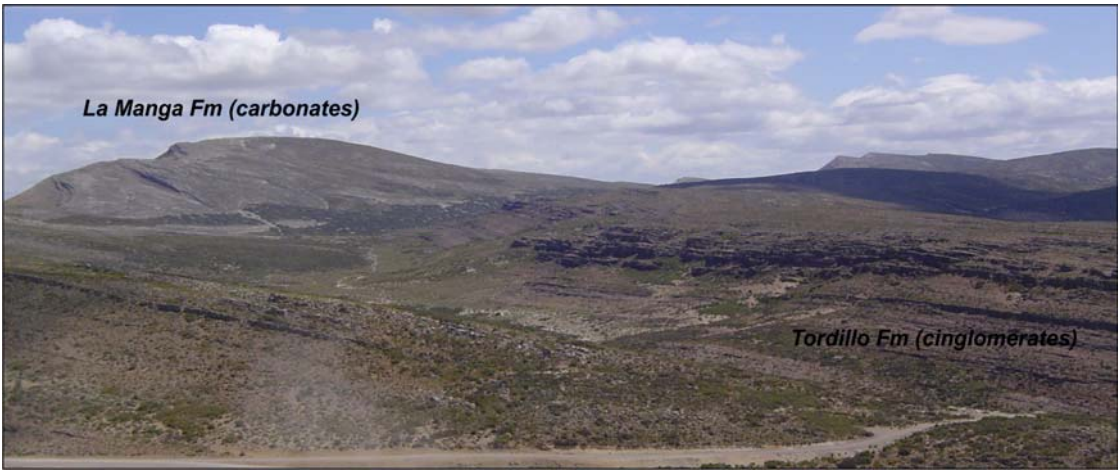


Figure 3.6. General view of the Upper Jurassic succession in the Vaca Muerta Hill (Stop 3-2).

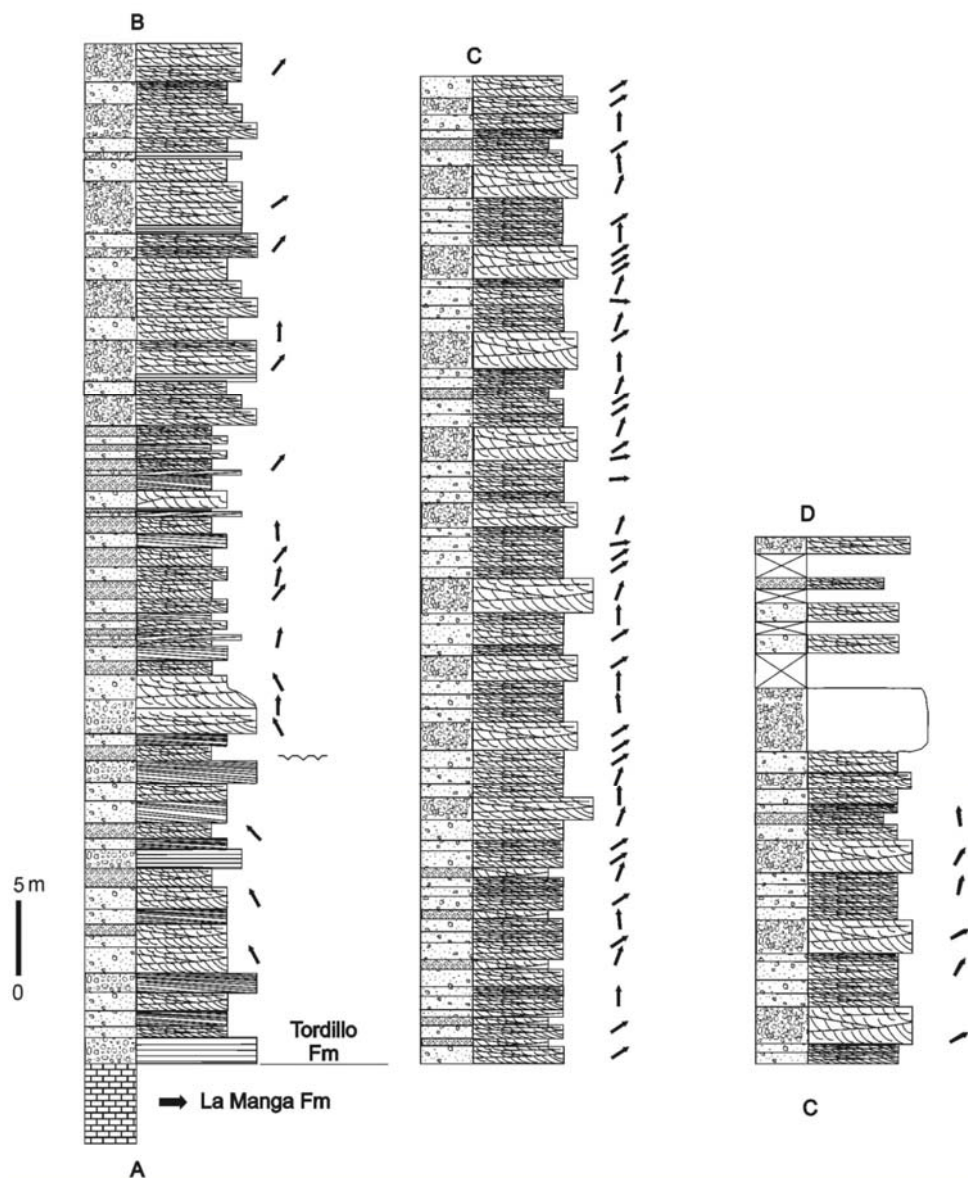


Figure 3.7. Detailed log of the Tordillo Formation at Manzano Guacho, Vaca Muerta Hill (Spalletti & Colombo, 2005).

STOPS 3-3 and 3-4. The Cainozoic Volcanic, Pyroclastic and Volcaniclastic Record of Western Neuquén

These two stops are planned to look at the younger units of the Austral Central Andes, where the sedimentary record is characterised by the accumulation of volcaniclastic units. The sedimentary facies are better developed towards the east of the Cainozoic volcanic chain, while the pyroclastic facies are preferentially located to the west, at the foot and within the Pino Hachado volcanic area.

The Huarenchenque Formation (Pleistocene) represents one of the sedimentary units of the youngest foreland record of the so-called Loncopué trough. It is essentially composed of coarse- to medium-grained conglomerates, pebbly sandstones and subordinated sandstone intercalations formed as the deposits of in-channel longitudinal and transverse bars. Though some of the conglomerate beds are massive, they preserve well developed primary structures, such as horizontal bedding and amazing large-scale cross-stratifications. Amalgamated channel deposits are frequently found, and single channels usually show a strongly scoured base. The coarse texture of these deposits, the amalgamation of channel bodies, the marked scoured base of the channel beds and the minor participation of mudstones suggest that the Huarenchenque Formation was

deposited in a proximal setting by strong bed-load currents and rapid migration in the location of fluvial channels and inter-channel bars. If we look at the outcrops and the neighbour Agrio river course we cannot avoid interpreting that these Pleistocene deposits are the testimony of the palaeo-Agrio river.

When moving westward, the sedimentary deposits are progressively replaced by pyroclastic units (Pino Hachado Volcanic Complex). Along the upper Haichal river the volcaniclastic deposits are formed by two main facies: ignimbrites and surge deposits. Ignimbrites are represented by two main types of deposits: A) whitish and coherent gravelly and sandy massive pyroclastic rocks that are typically massive, tabular, and forming single units that may reach 3 m or more in thickness. B) thick units (several tens of meters of successive cooling episodes) composed of welded tuffs and/or lapilli tuffs, showing spectacular polygonal cooling joints and ramp structures. Surge deposits are composed of a continuous succession (more than 30 m thick) of granule conglomerates, sandstones and siltstones. These deposits are arranged in tabular beds (some of them with marked basal scoured surfaces) with common high-regime primary structures such as planar and monticular (hummocky) internal laminations.

Notes:

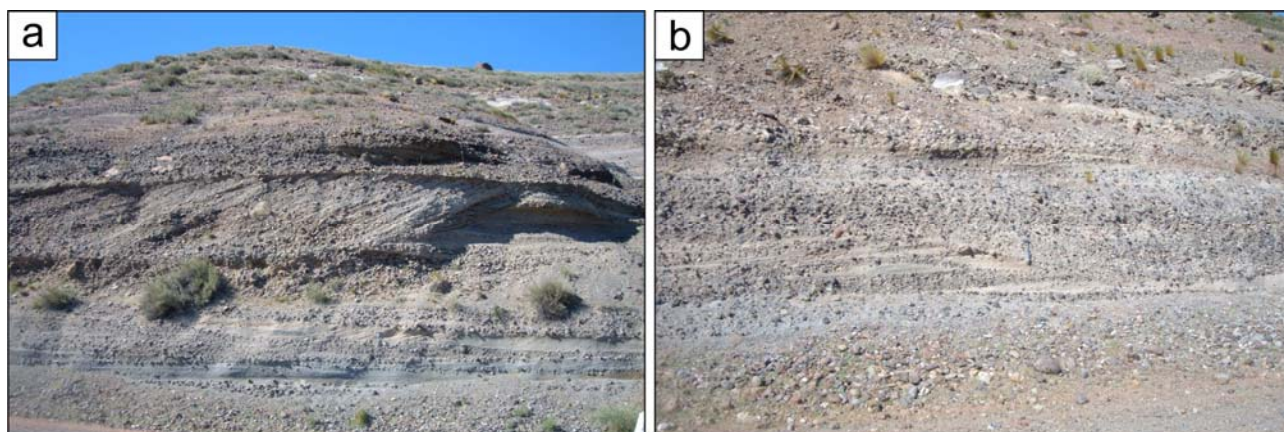


Figure 3.8. Detailed views of the volcaniclastic gravelly fluvial deposits of the Huarenchenque Formation (Pliocene) (Stop 3-3).

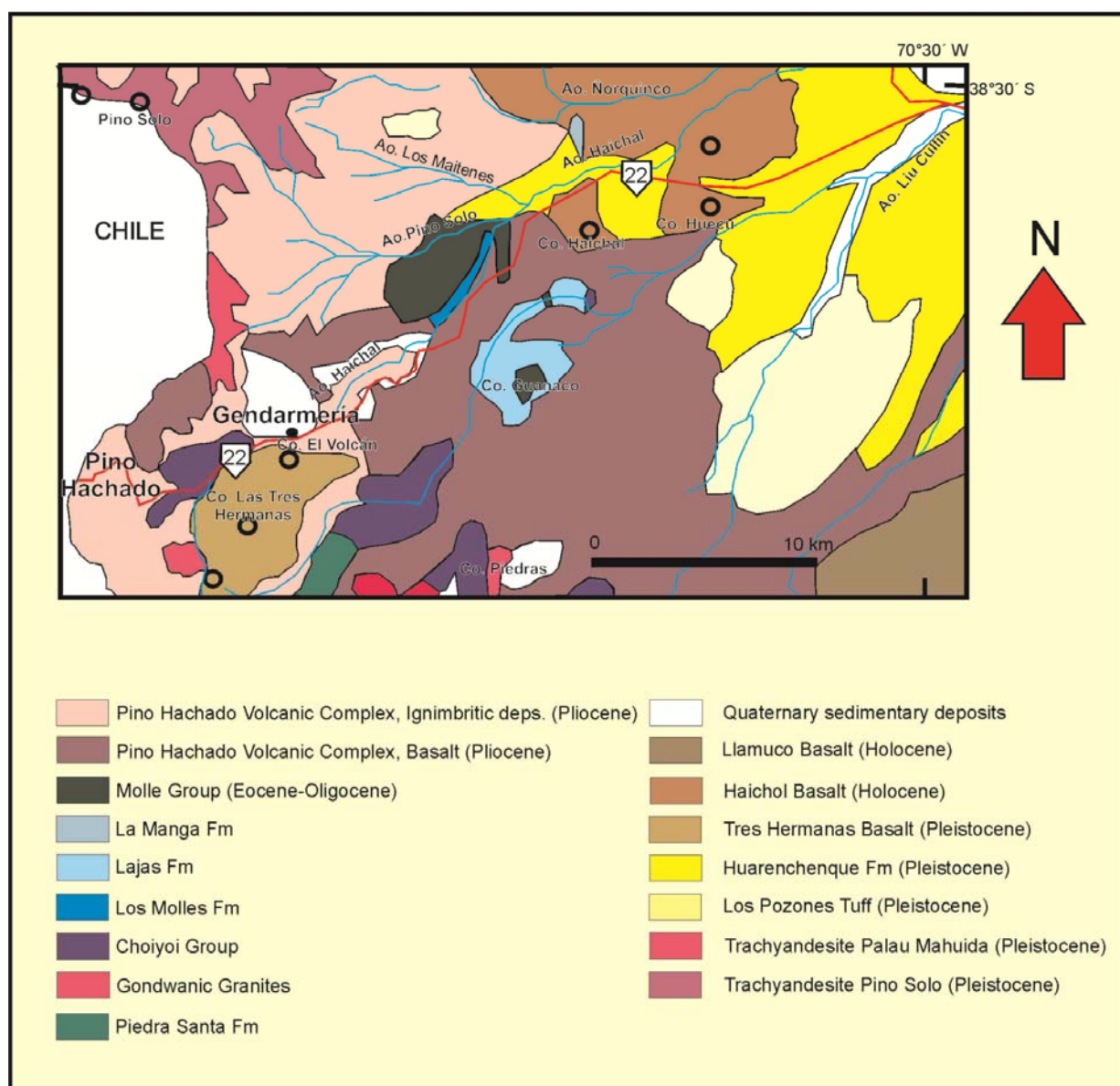


Figure 3.9. Geologic map of the Pino Hachado region (from Dirección Provincial de Minería, Neuquén Province).

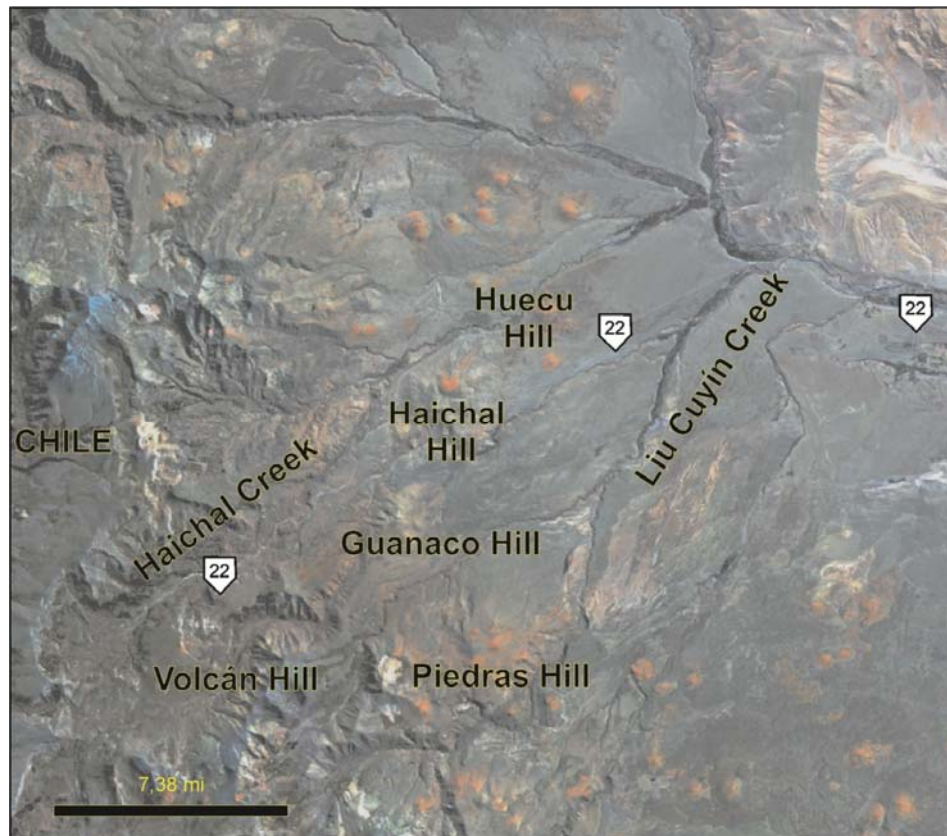


Figure 3.10. Satellite image of the Pino Hachado Volcanic Complex.

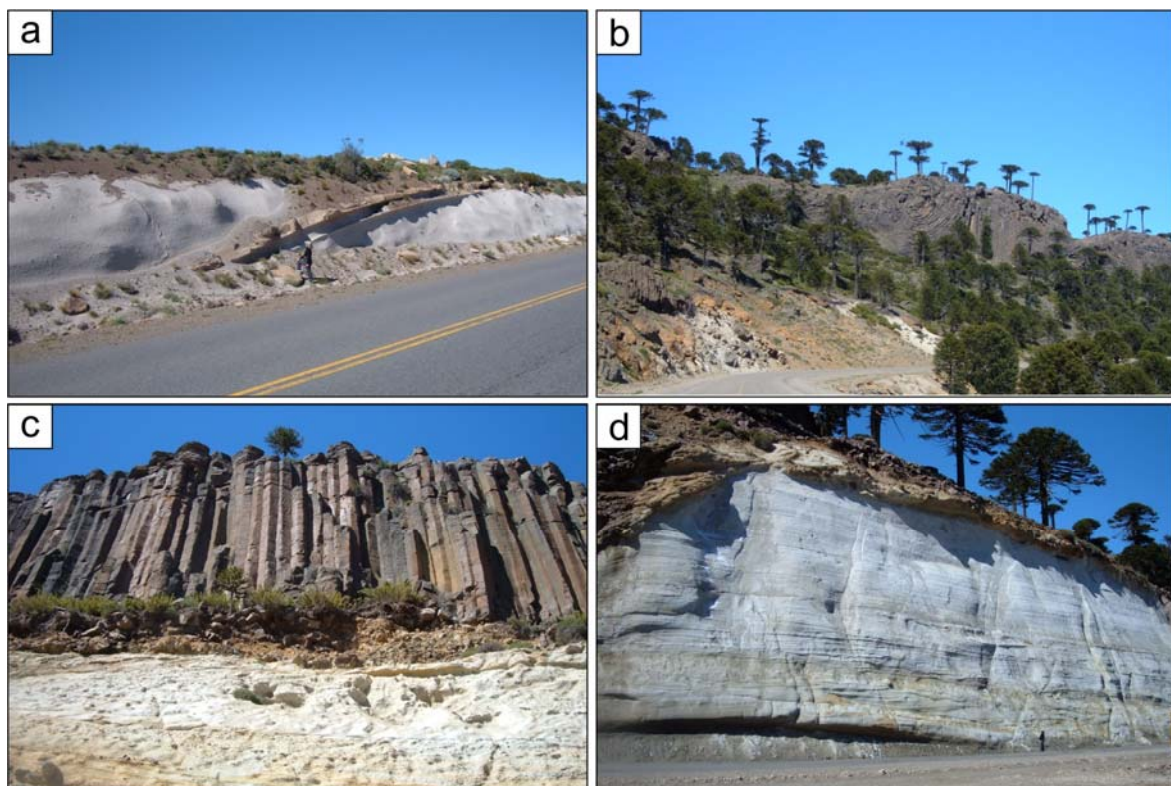
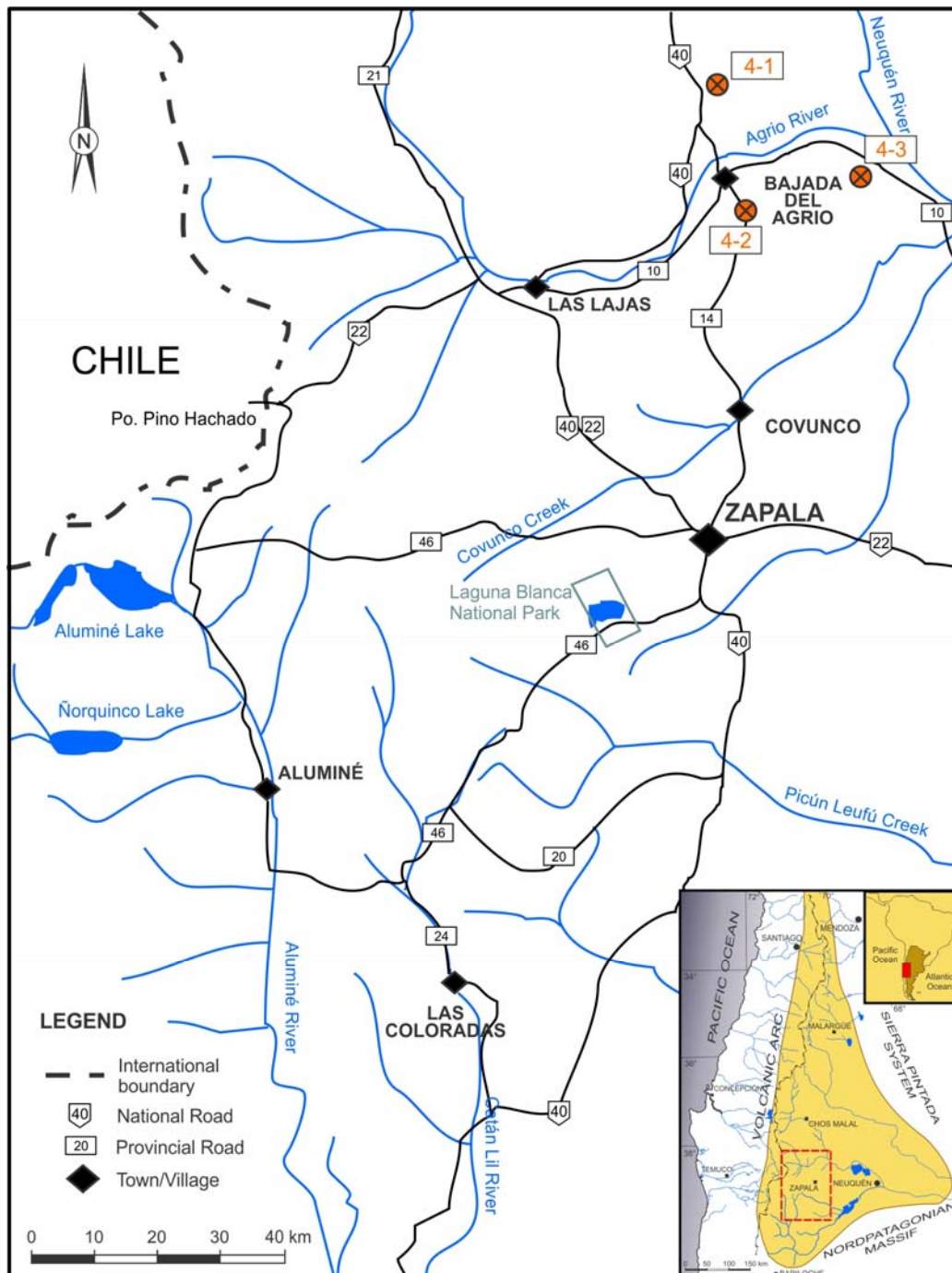


Figure 3.11. General features of the Volcanic and pyroclastic deposits of the Pino Hachado Volcanic Complex (Stop 3-4). a) Pyroclastic flow deposits (pumiceous lapilli tuffs). Huarenchenque Formation. b) Araucaria forest and curved contractional joints. Ignimbritic deposits. c) Giant contractional joints. Ignimbrite of the Pino Hachado Volcanic Complex. d) Pyroclastic surge deposits.

DAY 4 – October 6th

**TRANSGRESSIVE-REGRESSIVE CYCLES IN THE LOWER CRETACEOUS
AND THE TRANSITION TO THE FORELAND STAGE**

This day also has two main objectives. The first one is to examine the well-exposed stratigraphic architecture of the Lower Cretaceous succession north of Zapala, at the Salado River and Bajada del Agrio. The second is to look at the red-bed deposits that characterise the final geodynamic stage of the Neuquén Basin evolution, associated with the growth of the magmatic arc to the west (foreland stage).



Cumulative distance from ZAPALA (km)	Geographic – Geologic Reference
0	Zapala. National Roads 40/22 north.
55.0	Access to Las Lajas. Take National Road 40 north.
57.7	Agrio River (bridge)
67.5	Pilmatué Creek (bridge)
92	Deviation to Bajada del Agrio (Provincial Road 14). Stay on Road 40
97.9	Shingle Road along the Salado river. Take South to Bajada del Agrio
100.43	General View of the Mulichinco Fm.
102.8	STOP 4-1. The Lower Cretaceous Succession at the Salado River. The Mulichinco and Agrio Formations.
108.5	General view of the Rayoso Fm. red beds.
112.0	Agrio River (bridge). Junction Provincial Road 14.
116.1	Provincial Road 14. Access to Bajada del Agrio
117.7	Main Access to Bajada del Agrio
119.4	STOP 4-2. The Uppermost Agrio Fm and contact with the Huitrín Fm.
120.9	Deviation to Quili Malal.
128.2	Outcrops of the Avilé Sandstone.
132.9	STOP 4-1. Agrio del Medio. General view of the red beds of the Foreland Stage.

STOP 4-1. The Lower Cretaceous Succession at the Salado River. The Mulichinco and Agrio Formations.

Deposition in the Neuquén Basin during the Early Cretaceous (Berriasian-Barremian) was characterised by well-developed cycles showing a complete record of lowstand, transgressive and highstand systems tracts within a predominantly low-relief marine setting. During the late Early Valanginian, following a tectonically-enhanced relative sea-level fall, sedimentation was limited to the central part of the Neuquén Basin, with the deposition of a predominantly clastic, continental to shallow marine wedge on top of basinal black shales and outer-ramp deposits. This lowstand wedge is called the Mulichinco Formation and consists of a third-order sequence that lasted about 2 m.y. and contains high frequency lowstand, transgressive, and highstand deposits (Schwarz & Howell, 2005).

The basal deposits of the Mulichinco Formation immediately above the bounding surface form a widespread alluvial sheet, about 20-35 m in thickness, composed of amalgamated channel-fill units. Channel fills are closely associated with non-channelised units composed of siltstones and planar-laminated sandstones interpreted as flood plain deposits (Schwarz et al., 2006). The overlying 70 m of the Mulichinco Formation are characterised by channelised units where large-scale inclined strata are common, interbedded with a higher proportion of non-channelised units. The uppermost part of the succession in the region is dominated by dark grey, carbonaceous shales and siltstones, with minor sandstones. Marine ostracods, scattered shells and rare *Palaeophycus* and *Teichichnus* were

found within this section, together with well-preserved vascular plant remains (Schwarz et al., 2006). This upper section is interpreted to represent a coastal plain/bay environment.

The Mulichinco Formation is drastically overlain by dark, organic rich, fine-grained deposits that represent a return to offshore marine conditions as part of a second-order transgressive event. These distal deposits represent the base of the Lower Member of the Agrio Formation (Late Valanginian - Early Hauterivian). The unit in the Salado River area is about 500 m thick and is mostly composed of mudstones and very fine sandstones with abundant interstratified thin carbonates, representing from outer to inner ramp settings. In the second-order sequence stratigraphic framework, most of this marine unit represents a long-term highstand.

During the late Early Hauterivian times a major relative sea-level fall led to the accumulation of a second lowstand wedge, composed of fluvial and eolian deposits named the Avilé Member of the Agrio Formation. This non-marine unit is exceptionally well exposed in the central part of the Neuquén Basin where it reaches up to 150 m. However, in marginal areas, the unit is relatively thin and characterized by amalgamated fluvial deposits accumulated in a low-accommodation setting (Veiga et. al., 2007). The basal contact of this sandstone unit is interpreted as a major sequence boundary whereas the upper boundary is marked by the accumulation of deep-marine black shales of the Upper Member of the Agrio Formation (Early Hauterivian-Barremian) across a sharp and regionally developed transgressive surface.

Notes:

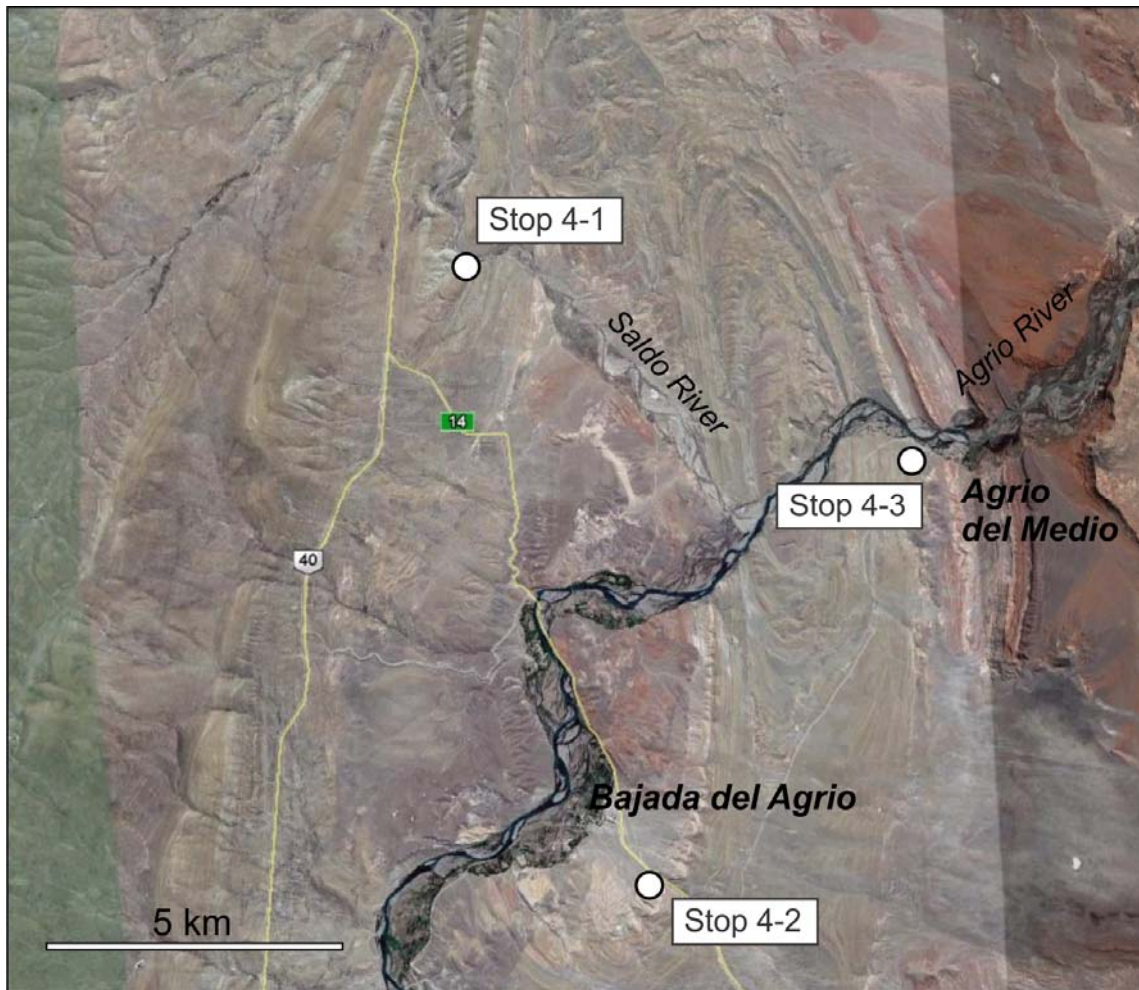


Figure 4.1. Satellite image of the Bajada del Agrio region and location of stops during Day 4.



Figure 4.2. General view of the Mulichinco Fm in the Salado River valley (Stop 4-2).



Figure 4.3. Closer view of the lower section of the Mulichinco Formation outcrops. Western margin of the Salado River valley.

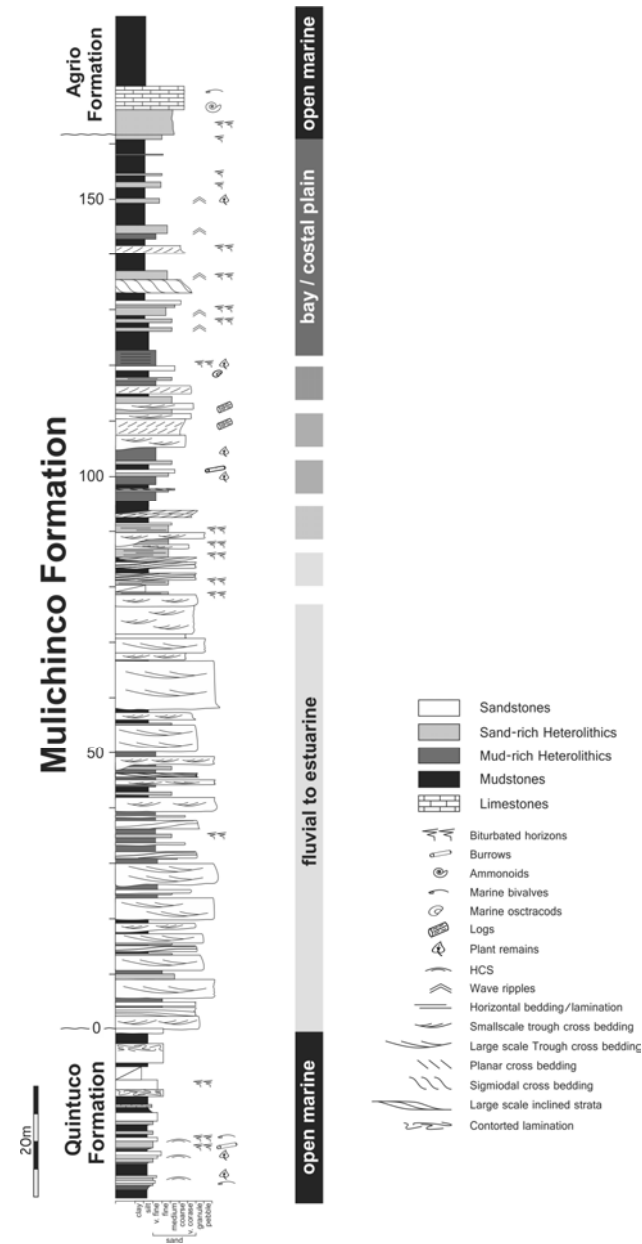


Figure 4.4. Closer view of the lower section of the Mulichinco Formation outcrops. Western margin of the Salado River valley.

STOP 4-2. The Lower Cretaceous Succession at Bajada del Agrio. The Agrio Fm and the transition to the Hutrín Fm.

The Lower Cretaceous marine sediments of the Neuquén Basin show not only second- and third- order sequences but also very well preserved high-frequency cyclic successions. The Upper Member of the Agrio Formation (Hauterivian – Barremian) is composed of several siliciclastic facies (dark grey shales, heterolithic couplets, silty sandstones, massive sandstones, medium-scale ripple-bedded sandstones, HCS sandstones) and carbonate facies (cross-stratified bioclastic grainstones, fine-grained skeletal carbonates, oyster/serpulid shell beds, skeletal/oolitic grainstones) (Spalletti et al., 2001).

These deposits were formed in an open marine ramp, at depths between the shoreface

and the proximal offshore (slightly deeper than the storm wave base). Trace fossils belong to the Cruziana icnofacies and are common in sandy and heterolithic facies. In the uppermost 130 m of the Agrio Formation, 19 high-frequency sequences were recognised. During relative sea-level rise a carbonate-rich TST suggests flooding and starvation of the ramp. Subsequent decreasing accommodation resulted in progradation of HST siliciclastic deposits, characterised by a marked shallowing-up stacking pattern. Systematic changes in substrate conditions, siliciclastic contribution and carbonate productivity are interpreted to result from the influence of global climatic oscillations. The scale of high frequency sequences, in the fourth-order hierarchy, would therefore correspond to the excentricity (E1) cycles of the Milankovitch band (Spalletti et al., 2001).

Notes:

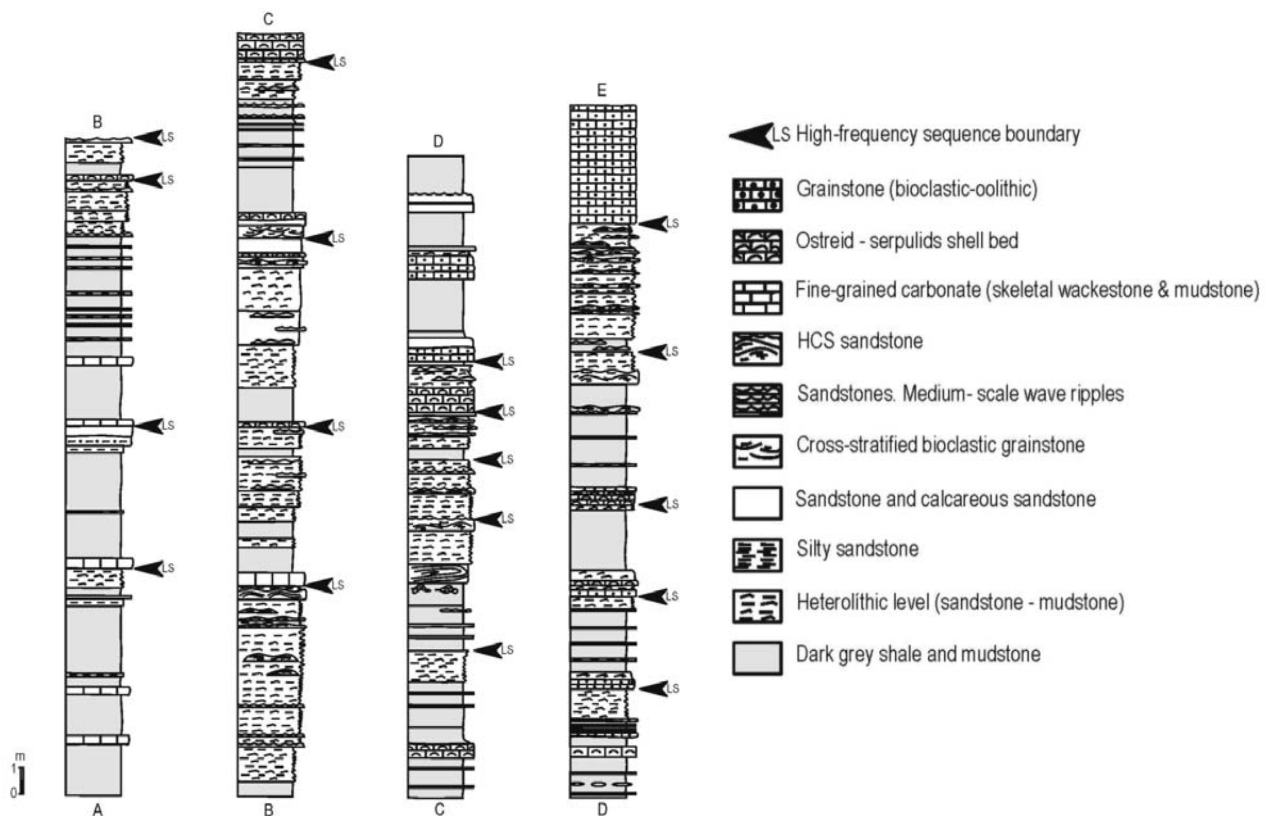


Figure 4.5. High-frequency cycles in the upper member of the Agrio Formation, east of Bajada del Agrio (from Spalletti et al., 2001).

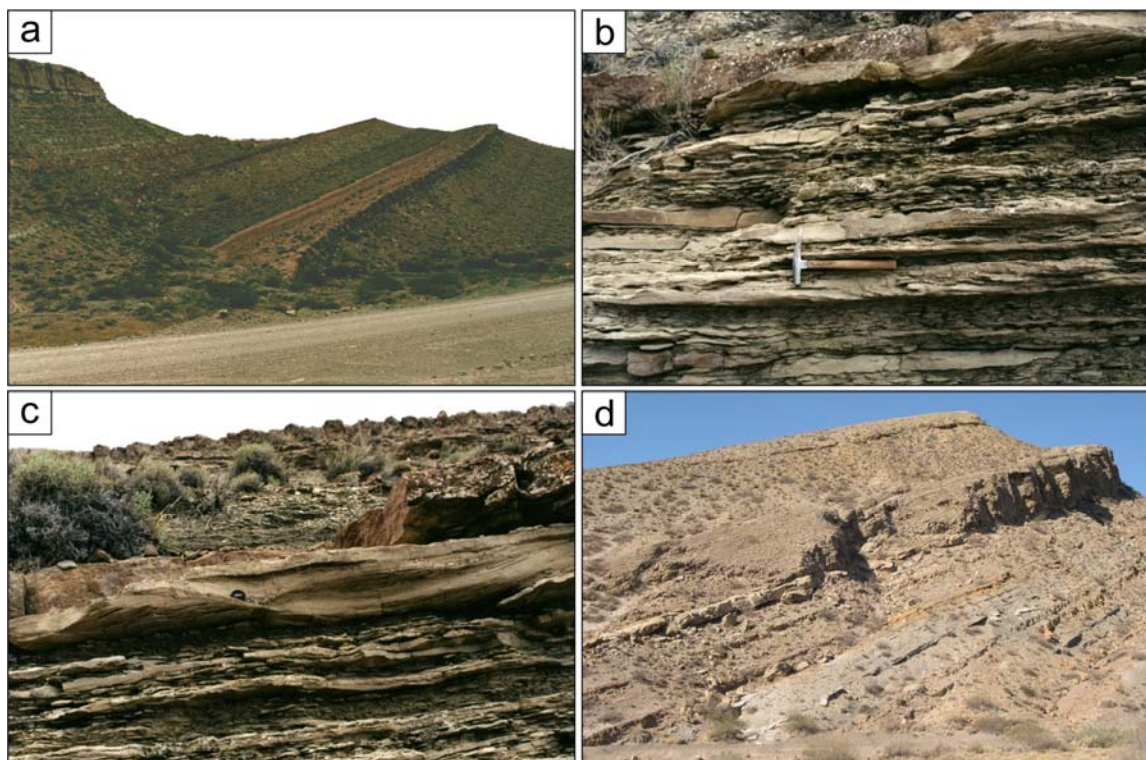


Figure 4.6. a) General view of the high-frequency cycles in the upper member of the Agrio Formation near Bajada del Agrio (Stop 4-2). b) and c) Detailed views of wave-dominated high-frequency cycles. d) The upper section of the Agrio Fm at Bajada del Agrio and the contact with the fluvial deposits and evaporites of the Huitrín Fm.

STOP 4-3. The Foreland Stage: the Neuquén Group (Candeleros Member, Río Limay Formation) at Agrio del Medio

Towards the end of the Early Cretaceous changes in the rates of South Atlantic spreading and a reorganisation of the Pacific plates, including a decrease in the angle of slab subduction, resulted in the development of a compressional tectonic regime which caused inversion of previous extensional structures (Vergani et al. 1995). At this stage the Neuquén region became a retroarc foreland basin, and significant variations in the size and shape of the basin (Legarreta & Uliana 1991) together with an eastwards migration of the depocentres occurred (Franzese et al. 2003). The active depositional systems within the Neuquén Basin were strongly controlled by the compressive regime. Uplift and tectonic inversion in the mountain chain to the west led to the deposition of more than 2,000 m of continental deposits in the main depocentres (Rayoso and Neuquén Groups). This thick foreland succession includes a rich world-known fauna of terrestrial reptiles.

The Rayoso Formation in the surroundings of Bajada del Agrio is mostly composed of laterally extensive fine-grained redbed deposits. They are essentially composed of sandstone and heterolithic intervals interpreted to be the result of unconfined sheet splays produced by episodic low-energy flooding in a mudflat and/or playa environment. Coarser-grained 2 – 5 m thick sandstone lobes produced by expanding sheetfloods and meter-scale sandstone ribbons interpreted as the deposits of shallow distal channels are less common. These deposits may be composed of a single bed or amalgamated parallel-stratified, trough cross-bedded and cross-laminated strata. Solitary

aeolian dunes also intercalate between fine-grained successions. They are characterized by large-scale wedge-shaped sandbodies arranged in cross-stratified sets with planar to tangential foresets.

The younger Neuquén Group (or “Dinosaur Bearing Strata”) is discordantly overlying the Rayoso Formation. The lowermost section of this redbed succession is composed of fine sandstones and mudstones with subordinated extra and intraformational conglomerates. At Agrio del Medio the succession (< 40 m thick) shows three distinct types of facies associations and sedimentary bodies: a) cross-bedded and ripple-bedded sandstones formed by sandwave, dune and current-ripple migration, b) tabular sections of intraconglomerates, massive and rippled mudstones, and c) large scale IHS mud-rich sets characterized by successive 15 m long sigmoidal bundles. Paleocurrent trends suggest that these IHS sets were built by lateral accretion processes. The tabular, multistorey and amalgamated cross-bedded sandstone bodies of the lower section suggest a low sinuosity and bed-load fluvial depositional system. This system is followed by an association of aeolian and poorly channelized fluvial sediments represented by loess-type muddy deposits and levee - crevasse splay intraconglomerates and rippled mudstones. The third and most interesting interval, identified towards the top of the sequence, is a suspended-load dominated fluvial system, mainly represented by the IHS mud-rich sets. This model resembles the deposits of tidally influenced point bars, but it is assigned here to a high sinuosity meandering system with very wide bends, developed in a low gradient continental flood plain (Gazzera & Spalletti, 1990).

Notes:



Figure 4.7. Panoramic view of the Rayoso Fm at Agrio del Medio (Stop 4-3).

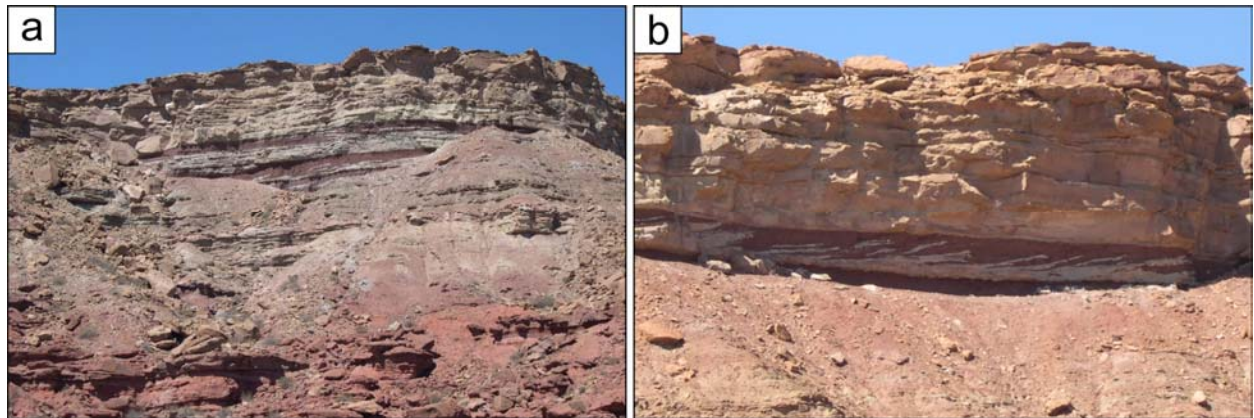


Figure 4.8. Views of the outcrops of the Candeleros and Huincul Members of the Río Limay Formation (Neuquén Group) at Agrio del Medio. Note large-scale heterolithic lateral accretion structures (IHS).

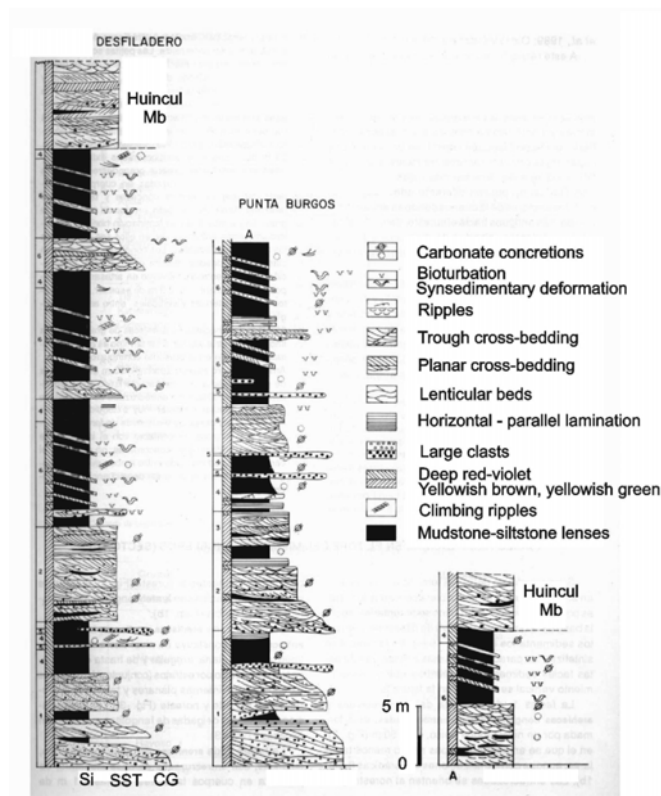


Figure 4.9. Sections of the Candeleros Member of the Río Limay Formation (Neuquén Group) at Agrio del Medio (from Gazzera & Spalletti, 1990)

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