CRETACEOUS STRATIGRAPHY OF SIERRA DE BEAUVOIR, FUEGIAN ANDES, ARGENTINA

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ABSTRACT

The Cretaceous stratigraphy north of Lago Fagnano, Tierra del Fuego, was poorly known until the last decade of the twentieth century. Stratigraphic, sedimentologic, and paleontological observations in sierra de Beauvoir and surroundings enabled the recognition of two main packages of dominant marine mudstone. 1) A more than 450 m thick package of slate, shale and mudstone, constituted by the revised Lower Cretaceous Beauvoir Formation. A type locality in the core of sierra de Beauvoir, with diagnostic Aptian-Albian fossils including inoceramids of the *Inoceramus neocomiensis* group and *Aucellina* sp., is proposed for this unit. 2) A more than 1,500 m thick, mudstone-dominated, but sandier upward, package consisting of at least three Upper Cretaceous units. Arroyo Castorera Formation (*nom. nov.*) bears Turonian inoceramids of the *I. hobetsensis* group and *I.* cf. *lamarcki.* Río Rodríguez Formation (*nom. nov.*) has Coniacian inoceramids, *cf. Cremnoceramus* sp. Policarpo Formation bears poorly preserved ammonites (*Grossouvrites* sp., *Maorites* sp., and *Diplomoceras* sp.), together with diagnostic Maastrichtian dinocysts (*Manumiella* spp. complex, *Operculodinium* cf. *azcaratei*, some specimens of *Fibrocysta-Exochosphaeridium* complex, and *Palaeocystodinium granulatum*). Both packages were deposited in deep-marine environments and show, as a whole, a coarsening upward trend in the succession of Cretaceous rocks. Beauvoir Formation is part of the back-arc basin-fill of the former Rocas Verdes marginal basin. Arroyo Castorera Formation appears as a transition to the initiating Late Cretaceous Austral foreland basin evolution, clearly represented by turbiditic deposits of Río Rodríguez and Policarpo formations that were progressively accumulated in front of the rising Fuegian Andes.
Keywords: *Tierra del Fuego, Austral Basin, Aptian-Maastrichtian, paleontology, inoceramids.*

RESUMEN

Estratigrafía del Cretácico de sierra de Beauvoir, Andes Fueguinos, Argentina.
El Cretácico al norte del lago Fagnano, Tierra del Fuego, estaba poco definido hacia fines del siglo veinte. Estudios estratigráficos, sedimentológicos y paleontológicos revelan la sucesión fangolítica de sierra de Beauvoir y adyacencias, donde hay dos paquetes principales de rocas de origen sedimentario marino. 1) Un paquete (espesor > 450 m) constituido por pizarras, lutitas y fangolitas de la Formación Beauvoir (Cretácico Inferior) revisada. Para ésta se propone una localidad tipo con bivalvos fósiles aptiano-albianos del grupo de *Inoceramus neocomiensis* y *Aucellina* sp. 2) Un paquete dominado por fangolitas (espesor > 1500 m), progresivamente más arenoso hacia los horizontes más jóvenes, conformado por al menos tres unidades del Cretácico Superior, definidas o reconocidas aquí como Formaciones Arroyo Castorera (*nom. nov.*), Río Rodríguez (*nom. nov.*) y Policarpo. Éstas contienen, respectivamente, elementos diagnósticos del Turoniano (grupo de *I. hobetsensis* e *I.* cf. *lamarcki*), Coniaciano (cf. *Cremnoceramus* sp.) y Maastrichtiano (*e.g.* dinoquistes: complejo *Manumiella* spp., *Operculodinium* cf. azcaratei, complejo *Fibrocysta-Exochosphaeridium* y *Palaeocystodinium granulatum*; géneros de amonites: *Grossouvrites*, *Maorites* y *Diplomoceras*). Ambos paquetes se depositaron en un ambiente marino profundo, mostrando una tendencia granocreciente en la sucesión de unidades cretácicas. La Formación Beauvoir completa el relleno profundo de la previa cuenca marginal de Rocas Verdes. La Formación Arroyo Castorera surge como transición en la evolución inicial de la cuenca Austral de antepais, definitivamente representada por depósitos turbidíticos de las formaciones Río Rodríguez y Policarpo, acumuladas al frente de los Andes Fueguinos en ascenso.

Palabras clave: *Tierra del Fuego, Cuenca Austral, Aptiano-Maastrichtiano, paleontología, inocerámidos.*

INTRODUCTION

The sedimentary rocks of Sierra de Beauvoir and the neighbouring areas in central Tierra del Fuego, Argentina, are mudstone-dominated. Because of their homogeneous composition and lack of diagnostic fossils, the slate, shale, and mudstone of the area were mostly grouped within a single geologic unit named Beauvoir Formation (Lower Cretaceous; Camacho 1948, 1967, Furque 1966, Caminos 1980, Buatois and Camacho 1993). Its age was based mainly on the presumed correspondence with the Hito XIX Formation at Monte Taarsh, near the international landmark Hito XIX, where the first discovery of late Early Cretaceous diagnostic fossils in Tierra del Fuego was achieved (Doello Jurado 1922, Richter 1925, Kranck 1932, Camacho 1949, Macellari 1979). Few authors mentioned or figured Upper Cretaceous rocks in the area (*e.g.* de Ferrariis in Fossa-Mancini *et al.* 1938, Yrigoyen 1962, Mingramm in Caminos 1980, p. 1485, Mingramm 1982 in Kraemer 2003, p. 736), but no formal proof of exposures of sedimentites of this age had been given in outcrops for the region until the initiation of the present study in the mid 1990s.

Intermittent field research in Sierra de Beauvoir over the past two decades enabled the identification of subtle sedimentological differences among disseminated mudstone exposures. The sedimentological observations were accompanied by the finding of a minimum of four different Cretaceous fossil bearing horizons. Three of the distinctive fossil horizons contain age diagnostic, variably preserved Aptian-Albian, Turonian, and Coniacian inoceramid bivalves; and an uppermost section has an assemblage of diagnostic Maastrichtian dinocysts and ammonites. The purpose of this contribution is to describe the Cretaceous and, particularly, the Upper Cretaceous stratigraphy of the area north of Lago Fagnano.

The collected fossil invertebrates are housed within the Paleontology Collection at the *Centro Austral de Investigaciones Científicas* in Ushuaia, Tierra del Fuego; otherwise the illustrated material corresponds to georreferenced field photographs.

GEOLOGIC FRAMEWORK

The Cretaceous rocks of central Tierra del Fuego are in an intermediate geographic position that links them in space and time with the evolution of (a) the Rocas Verdes marginal basin (Dalziel *et al.* 1974) to the south, (b) the Austral (Magallanes) foreland basin (Biddle *et al.* 1986) to the north and northwest, and (c) the western Malvinas foreland basin (Yrigoyen 1989) to the east (Fig. 1a). The Cretaceous mudrocks of Sierra de Beauvoir were deposited after the Late Jurassic submarine eruptive events that accumulated the predominantly volcanic and volcaniclastic Lemaire Formation (Borrello 1969; or Tobífera Formation, Thomas 1949a, b) that crops out south and west of the study area (Fig. 1b). The bulk of the Early Cretaceous sedimentation occurred in a deep-marine basin behind an active, "Pacific facing", volcanic arc (see Fig. 4 in Olivero and Martinioni 2001, and references therein), and in the tectonic context of the extensional regime that ruled the evolution of the marginal basin. Late Albian sedimentation in the marginal basin is documented by diagnostic inoceramids in the Yahgan Formation south of the area (Olivero and Martinioni 1996a) and in the Beauvoir Formation east of the study area (Olivero and Medina 2001, Olivero *et al.* 2009). The Paleogene sinorogenic sandstone and conglomerate strata (Martinioni *et al.* 1998, 1999a, Olivero and Martinioni 2001) of the Río Claro Group (Olivero *et al.* 2007, Olivero and Malumián 2008), reflect the contractional regime that led to the foreland basin evolution. A Paleocene conglomeratic unit unconformably rests on Cretaceous rocks in the Sierra de Apen, north of Sierra de Beauvoir (Fig. 2; Martinioni 1997, 2010, Martinioni *et al.* 1999a). The lower Upper Cretaceous unit in the area (Arroyo Castorera Formation, see below) appears to record the transition from extensional to contractional tectonic regimes.

The rocks that crop out in Sierra de Beauvoir, *i.e.* north of Lago Fagnano and south of the Río Mio and Río Claro valleys, are essentially Cretaceous (Figs. 1b, 2, Table 1). Dense forests, grasslands, glacial, and post-glacial Quaternary deposits considerably reduce their exposures to scattered patches or narrow stripes along the valleys or mountain crests. The described units are all exposed in Sierra de Beauvoir, where the stratigraphic relationships must be considered as preliminary since their contacts seem to be covered or of tectonic origin. The uppermost Cretaceous beds are unconformably covered in Sierra de Apen by the Cerro Apen Beds (Danian, Martinioni 2010; see also Martinioni *et al.* 1999a).

CRETACEOUS STRATIGRAPHY OF SIERRA DE BEAUVOIR

The Cretaceous rocks of Sierra de Beauvoir (see Table 1 and Fig. 2) are grouped into a more than 450 m thick Lower Cretaceous package that involves mainly the revised Beauvoir Formation, and a more than 1,500 m thick Upper Cretaceous package, including the Arroyo Castorera and Río Rodríguez formations, named and defined herein, and the Policarpo Formation, thoroughly recognized north of Lago Fagnano.

LOWER CRETACEOUS PACKAGE

The Lower Cretaceous package consists of tightly folded and faulted marine fossiliferous slate and shale successions included within the Beauvoir Formation.

Beauvoir Formation

The original name Beauvoir Formation, given by Furque (1966) to the Beauvoir Series studied by Camacho (1948, 1967), is retained for most of the Lower Cretaceous (*s.l.*) sedimentary and meta-sedimentary rocks (shale and slate) of Sierra de Beauvoir (*cf.* Olivero *et al.* 2007, Olivero and Malumián 2008). The formation has been previously described as Lower Cretaceous in a broad sense (*e.g.* Caminos 1980) and, according to different authors, appeared restricted to the Hauterivian-Barremian (Camacho 1967, Riccardi 1988) or to the "Neocomian" (Buatois and Camacho 1993); however, the unit was not fully defined and its presumed age was not supported by diagnostic data from Sierra de Beauvoir.

Type locality and distribution: A section with a minimum of 300 m of fairly continuous stratigraphic thickness involving a few horizons with poorly preserved Aptian-Albian marine fossil invertebrates in the upper Río Rodríguez valley is proposed as the type locality for the Beauvoir Formation (Fig. 3). There, the section is partially exposed between two fixed points (D132: lat. 54° 29' 41.52" S, long. 68° 8' 45.36" W; and D133: lat. 54° 29' 35.52" S, long. 68° 9'

33" W) and is characteristic for the rocks of the unit in Sierra de Beauvoir (Figs. 1b, 2). The provisional inclusion in the Beauvoir Formation of similar mud-rocks with no diagnostic fossils that show up along the northern shore of Lago Fagnano (Fig. 2), which were mapped and described as "*Pizarras del Lago Fagnano*" (Martinioni 2010), might extend the unit to older, presumably pre-Aptian, horizons. Two roughly comparable horizons outside Sierra de Beauvoir (Fig. 1b), one to the west-northwest, Hito XIX, containing *Aucellina radiatostriata* and *A. andina* (Macellari 1979), and another to the east-southeast of Lago Fagnano, Cerro Heuhuepen, with *A. euglypha* (Olivero and Medina 2001), Aptian-Albian and upper Albian respectively, were attributed to the Beauvoir Formation (see Olivero *et al.* 2009, and references therein). Mafic dykes cut through the unit at Cerro Rodríguez, and, at Cerro Kranck, this meta-sedimentary unit is the host rock of a plutonic intrusion (Fig. 2, Martinioni *et al.* 1999b, Olivero *et al.* 1999a, 2007, González Guillot *et al.* 2012). In the adjacent Chilean area the mudstone-dominated rocks occur between Lago Deseado and Lago Fagnano (Martinioni 2010), and to the west along the northern shore of Seno Almirantazgo (Fig. 1b; La Paciencia Formation in Klepeis 1994; see also "Columna Sur" in Hünicken *et al.* 1975).

Lithology: Near Lago Fagnano, this foliated unit has slaty cleavage, defined by preferred alignement of laminar minerals (phyllosilicates). The cleavage becomes spaced towards the interior of Sierra de Beauvoir, where the unit retains the original sedimentary fabric. The succession is quite homogeneous, with beds of a variable thickness, between a few centimetres and approximately one meter, made up mainly of dark grey, greenish-grey and dark brown to black slate and shale with scattered, thin, lighter grey to yellowish coloured, very fine-grained sandstone (Fig. 3a-c). Beds are mainly massive, some show faint parallel lamination, and very few are normally graded. Mudstone under the microscope has a prevalent sub-microscopic matrix and the coarser recognizable fraction (average clast Ø ≤ 0.03 mm) is constituted mainly of quartz. This unit includes scattered layers (≤ 2 cm thick) with fossil invertebrate remains (Fig. 3j), and very thin beds (~0.5 cm thick) rich in calcareous microfossils (Fig. 3h).

Stratigraphic relationships, contacts, and thickness; structural features: The strata of the unit are generally folded and fractured (Fig. 3a-c). In the surroundings of Cerro Rodríguez the folds have axes that barely plunge to the east (less than ten degrees) and the bedding strike varies between 90° and 130°. The foliation strike is 100°; the dip is nearly vertical, to the south. The

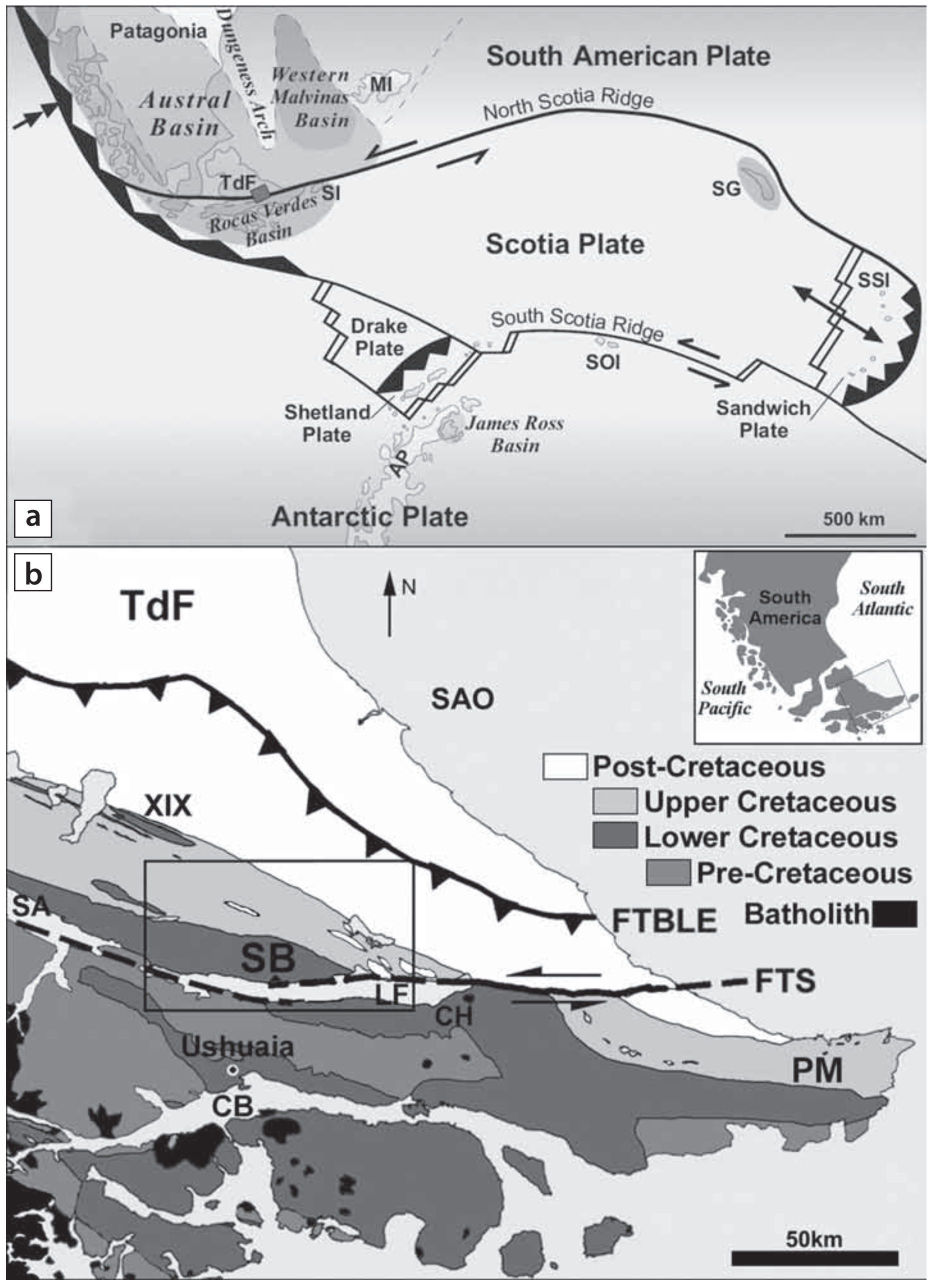

Figure 1: a) Geotectonic context of Tierra del Fuego that comprises the boundary between the South American and Scotia plates and involves the Rocas Verdes marginal basin and Austral foreland basin domains. b) Cretaceous outcrops in central and eastern Tierra del Fuego. The small grey square in **a** and the rectangle in b indicate the study area in central Tierra del Fuego (TdF; Staten Island, SI; Malvinas Islands, MI; South Georgia, SG; South Sandwich Islands, SSI; South Orkney Islands, SOI; Antarctic Peninsula, AP; Sierra de Beauvoir, SB; Lago Fagnano, LF; Península Mitre, PM; Seno Almirantazgo, SA; South Atlantic Ocean, SAO; Canal Beagle, CB; Hito XIX, XIX; Cerro Heuhuepen, CH; leading edge of the fold and thrust belt, FTBLE; Fagnano transform system, FTS).

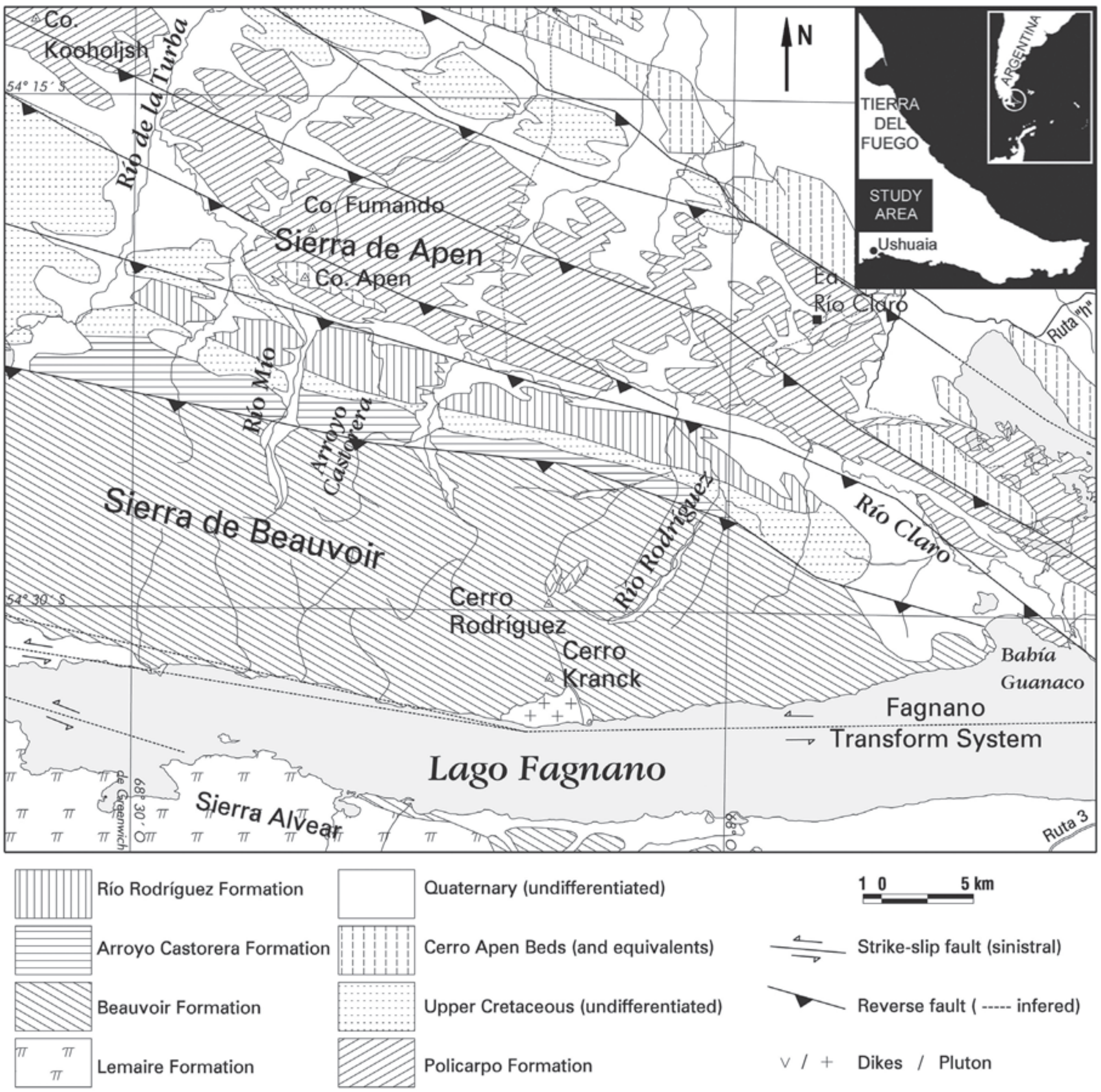

Figure 2: Geologic map of the study area north of Lago Fagnano in central Tierra del Fuego, Argentina (see inside; Co., Cerro; Ea., Estancia).

folds are mostly asymmetrical; their axes are roughly east-west oriented, which is typical for the structural style of the unit observed in the area. Preliminary mapping based on observation of satellite images and air photos enabled to interpret the prevalent north verging low angle reverse faulting in Sierra de Beauvoir. North-south oriented sub-vertical fractures with minor to negligible displacements are recorded at the uppermost Río Rodríguez valley. The total thickness of the whole unit and its contacts could not be established because of the intricate structure and the existence of important covered sectors. Nevertheless, the composite section recorded between the two fixed points D132 and D133 in the proposed type locality, the uppermost Río Rodríguez valley, involves more than 300 m of almost continuous stratigraphic thickness. Although not precise, the minimum thickness might add at least 150 m, when the exposures between the divide and Lago Fagnano in Sierra de Beauvoir are considered.

Paleontological content: Only restricted horizons of this uniform and widely distributed unit contain marine fossil invertebrates and some trace fossils (Fig. 3d-j). The fossil invertebrates are dominantly constituted by inner moulds and impressions of inoceramid bivalves, some with articulate valves; equinoid remains were also found. The fossils are poorly preserved and incomplete, which prevents a precise classification. One of the inoceramids (Fig. 3d), found in the lower fossiliferous level, has general affinities with the *Inoceramus neocomiensis* group (*sensu* Crame 1985). This specimen has been found associated with an undetermined regular echinoid that preserves some of the spines around the crushed test (Fig. 3g). Another bivalve specimen (*cf. Aucellina* sp.; Fig. 3f) has been found in an upper horizon of the unit, and elsewhere in the inner part of Sierra de Beauvoir. The poor

TABLE 1: Schematic correlation chart of the Cretaceous stratigraphic units of Tierra del Fuego mentioned in the text, emphasizing on the Fuegian Andes outcrops of the Rocas Verdes and Austral basins, and the adjacent subcrops of the Austral (Magallanes) and western Malvinas basins. Main sources of information: (@) this study (* age diagnostic paleontological data in the revised and new units -in grey, with doubts-); (1) Olivero and Martinioni 1996b, Olivero and Malumián 2008; (2) Yrigoyen 1962, Camacho 1967, Hünicken *et al.* 1975; (3) Olivero and Medina 2001, Olivero *et al.* 2002, 2003, (#) means also present in Staten Island, see Olivero *et al.* 2007; (4) Flores *et al.* 1973; (5) Natland *et al.* 1974; (6) Yrigoyen 1989, Galeazzi 1998, see also Biddle *et al.* 1986.

Surface / Subsurface		Sierra de Beauvoir Fuegian Andes Argentina (@)	Canal Beagle Region Fuegian Andes Argentina - Chile (1)	Central Tierra del Fuego Fuegian Andes Argentina - Chile (2)	Península Mitre Fuegian Andes Argentina (3)	Austral Basin (onshore - offshore) Argentina (4)	Magallanes Basin System of Stages Chile (5)	Western Malvinas Basin Continental Shelf Argentina (6)
UPPER CRETACEOUS	Maastrichtian	* Policarpo F.		Cerro Cuchilla F.	Policarpo F.	("Arcillas Fragmentosas")		"Zona Glauconítica"
	Campanian	*			Bahía Thetis F.		Riescoian	
	Santonian			Río García F. -		Cabeza de León F.		"Upper Inoceramus"
	Coniacian	Río Rodríguez F. *		Cerro Matrero F.				
	Turonian	*Arroyo Castorera F.			Buen Suceso S.	Arroyo Alfa F.	Lazian	"Middle Inoceramus"
	Cenomanian						Peninsulian	
LOWER CRETACEOUS	Albian	* Beauvoir F.	Hardy F. / Yahgan F.	Hito XIX F. - Vicuña F.	Beauvoir F. (#)	Nueva Argentina F.	Tenerifian	"Margas Verdes"
	Aptian			Beauvoir F. - La Paciencia F.				
	Barremian						Pratian	"Lower Inoceramus"
	Hauterivian					Pampa Rincón F.		
	Valanginian							
	Berriasian					Springhill F.	Esperanzian	Springhill F.

preservation does not enable to make a detailed classification. A loose rock fragment from the section with an accumulation of inoceramids (Fig. 3e) contains moulds that could be referred to *I. anglicus* Woods (*cf.* Olivero *et al.* 2009). On the west end of Bahía Guanaco at Lago Fagnano (Fig. 2) a layer has an accumulation of calcispheres of the group of *Pithonella* sp. (Fig. 3h). Few undeterminable agglutinated foraminifera were observed in thin sections of samples of the unit. Scarce to moderate bioturbation is present only in restricted horizons (Fig. 3i).

Age and correlations: The inoceramids recorded in the Beauvoir Formation are comparable with specimens described for the late Early Cretaceous of New Zealand, Antarctica, South Georgia, and Tierra del Fuego (Wellman 1959, Crame 1985, Medina 2007, Olivero *et al.* 2009). Specifically the *Inoceramus neocomiensis* group spans the Barremian-Aptian, with a possible extension to the Valanginian-Hauterivian (Crame 1985). *I. anglicus* Woods is a form known in general from the Albian (Crame 1985). In a stricter sense *I. anglicus* is known from the middle to upper Albian with possible extensions to the lower Albian and to the lower Cenomanian (Crame 1985, Medina 2007, Olivero *et al.* 2009). *Aucellina* spp. are documented for different localities of southernmost South America and Antarctic Peninsula (*e.g.* southern Patagonia, Tierra del Fuego, South Georgia, Alexander Island, and James Ross Island) ranging from Barremian to upper Albian/lower Cenomanian (Macellari 1979, Crame 1983, Medina and Buatois 1992, Olivero and Medina 2001).

The first records of calcispheres represented by the genus *Pithonella* are from the lower Albian, as witnessed in the "Deep See Drilling Project" site 511 (Krasheninnikov and Basov 1983, Malumián and Náñez 1996). A mono-specific association of *Pithonella* is recorded in the upper lower Albian and a more diverse number of species of the genus is characteristic of the upper Albian (Krasheninnikov and Basov 1983, Malumián and Náñez 1996). The calcispheres of the Beauvoir Formation are considered to be of a late Albian age.

Despite its poor preservation, the available fossil record of the section at the upper Río Rodríguez valley suggests that the Beauvoir Formation can be assigned to the Aptian-Albian. A rock sample of the Cerro Rodríguez basic dykes that cut through the lowest and middle levels of this section has a whole rock K-Ar age of 104±4 Ma (Martinioni *et al.* 1999b). In Cerro Kranck (Fig. 2) the Beauvoir Formation is in contact with a pluton of 95.1±2.9 Ma (mineral K-Ar age on amphibole, Cerredo *et al.* 2011a) and in Cerro Heuhuepen (Fig. 1), where the unit has late Albian fossils (Olivero and Medina 2001), it is the host rock of a plutonic body dated at 93±4 Ma (whole rock K-Ar age on diorite, Acevedo *et al.* 2000) and at 72±1 (U/Pb zircon age on monzonite, Cerredo *et al.*, 2011b; see these dates compiled in González Guillot *et al.* 2012). The composition of the two plutons suggests separate magmatic events (see González Guillot *et al.* 2012). Hitherto, the intrusions of the Beauvoir Formation in Cerro Kranck and Cerro Heuhuepen might have had an earlier magmatic episode affecting the sedimentary rocks at Cerro Rodríguez.

In Sierra de Beauvoir, according to the complete biocrons of some the inoceramids, it cannot be discarded that the oldest horizons could be as old as Valanginian and the youngest as young as latest Albian (perhaps earliest Cenomanian). Herein, the Beauvoir Formation is considered to embrace provisionally the slates that crop out along the northern shore of Lago Fagnano to the west of Bahía Guanaco ("*Pizarras del Lago Fagnano*" in Martinioni 2010). The stratigraphic relationships suggest that these slates with a higher deformation are

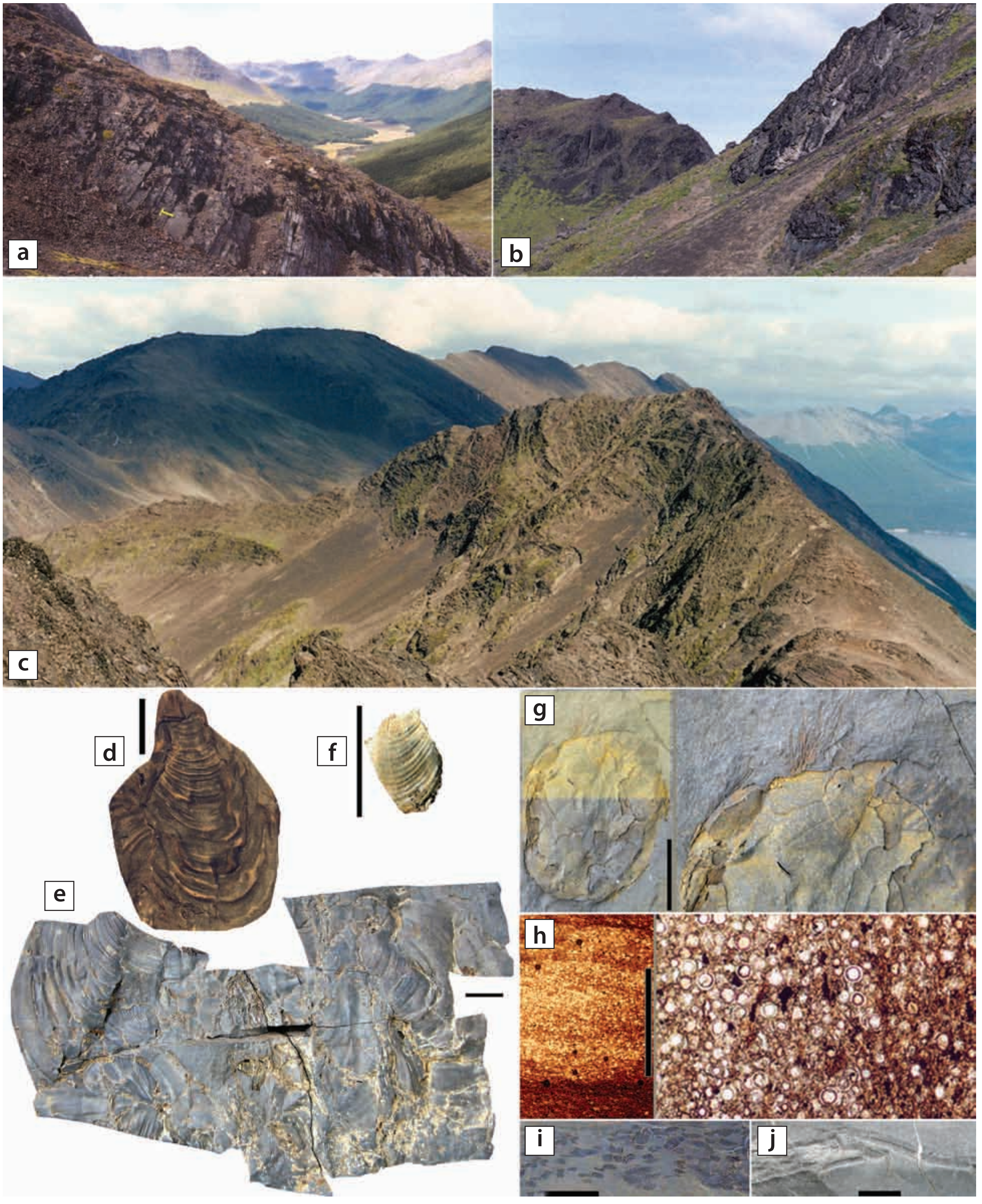

Figure 3: Beauvoir Formation. a) Outcrops in the type locality (geologic hammer for scale); b) Río Rodríguez upper valley in the core of Sierra de Beauvoir, folded strata crosscut by mafic dykes at Cerro Rodríguez; and **c**) exposures at the divide in Sierra de Beauvoir (in the background to the right, Lago Fagnano and Sierra Alvear). Diagnostic fossil bivalves: d) internal cast ascribable to the *Inoceramus neocomiensis* group; **e**) rock sample of a horizon with a concentration of inoceramid fragments including forms of *I.* cf. *anglicus*, f) fragment attributable to the genus *Aucellina*. Paleoecological indicators: g) Crushed regular equinoid test with remainders of the spines preserved at its rim (magnified on the left); h) vertical thin section of a hemipelagic level of western Bahía Guanaco containing calcispheres (left) and detailed view of a bedding plane parallel thin section (right; magnified, no scale); **i**) probable *Phycosiphon* isp. (vertical view); and j) concentration of inoceramid shell fragments (vertical view) (scale bars = 1 cm).

older than the bulk of the Beauvoir Formation, thus they were originally seated in a stratigraphically lower position, underneath the rest of the unit.

The mudstone-dominated beds of the Arroyo Castorera Formation accumulated after the lithologically similar beds of the Beauvoir Formation, since they are carrying a younger fossil assemblage, but no contact could be observed between them. Regionally, the Beauvoir Formation can be correlated with the succession of La Paciencia and Vicuña formations in Chile, and with the pair formed by Pampa Rincón and Nueva Argentina formations (part of Lower Inoceramus and Margas Verdes) in the subsurface of north-eastern Tierra del Fuego (Flores *et al.* 1973, Yrigoyen 1962, 1989, Biddle *et al.* 1986, Galeazzi 1996, 1998). Although they are separated by less than 35 km, there is no clear definition on the lateral relation between outcrops of the Beauvoir and the Hito XIX formations. As it has been provisionally suggested (Olivero and Malumián 2008; see also Olivero and Medina 2001, Olivero *et al.* 2009), the second is interpreted as an upper Albian lateral counterpart that perhaps interfingers with the uppermost strata of the Beauvoir Formation as it happens with subsurface equivalents (Margas Verdes or Nueva Argentina Formation; Flores *et al.* 1973, Biddle *et al.* 1986, Malumián 1990, Galeazzi 1998). The intrusion of igneous rocks during the "mid" Cretaceous in the sedimentary rocks of Beauvoir Formation suggests that magmatic events were occuring possibly since the latest Albian, during the late Cenomanian-early Turonian and at least until the Campanian (see ages compiled in González Guillot *et al*. 2012).

The Yahgan Formation (Lower Cretaceous *s.l.*) represents the infill of the main depocenter of the basin, located several tens of kilometres to the south (Olivero and Martinioni 2001). The unit has a late Albian youngest age supported by the occurrence of *Inoceramus carsoni* McCoy and *Actinoceramus concentricus* (Parkinson) in its upper horizons (Olivero and Martinioni 1996a; see also Olivero *et al.* 2009). This suggests a northward lateral replacement of the interbedded sandstone-mudstone Yahgan Formation by the mudstone-dominated Beauvoir Formation.

Paleoenvironmental interpretation: The paleoenvironment corresponds to deep-marine slope to basin plain conditions, with processes dominated by fallout-from-suspension according to the very fine-grained clastic fraction and to the general preservation of the marine fossil invertebrates. Only a few restricted layers have fragmented bivalve bioclasts (Fig. 3j). Since no evidence points toward the occurrence of any bottom currents or gravity flows as strong as to transport centimetre-scale clasts, they could be an *in situ* bioclastic accumulation after the winnowing and by-pass of the finer clastic particles by means of only weak bottom currents. Some articulate bivalve remains and the spines preserved around a collapsed regular echinoid test suggest *in situ* death of organisms, without any further sedimentary rework, in agreement with the interpreted paleoenvironmental conditions. However, horizons with high concentration of valves could correspond to periods with a generalized low sedimentation rate and/or to an increase in the colonization of the substrate as a response to more suitable sea-bottom conditions (*e.g.* richer in oxygen). The moderate to low bioturbation is only restricted to certain horizons, as it happens with the fossil invertebrates, and is not observed in the whole section, suggesting fluctuations between aerobic -at least disaerobic- and anaerobic conditions (*cf.* Savrda *et al.* 1991). Low sedimentation rate and/or high micro-organism productivity periods are also evidenced by the hemipelagic layers with calcispheres in the Beauvoir Formation. The very small microscopically discernible clastic fraction within these mudstone-dominated beds and the lack of indicative elements, like paleocurrent indicators, inhibit to infer the sediment source.

UPPER CRETACEOUS PACKAGE

The Upper Cretaceous sedimentary units are less deformed than the Lower Cretaceous rocks and no mineral reorientation has been observed; however, they are faulted, variably folded, and show spaced cleavage. Exception made for the Arroyo Castorera Formation that resembles strongly the Beauvoir Formation; the Río Rodríguez and Policarpo formations have characteristic sedimentary features that favour their division. The Arroyo Castorera Formation might constitute transitional deposits representing the progressive change in the monotonous lithological composition typical of the mudstone-dominated Lower Cretaceous. Sandstone intercalations occur more frequently and gradually up section, up to the presence of conglomeratic sandstone in the uppermost Cretaceous horizons. Despite the identification of different groups of rocks of different ages, based on stratigraphic relationships and distinctive fossil content, it is highly complicated to define the precise distribution of each of the identified lithostratigraphic units. Consequently, a wide area was usually indicated as Upper Cretaceous (*s.l.*) in previous geologic maps concerning Sierra de Beauvoir (*e.g.* Olivero *et al.* 1999a, 2007). As a major result of this contribution the outcrop localities and the minimum probable outcrop extensions of Arroyo Castorera, Río Rodríguez, and Policarpo formations are depicted in our geologic map (Fig. 2).

Arroyo Castorera Formation (*nom. nov.*)

The Arroyo Castorera Formation is proposed for the mudstone succession exposed north of the main watershed of Sierra de Beauvoir along the lower valley of Arroyo Castorera (Figs. 2, 4a). The uniformity of these rocks inhibited a convincing differentiation from those of the Beauvoir Formation until diagnostic inoceramid bivalves were found (Fig. 5; see Martinioni 2010).

Type locality and distribution: Upper Cretaceous fossil bearing mudstone beds in localities of the northern drainage area of Sierra de Beauvoir were initially mentioned in preliminary presentations (Martinioni 1997). The Arroyo Castorera Formation is exposed along a latitudinal stripe to the south of the depression of the Río Claro valley and its western continuation along the Río Mio valley (Fig. 2). The type locality is designated near the confluence of Arroyo Castorera and Río Claro, where scattered outcrops preserving a partial, but representative section of the unit are exposed (Figs. 2, 4a). The type locality is restricted to the west-to-east trending part of the stream bed that involves a key fossil locality (Fig. 5), with an eastern local limit at the convergence of both water streams, and an inferred continuity to the east (Fig. 2).

Lithology: The unit is mainly constituted by very homogeneous mudstone beds that usually do not exceed one meter in thickness (Fig. 4a, b). Subordinated lithological varieties include dark coloured siltstone and fine- to very fine-grained muddy sandstone, and a minor participation of thin, discrete layers of possible tuff and very thin, fine to very fine-grained sandstone. Beds are generally massive or faintly laminated.

Stratigraphic relationships, contacts, and thickness; structural features: The bedding strike varies between east and southeast; the prevalent dip is to the south and southwest (~45º ≤ ~75º) with changes in the surroundings of the type locality where the succession is folded. Towards the confluence of Arroyo Castorera and Río Claro, just east of the main fossil locality, a symmetric fold has a gently, east plunging axis (~10º). The foliation strike has an east trend (~100º) with a nearly vertical dip. Fold axes orientations in the area appear related to north verging, east-west oriented thrusts. It is possible that the alluded reverse faulting could repeat part of the homogeneous succession. No lower or upper contacts of the Arroyo Castorera Formation were observed. The almost exclusively mudstone-dominated composition and the dispersion of small outcrops hinders the chance to build a complete section, nevertheless, a minimum thickness of ~300 m is estimated.

Paleontological content: This unit bears fossil bivalves in a few restricted levels; some of them preserved with articulate valves (Fig. 5a-j). The fossils are dominantly inoceramid bivalves different from those of the Beauvoir and Hito XIX formations. Almost complete (and fragmentary) specimens attributable to the *Inoceramus hobetsensis* group of Nagao and Matsumoto (1939; Fig. 5a-c, h-j; see also Noda 1975, Elder and Box 1992, Noda and Matsumoto 1998) and *I.* cf. *lamarcki* Parkinson (1819; *cf.* Fig. 5e-g) were recognized (see Woods 1912, Crame 1981, Walaszczyk 1992, Crampton 1996). Both closed and open articulated inoceramid bivalves have a variable degree of preservation, with the shell partially preserved in some specimens. Internal moulds and external casts with apparently little or no deformation at all occur together with completely crushed, almost flattened specimens. A small fragment of an undetermined heteromorph ammonite (Fig. 5k), and lithified fossil wood fragments were also found (Fig. 5d). Bioturbation manifested as a diffuse mottling (*cf.* Fig. 4b) is present in some particular thin siltstone and/or possible tuff layers. In some of these beds the ichnogenera, *Chondrites*, *Planolites*, and/or *Palaeophycus* among other simple tubes, were recognized. Some of the inoceramid internal moulds show evidences of bioturbation (Fig. 5g, right valve of the specimen depicted in Fig. 5e, f).

Age and correlations: The recorded inoceramids are comparable with specimens found in association with Turonian ammonites, *Collignoniceras woolgari* (Mantell) and *Subprionocyclus* cf. *S. neptunei* (Geinitz), in Japan, North America, and Europe (see Woods 1912, Nagao and Matsumoto 1939, Noda 1975, Crame 1981, Elder and Box 1992, Walaszczyk 1992, Crampton 1996, Noda and Matsumoto 1998). The age of this paleofauna confirmes that the Arroyo Castorera Formation is younger than the Beauvoir and Hito XIX formations. The Arroyo Castorera Formation underlays the herein introduced Río Rodríguez Formation, a mudstone-dominated unit with more regularly interbeded siltstone to very fine-grained sandstone. The paleofauna allows the correlation of the Arroyo Castorera Formation with the lowermost part of the sections of the Cerro Matrero and Río García formations (Hünicken *et al.* 1975, Álvarez-Marrón *et al.* 1993) in Chile; and with the second part of the Cabeza de León Formation (Flores *et al.* 1973), the Lazian Stage (Natland *et al.* 1974) or the Middle Inoceramus in the subsurface of the Austral (Yrigoyen 1962, Biddle *et al.* 1986) and Malvinas (Yrigoyen 1989, Galeazzi 1996, 1998) basins. In Península Mitre, it also correlates with the lowest horizons of the Buen Suceso Strata (Olivero *et al.* 2007, Olivero and Malumián 2008) that bear a Turonian-Coniacian *Inoceramus* (=*Tethyoceramus*) *madagascariensis* paleofauna (Olivero and Medina 2001, Olivero *et al.* 2009).

Paleoenvironmental interpretation: The paleoenvironment attributed to this unit is deep-marine, dominated by fallout-from-suspension, based on its fine-grained sedimentary rock composition and on the *in situ* preservation of the fossil inoceramids with articulate shells. The sections with no fossils and no bioturbation that appear massive or faintly laminated are suggestive of accumulation during oxygen deficient (disoxic) to anoxic periods. Those sections alternate with thin beds that have biotur-

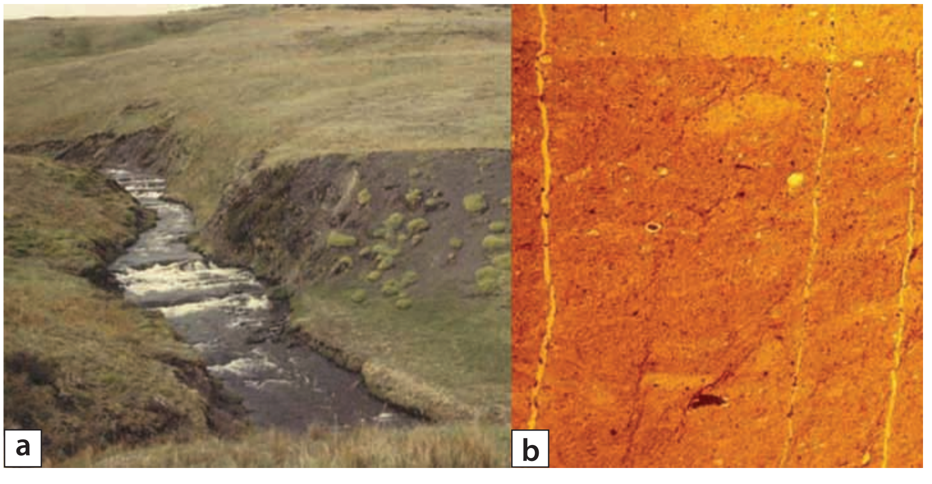

Figure 4: Arroyo Castorera Formation. a) The fossil locality at the valley of the Arroyo Castorera, where few scattered outcrops are typical for the unit (scale: creek ≤ 2 m wide). b) Thin section of a bioturbated mudstone sample to illustrate the characteristic fine-grained composition of the rocks of the unit (no scale).

bation, and/or marine invertebrate fossil remains that are assumed to indicate relatively richer oxygenation events.

Petrographic information did not allow the assessment of the sediment provenance in the Arroyo Castorera Formation. The presence of wood is the proof of an emerged area with forests that could be either, just an isolated island or, perhaps, part of the incipient Andean orogen in progressive uplift after the closure of the marginal basin. The sedimentary unit is interpreted to be constituted by distal turbiditic deposits accumulated in a deep-marine paleoenvironment that might comprise either the base-of-slope and/or the basin-floor. The inferences are consistent with the *in situ* paleofaunal occurrences, with the appearances at restricted horizons -in pulses- of fossils and ichnofossils, and with the subtle, but general, increase in the degree of bioturbation when compared with the Beauvoir Formation.

Río Rodríguez Formation (*nom. nov.*)

The Río Rodríguez Formation consists of a succession of mudstone with alternation of sharp based and normally graded beds of siltstone and very fine-grained sandstone.The best exposures with diagnostic inoceramids are along the Río Rodríguez. Prior to the discovery of fossils, these rocks were also included in the Beauvoir Formation. The herein introduced sedimentological and paleontological information, and the stratigraphic relationships enable to consider the Río Rodríguez beds as an independent unit, distinct from the previously described ones, as well as from rocks exposed further north (see Policarpo Formation).

Type locality and distribution: This unit is well represented north of the divide of Sierra de Beauvoir, near to the confluence of Río Rodríguez and Río Claro, south of the depression between Sierra de Beauvoir and Sierra de Apen (Fig. 2). To the north of Arroyo Castorera, along the water-stream that flows towards Río Mio (Fig. 2), and, precisely, in the small canyon of the lower Río Rodríguez valley there are extensive exposures of faulted and folded mudstone packages and alternating mudstone - very fine-grained sandstone successions (Fig. 6a-c). These beds correspond to the "unnamed strata" located to the south and roughly parallel to the Río Claro-Río Mio valley depression (Martinioni 1997, 2010, Martinioni and Olivero 2008).

Lithology: The succession comprises mainly normally graded siltstone to very fine-grained sandstone beds that pass upward into a relatively thicker mudstone portion. Beds are sharp based; some of them have an erosive lower contact. The average bed thicknesses fall within a range of 0.1 to 0.5 m (Fig. 6c-d). These deposits present a marked and characteristic recurrence of packages with coarsening and thickening upwards stratal arrangements (Fig. 6c), which is a clear distinction from the more homogeneous bedding features observed in the Beauvoir and Arroyo Castorera formations. As a whole, the Río Rodríguez Formation has more definite bedding and a slightly coarser average grain size than the older units herein described.

Stratigraphic relationships, contacts, and thickness; structural features: The contacts of the Río Rodríguez Formation were not observed, but it is inferred that their deposits are stratigraphically bracketed between the older Beauvoir and Arroyo Castorera formations, exposed to the south, and the younger Policarpo Formation (uppermost Cretaceous) that lacks inoceramids and outcrops mostly to the north of the Río Mio and Río Claro valleys (Fig. 2). Only a minimum thickness has been estimated for the unit, which adds up to ~300 m, according to the exposures in the lower Río Rodríguez valley. Because of the Quaternary and vegetation cover, as it is the case in the whole Sierra de Beauvoir, continuous outcrops are lacking, which, together with the tectonic disturbance, are against the construction of a single, columnar section of the sedimentary unit. In the southern outcrops area, where the Río Rodríguez flows from south to north, the unit presents open folds, and downstream, where the course of the river turns to the west, folds are tighter, of quasi-chevron type (*e.g.* Fig. 6a-b). Minor fractures with slikensides associated to mudstone beds and major reverse faults were observed. A north verging thrust fault with a southeast strike is inferred just north of this last part of the stream between Río Rodríguez and Río Claro valleys. Tectonic repetition of the stratigraphy produced by this reverse faulting is not discarded.

Paleontological content: In few locations some horizons with trace fossils were observed and only a short number of localities yielded fragments of bivalves. The fossil material is different from the previously mentioned, but their fragmentary nature allows for a provisional generic assignation only. Some inoceramids (Fig. 7a-h) are preliminarily attributed to *Cremnoceramus* spp. and related forms (including a posible *C. waltersdorfensis, cf.* Walaszczyk 1992). Only one of the collected inoceramid fragments, found in a location nearby Río Mio to the west-northwest of most of the other fossil localities, is of a different kind and could correspond to *Inoceramus andinus* Wilckens (Fig. 7i). The trace fossils *Chondrites* isp. and *Planolites* isp. are restricted to some mudstone beds.

Age and correlations: The possible presence of the inoceramid genus *Cremnoceramus*, and especially specimens attributable to *C. waltersdorfensis*, suggests a Coniacian age. The presence of a probable *Inoceramus andinus* might extend the age of the unit to the early Campanian, which is, so far, the youngest inoceramid record in Sierra de Beauvoir. In Península Mitre the material studied by Olivero and Medina (2001) contains other younger forms refered to the Santonian-Campanian, such as *Inoceramus* (*Platiceramus*) sp. and *Sphenoceramus* sp., which are not documented in the studied sector.

Despite the absence of visible contacts, based on the age of the fossils, and on the field relationships, the Río Rodríguez Formation follows the Arroyo Castorera Formation, and is followed by the uppermost Cretaceous, herein described, Policarpo Formation that incorporates progressively more sandstone, has an increased bioturbation degree, and lacks inoceramid bivalves (see "*Fangolitas del Cretácico Superior*", *i.e.* Upper Cretaceous Mudstones, in Martinioni *et al.* 1999a). In a broad sense, the age of the Río Rodríguez Formation is considered to cover from the Coniacian to the Campanian, thus the Buen Suceso Strata (Olivero and Medina 2001, Olivero *et al.* 2003, 2009,

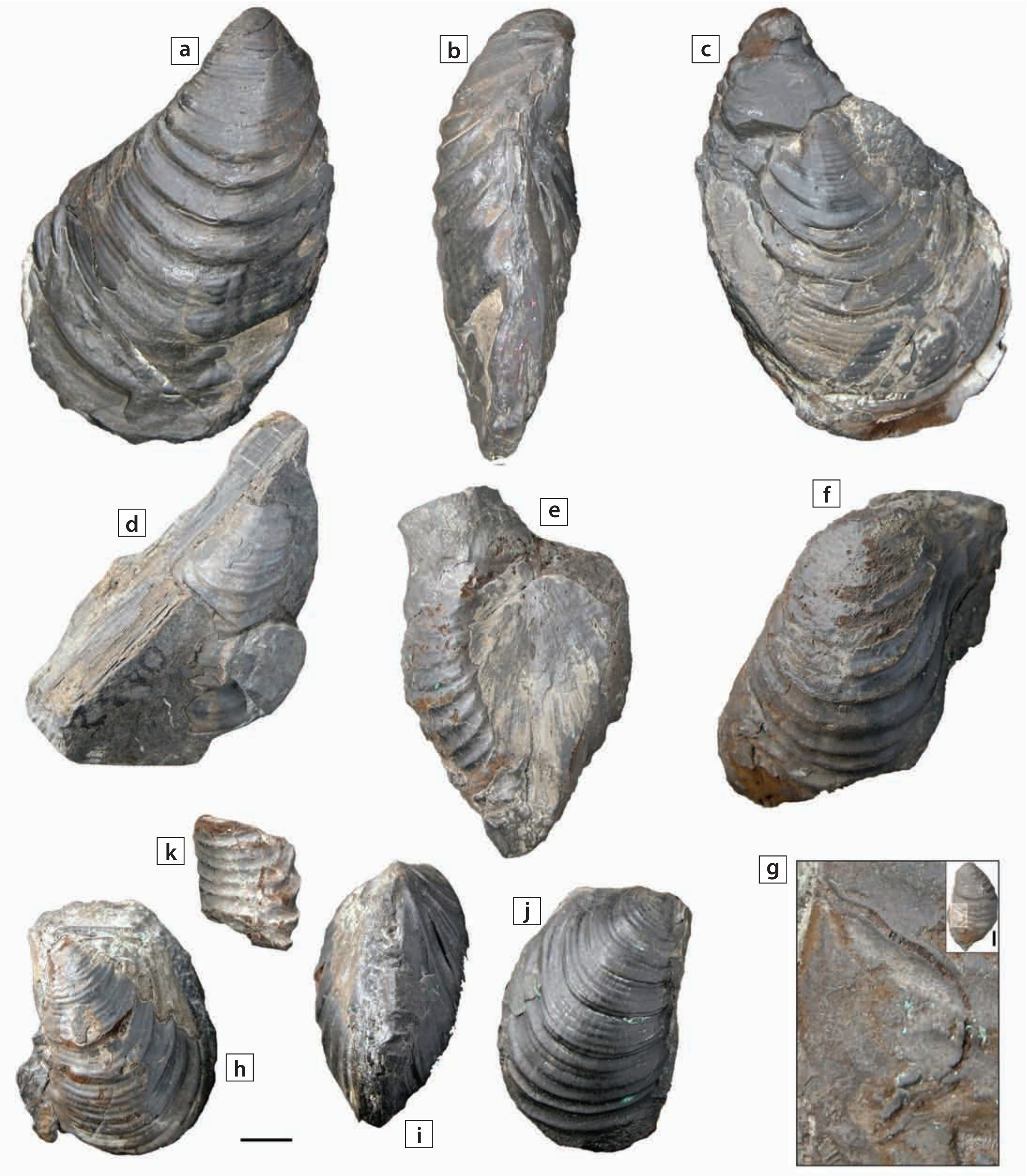

Figure 5: Arroyo Castorera Formation. a-c) Inoceramid attributable to the *Inoceramus hobetsensis* group of Nagao and Matsumoto 1939 (left valve; posterior view; right valve). d) *I.* sp. incrusted in fossilized wood. e-g) Inoceramid attributable to *I.* cf. *lamarcki* (anterior view; left valve; internal mould of right valve with bioturbation marks). h-j) Inoceramid attributable to the *I. hobetsensis* group (CADIC PI 211, left valve; posterior view; right valve). k) Heteromorph ammonite *indet*. (scale bars = 1 cm).

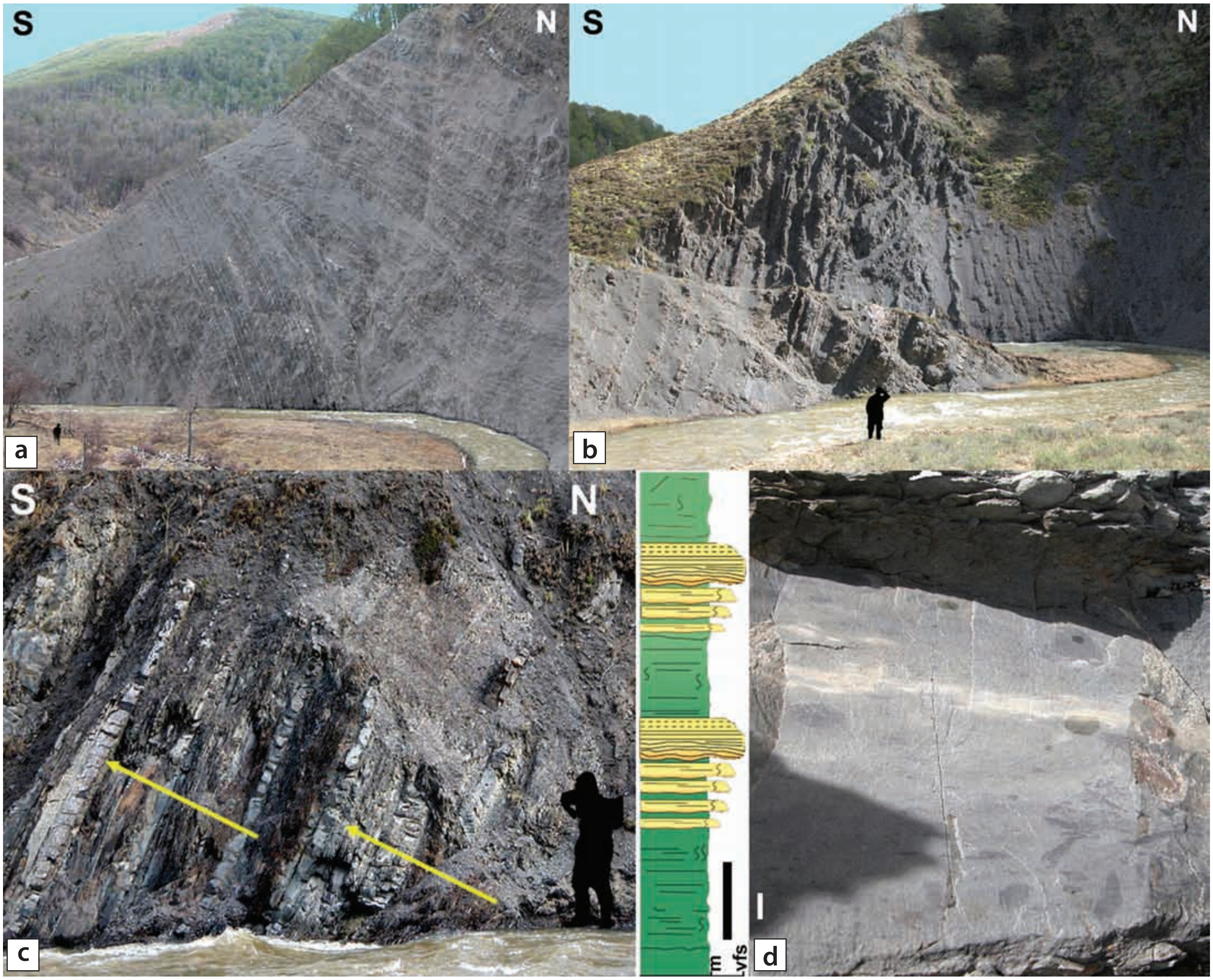

Figure 6: Río Rodríguez Formation. a, b) Two typical views of faulted and folded strata of the unit along the lower Río Rodríguez valley (persons for scale). **c)** Closer view of the bedding (person for scale), and a schematic section (left) of the coarsening upward cycles of silty mudstone (m) to very fine-grained sandstone (vfs), both variably bioturbated and faintly laminated (scale bar = 50 cm). d) Detail of a bioturbated mudstone bed (scale bar = 1 cm).

Olivero and Malumián 2008) of Península Mitre correlate with it, while the relation with Bahía Thetis Formation (Olivero *et al.* 2003, 2004) remains unsolved. The Río Rodríguez Formation correlates with the (inoceramid bearing) lower part of the Cerro Matrero and Río García formations that crops out in Chile (Hünicken *et al.* 1975, Hromic 1988, Macellari 1988a, b, Riccardi 1988), and, in the subsurface, partially with the second and with the third parts of the Cabeza de León Formation (Flores *et al.* 1973) in the Austral Basin or with the Upper Inoceramus (Biddle *et al.* 1986, Yrigoyen 1989, Galeazzi 1996, 1998) of Austral and Malvinas basins.

Paleoenvironmental interpretation: The upward coarsening-thickening stratal arrangement of internal cycles with graded beds, and dominant tabular bed geometry suggests the accumulation of prograding lobe successions in a deep-marine paleoenvironment. The prevailing sedimentary process is interpreted as distal turbiditic currents that were deposited at the base of the depositional slope and/or the basin-floor. No diagnostic sedimentary or petrographic elements enable to infer the sediment provenance or dispersal.

Policarpo Formation

The Policarpo Formation was formally established by Furque and Camacho (1949) for beds exposed at the Atlantic coast of Tierra del Fuego in Península Mitre (see Olivero *et al.* 2007). Equivalent sedimentites are extensively exposed in Sierra de Apen, to the northwest, and to the southeast of the mountain range; but particularly in the mountain called Cerro Fumando (Figs. 2, 8a-d). The unit includes the Upper Cretaceous mudstones informally described as "*Fangolitas del Cretácico Superior*" (Martinioni *et al.* 1999a) that gradually include higher proportions of sandstone (Fig. 8c) in both Cerro Fumando and Cerro Kooholjsh (Figs. 2, 8b, d). This transition from mudstone-dominant to sandstone-dominant strata is not observed in the continuous section of Cerro Apen that largely presents the mudstone-dominated part of the unit (Fig. 8a, c, e). In fact, the Policarpo Formation is constituted by a lower portion that is dominated by mudstone with abundant bioturbated calcareous concretions that is replaced up-section by a portion with a significantly higher amount of sandstone, up to its dominance (Fig. 8d). Hence, both portions are informally presented herein as mudstone- and sandstone-dominated members, respectively (Fig. 8c, d).

Type locality and distribution: This Formation can be traced mainly along the east-southeast oriented Río Mío and Río Claro valleys; it has also fairly continuous outcrops in Sierra de Apen, north of Río Mio. Although over wide areas this unit is hidden under Quaternary deposits and recent vegetation, it can be recognized from the international border with Chile at Cerro Kooholjsh, to the the outlet of Río Claro by the western reaches of Sierra de las Pinturas (Fig. 2). The outcrops and subcrops of Sierra de Apen and, specially, the Cerro Fumando are almost entirely constituted by rocks of this unit. In the northern hillside of Cerro Apen, highest mountain in the homonymous range, the continuous exposures have a tectonic contact at its base and involve a composite continuous section up to its upper contact, marked by the unconformity that separates it from the younger Cerro Apen Beds (Fig. 8a, Martinioni 2010; see also Martinioni *et al.* 1999a).

Lithology: This unit is markedly different from those typical units of Sierra de Beauvoir made up almost exclusively of mudstone. The mudstone-dominated member of Policarpo Formation is constituted mainly by mudstone beds with fine-to coarse-grained (sometimes conglomeratic) sandstone beds. The beds do not exceed 2 m in thickness and are dominantly tabular at the scale of the outcrops (Fig. 8c), except for a few, small scale, lenticular ones. The calcareous concretions are a characteristic feature of the unit, usually ellipsoidal to subspheric with variable sizes up to an average diameter of 0.30 m, grey to light brownish grey, commonly preserving trace fossils. Although frequent, the bioturbation in the mudstone facies of this unit has a degree of variability that ranges between massive or laminated mudstone without discernible traces and mudstone with moderate to intense bioturbation (Fig. 8c). The portions constituted of massive to laminated mudstone are interbedded with sandstone. These sandstone beds are massive (some with a subtle normal gradation), parallel laminated and/or cross-laminated; occasionally, they have fluid-escape structures. Some medium-grained sandstone beds have convolute bedding, while others have only some internal centi- to decimetre scale sin-sedimentary deformation and load casts at their lower contacts. Several of these sandstone beds have scour marks; in a partial section of the unit by the Río Claro valley, south of the main buildings of the Estancia Río Claro, flute casts point to the east and the northeast.

The sections with a more homogeneous mudstone succession are constituted mainly by clayey siltstone up to very fine-grained muddy sandstone beds with a variable degree of bioturbation, where contacts are somewhat blurry and thicknesses average one meter (Fig. 8c). Beds appear massive, when bioturbation obliterates the internal sedimentary structures, in part visible as a subtle lamination, and, exceptionally, cross-lamination. In the upper portion of the mudstone-dominated member of the Policarpo Formation there is an increase of up to 0.50 m thick tabular beds (at the scale of the outcrops) of fine-grained sandstone with sharp erosive lower contacts. Internally those sandstone beds have a lower massive portion, followed up by parallel lamination and cross-lamination (Bouma $T_{a\text{-}c}$ divisions); convolute lamination and stratification is frequent. The paleocurrent indicators in one of the cross-laminated beds are consistently northwest directed (1SN1, Fig. 8e).

An averaged composition of total quartz, plagioclase and lithic fragments was obtained from ten sandstone samples of the 700 m thick mudstone-dominated member section in Cerro Apen (Fig. 8a, e). Clastic composition of the sandstone is constituted by quartz (~17%), lithic fragments (~63%, a majority of metamorphic and acidic volcanic rock fragments, and a minority of andesitic volcanic lithic fragments), and feldspar (~20%, mainly plagioclase); secondarily it includes a lesser proportion of biotite, epidote, glauconite, opaque minerals, among other minor components. The coarser, microscopically discernible, clastic fraction of the mudstone samples has a similar composition.

The sandstone-dominated member of the Policarpo Formation is chiefly constituted by fine- to medium-grained sandstone beds that have an interlayering of siltstone and mudstone (Fig. 8d). This coarser grained part of the unit, which in Cerro Fumando appears transitionally above the mudstone member, is not present in the more continuous section of Cerro Apen, where the top of the unit, still dominated by mudstone beds, appears erosively truncated by the Cerro Apen Beds (Fig. 8a, Martinioni *et al.* 1999a, Martinioni 2010). This enables to suggest at least two alternatives concerning the absence of the sandstone-dominated member at Cerro Apen: a) it laterally grades into sandy mudstone, which prevails there, or b) it has been eroded and wiped away, and then covered by the younger Cerro Apen Beds.

At Cerro Kooholjsh (Fig. 2) the sandstone-dominated member of the Policarpo Formation has an alternance between fine-grained sandstone and siltstone-mudstone with very little variations (*cf.* Fig. 8d, section). Bed thicknesses range between 0.20 and 0.70 m, although in some more homogeneous parts of the section some bed amalgamation was observed in both, sandstone and siltsone beds. Most of the beds are massive, but some sandstone beds are parallel laminated or have small scale cross-lamination, whereas siltstone-mudstone beds, although regularly massive, can have a blurry to delicate parallel lamination. Beds are tabular at the scale of the outcrops. The lower contacts of the sandstone beds are sharp, weakly erosive, and the upper contacts, when covered by mudstone, appear sharp and flat. In contrast with the average

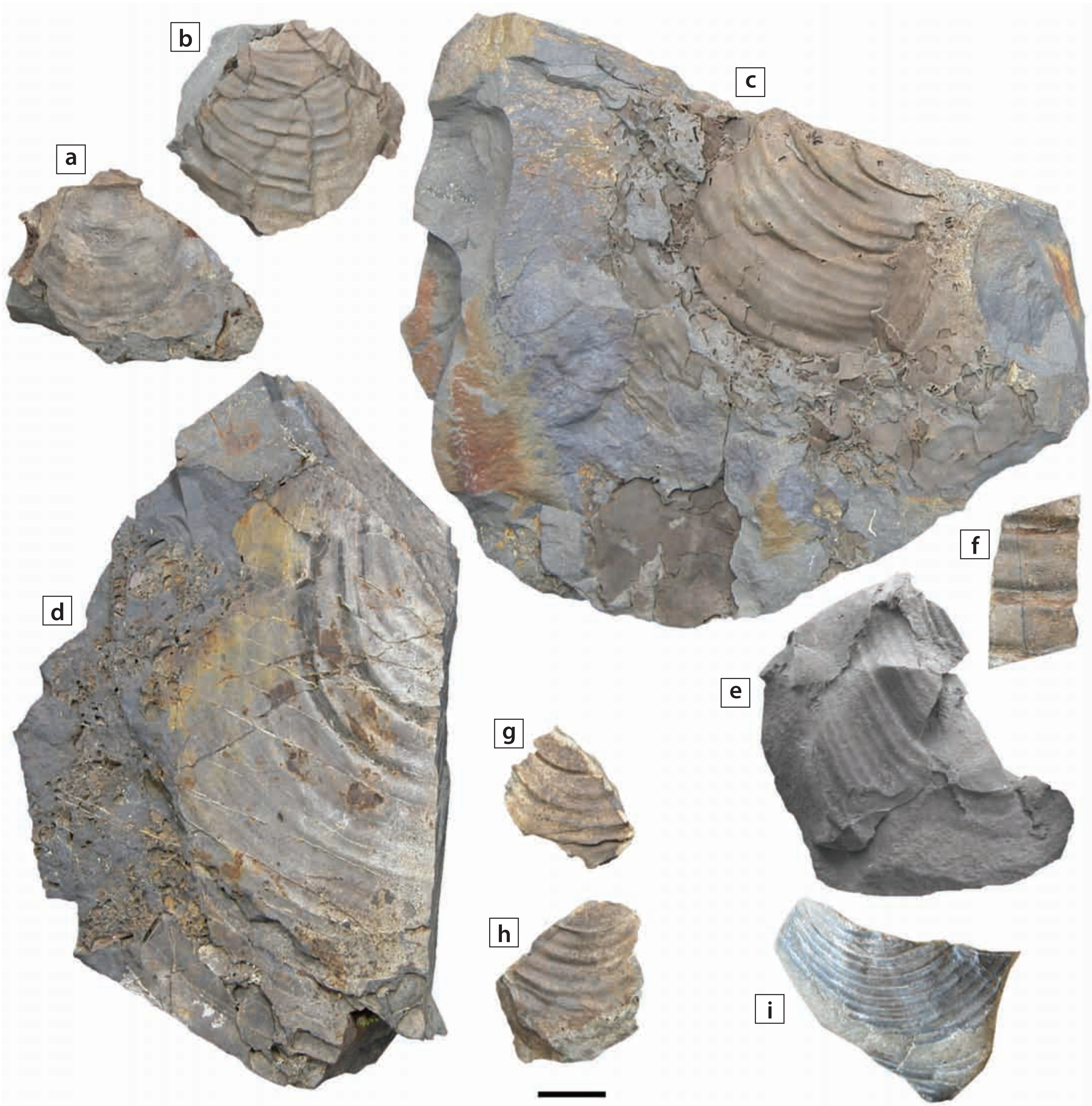

Figure 7: Río Rodríguez Formation. a-h) Inoceramid fragments, preliminarily ascribed to the genus *Cremnoceramus* (g and h are casts of each other). i) Fragment of a probable *Inoceramus andinus* (scale bar = 1 cm).

for the sandstone samples of the mudstone-dominated member (see Fig. 8e), the clastic composition of the sandstone-dominated member is constituted by a lower proportion of total quartz with an abundant amount of plagioclase and total lithic fragments, according to one sample analyzed by Torres Carbonell (2010; see sample 386-2: Q ~2.6%, P ~42.6%, Lt ~54.8%). This last composition is comparable only with some of the upper sandstone samples of the mudstone-dominated member of the Policarpo Formation in Cerro Apen (Fig. 8d, e; *e.g.* 3SN20: Q ~7%, P ~45.5%, Lt ~47.5%), were the lithic fragments have a higher proportion of andesitic volcanics. A sample from the lower levels of the section at Cerro Kooholjsh (1CK6) has a quartz-

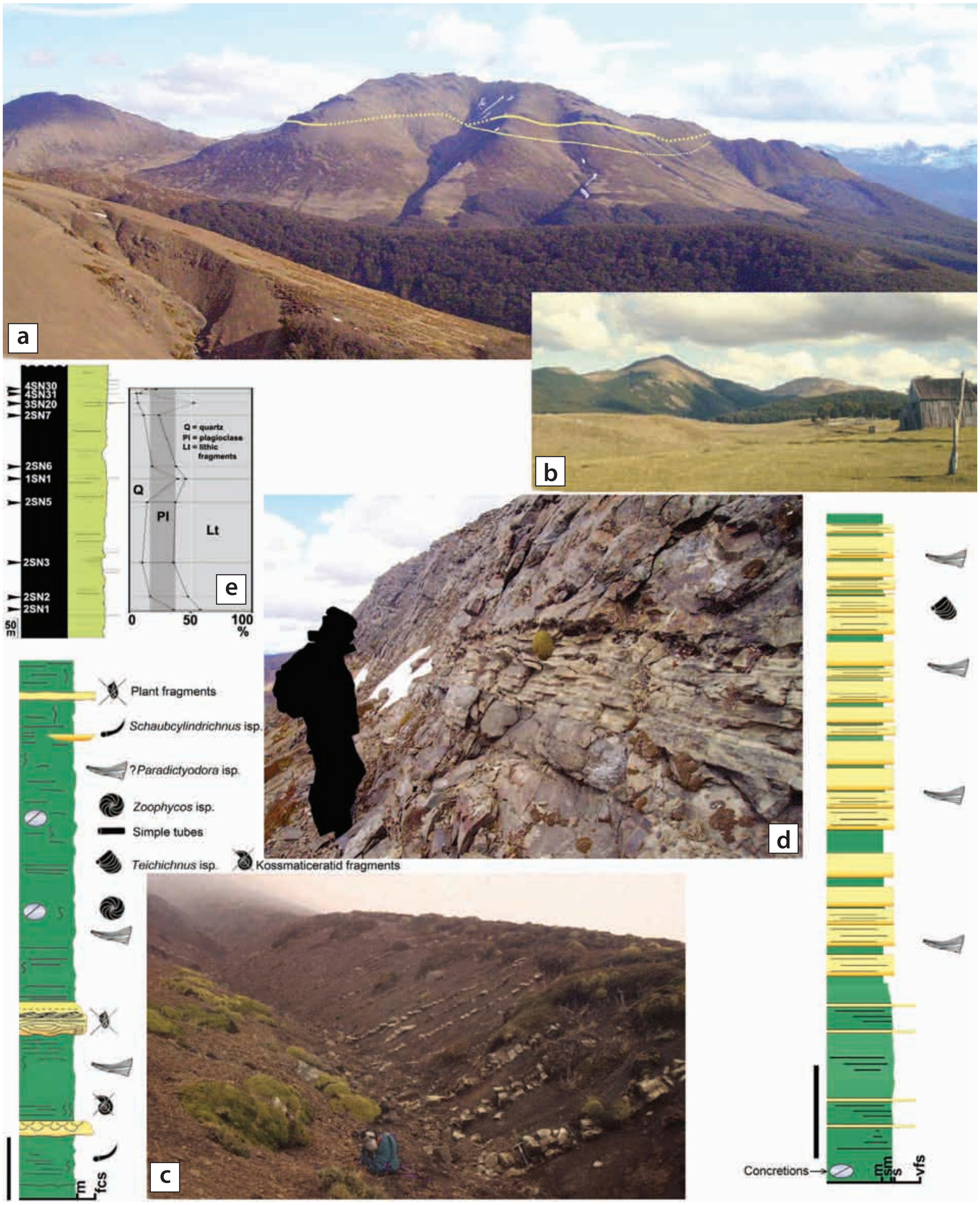

Figure 8: Policarpo Formation. a) Continuous section at Cerro Apen: the lower line marks the upper contact of the unit, covered by the overlaying Paleocene Cerro Apen Beds displaying the two members (the upper line indicates the contact between them; Martinioni 2010; see also Martinioni *et al.* 1999a). b) View to the SSE of Cerro Fumando (foreground) and Cerro Apen (background) in Sierra de Apen. c and d) General aspect and idealized sections of the two informal members (scale bars = 2 m); the mudstone-dominated member (c) with the typical intercalations of tabular sandstone beds in Cerro Apen (photo and section), and the sandstone-dominated member (d) in Cerro Fumando (photo) and in Cerro Kooholjsh (section) (m, mudstone; sm, silty mudstone; s, siltstone; vfs, very fine-grained sandstone; and fcs, fine- to coarse-grained sandstone; see the text for sedimentological characteristics). e) Clastic composition of ten representative samples over *ca.* 700 m of stratigraphic section of the mudstone-dominated member at Cerro Apen with average values of quartz (17%), plagioclase (20%), and total lithics (63%).

plagioclase-lithic fragments ratio of 14%-10%-76%, respectively, that is roughly close to the average observed for the unit.

Stratigraphic relationships, contacts, and thickness; structural features: The Policarpo Formation is repeated by north verging reverse faults that constitute part of a system of imbricate thrust sheets (Fig. 2; Martinioni *et al.* 1999a, Martinioni 2010). Without a specific focus on the detailed structural analysis, which is being performed by co-workers of the Laboratorio de Geología Andina (Torres Carbonell 2010; see also Torres Carbonell *et al.* 2009), the unit was studied in more detail attending to stratigraphic, sedimentological, and paleontological characteristics in the less disturbed homoclinal sections available on the up-thrusted sheets (*e.g.* Fig. 8a). In Sierra de Apen, the average structural deformation that affects these strata is moderate to low, and certainly not as intense as that observed in the preceding units. The stratification strike varies between east and southeast and the dip is variable between ~85º, at the base, and ~50º, to the top of the section, but consistent to the south, with ~1,000 m of minimum thickness including both informal members. No exposure of the basal contact was observed and the top of the unit appears truncated by an erosional surface (Fig. 8a; Martinioni *et al.* 1999a, Martinioni 2010).

The two informal members of the overlaying Cerro Apen Beds rest on their respective unconformities on top of the mudstone-dominated member of Policarpo Formation at the northern hillslope of Cerro Apen (Fig. 8a; Martinioni 2010). The sandstone-dominated member of the Policarpo Formation, with a thickness of less than 20 m in Cerro Fumando and close to 100 m in Cerro Kooholjsh, is not present in the section of Cerro Apen. There the sandstone could have been eroded or simply did not accummulate, as a lateral variation of the unit preserving just mudstone-dominated facies. In the neighborhood of Cerro Kooholjsh these beds are exposed between imbricate north verging reverse faults with an approximate east strike; the minimum thickness enclosed between these thrust sheets is ~400 meters. The succession in this area of low hills follows these structures and its stratal arrangement enables to infer open folds or a gentle warping associated to the faults. North oriented striations on north verging fault and bedding planes and the roughly eastern bedding strike with a southern dip of the strata agree with this. In Quebrada de Apen, a deep incised gorge of the Río Mio valley between Sierra de Beauvoir and Sierra de Apen (Fig. 2), the succession is cut across by subvertical clastic dykes of a sandy to fine conglomerate composition, with a northern strike. Along the Río Claro valley, to the east, the unit is affected by highly tectonized and sheared fault zones. East-west oriented horizontal striations, suggesting strike-slip displacement, were observed associated with the north verging reverse fault surfaces close to the outlet of Río Claro (Fig. 2), which seem to form part of subsidiary structures of the Fagnano Transform System, the main crustal feature that marks the boundary between the South American and Scotia plates (Figs. 1, 2).

Paleontological content: Several marine fossil invertebrates were recorded in the lower mudstone-dominated member of Policarpo Formation, including fragments of diagnostic ammonites (Fig. 9a-h). Additionally, fossil bivalves, *e.g.* internal mould of *Panopea* sp., regular echinoids, rests of belemnites, undeterminable gastropods, fossil shark vertebral disks, and minor rests of fossil plants (Fig. 9i-n). Ammonite genera include fragments of *Grossouvrites* and *Maorites*; a fragment of a crushed internal mould of *Diplomoceras* (Fig. 9a-c, g-h); and fragments of Gaudryceratidae and Phylloceratidae (Fig. 9e, f). No fossil invertebrates were found in the sandstone-dominated member of the unit. However, at Estancia Marina, nearby Cerro Kooholjsh (Fig. 2), a single specimen of the trigonid *Pterotrigonia* sp. probably from these beds had been previously recorded (E. B. Olivero, unpublished information).

The massive or laminated mudstone beds have low intensity of bioturbation with undeterminable trace fossils. The remaining beds of the mudstone-dominated member and portions of the sandstone-dominated member have a moderate to intense bioturbation with some mottled sectors of poorly recognizable trace fossils and some better preserved *Chondrites* isp., *Teichichnus* isp., *Zoophycos* isp., *Planolites* isp., *Ophiomorpha* isp., *Thalassinoides* isp., *Palaeophycus* isp., *Schaubcylindrichnus* isp., simple tubes, "J" shaped tubes with spreiten, and subhorizontal tubes with spreiten (Fig. 10). Many of these traces are preserved in characteristic calcareous concretions. In particular, the forms of *Zoophycos* show very systematic sediment utilization strategies (Fig. 10a-d; see Martinioni *et al.* 2004), if compared with older forms. According to Seilacher (1986), the elaborate pattern is attributed to the evolutionary behavior of the trace producers in order to adapt to increasingly deeper marine environments.

Undeterminable foraminifera were only observed in thin sections. Samples of the mudstone-dominated member in the Cerro Apen section (2SN1, 4SN29, 4SN28; Fig. 8e; see Martinioni *et al.* 1999a) yielded a palynological assemblage (Fig. 11), composed of the *Manumiella* spp. complex, *Operculodinium* cf. *azcaratei*, some specimens of the *Fibrocysta-Exochosphaeridium* complex, and *Palaeocystodinium granulatum*; where also an *Azolla* sp. massula (a freshwater pteridophyte) was found, among other poorly preserved undetermined forms. A redeposited specimen of the Albian-Cenomanian genus *Endoceratium* was discovered in sample 4SN29 (Fig. 8e, adjacent to 4SN30). A poorly preserved palynological assemblage was recovered from three samples of the sandstone-dominated member of Policarpo Formation in the Cerro Kooholjsh section (K2, K8, K17), with *Paleocystodinium* sp. in two of them (K2 and K8, in this last sample *Oligosphaeridium* sp. is also present); and a more abundant, poorly preserved, and undeterminable cysts assemblage in the third (K17).

Age and correlations: The approximately 700 m of the mudstone-dominated member of Policarpo Formation cropping out in Cerro Apen (Figs. 2, 8a, c, e) contains the *Manumiella* spp. complex, *Operculodinium* cf. *azcaratei*, specimens of the *Fibrocysta-Exochosphaeridium* complex, and *Palaeocystodinium granulatum* (Martinioni *et al.* 1999a). This palynological assemblage can be compared to that of the late Maastrichtian levels of the López de Bertodano Formation (Rinaldi *et al.* 1978, Rinaldi 1982) in Seymour (Marambio) Island (Palamarczuk *et al.* 1984, Askin 1988). The marine fossil invertebrates, specially the associated kossmaticeratids (*Maorites* and *Grossouvrites*) together with *Diplomoceras*, suggest a Maastrichtian age for the lower mudstone-dominated member of the unit by comparison with the fauna preserved in successions of James Ross Basin, Antarctica (MG Sequence, Olivero and Medina 2000; see also Olivero *et al.* 1992, 1999b, Olivero 2012). Similar invertebrate fossils are recorded in the Policarpo Formation on the Atlantic coast of Tierra del Fuego in Península Mitre (Olivero *et al.* 2002, 2003, 2009). This last locality comprises outcrops that are disconnected from the other sedimentites of Policarpo Formation, however, it is suggested that this succession, based on the palynological dating, involves a transition between the lower mudstone-dominated and the upper sandstone-dominated members of the formation, as an equivalent to the transition between the Río García-Cerro Matrero and Cerro Cuchilla formations in Chile (*cf.* Riccardi 1988; see also Hünicken *et al.* 1975, Álvarez-Marrón *et al.* 1993, Klepeis 1994, and the references therein).

Since no lower contact was seen exposed, the lowermost portions of the Policarpo Formation could be older than Maastrichtian. However, the absence of inoceramid bivalves in beds younger than Campanian-early Maastrichtian (*s.l.*) is consistent with the facts and the evaluation pointed out regarding the extinction of these bivalves in the Fuegian Andes and surroundings (Olivero *et al.* 2003, 2009). This dissapearence was also analyzed for this region in terms of the relationship it has with the variation in the intensity of bioturbation (Olivero *et al.* 2004, 2009). The bioturbation is more intense in the Maastrichtian sedimentites (Olivero *et al.* 2003; see also Martinioni *et al.* 1999a, Martinioni and Olivero 2008), which could be explained by the change in oceanic water conditions with the influence of Antarctic cold waters as previously discussed by several authors (Olivero *et al.* 2003, 2004; see also Crame 1983, Zinsmeister and Feldmann 1996, Olivero and Medina 2000; and the references therein). This fact also allows for the explanation of the diacronism in the extinction of the *Inoceramus* group at a global scale, which vanished earlier in high Antarctic and subantarctic latitudes (earliest Late Campanian, Olivero and Medina 2000, fig. 2; see also Crame 1985, Marenssi *et al.* 1992, Crame *et al.* 1996, Zinsmeister and Feldmann

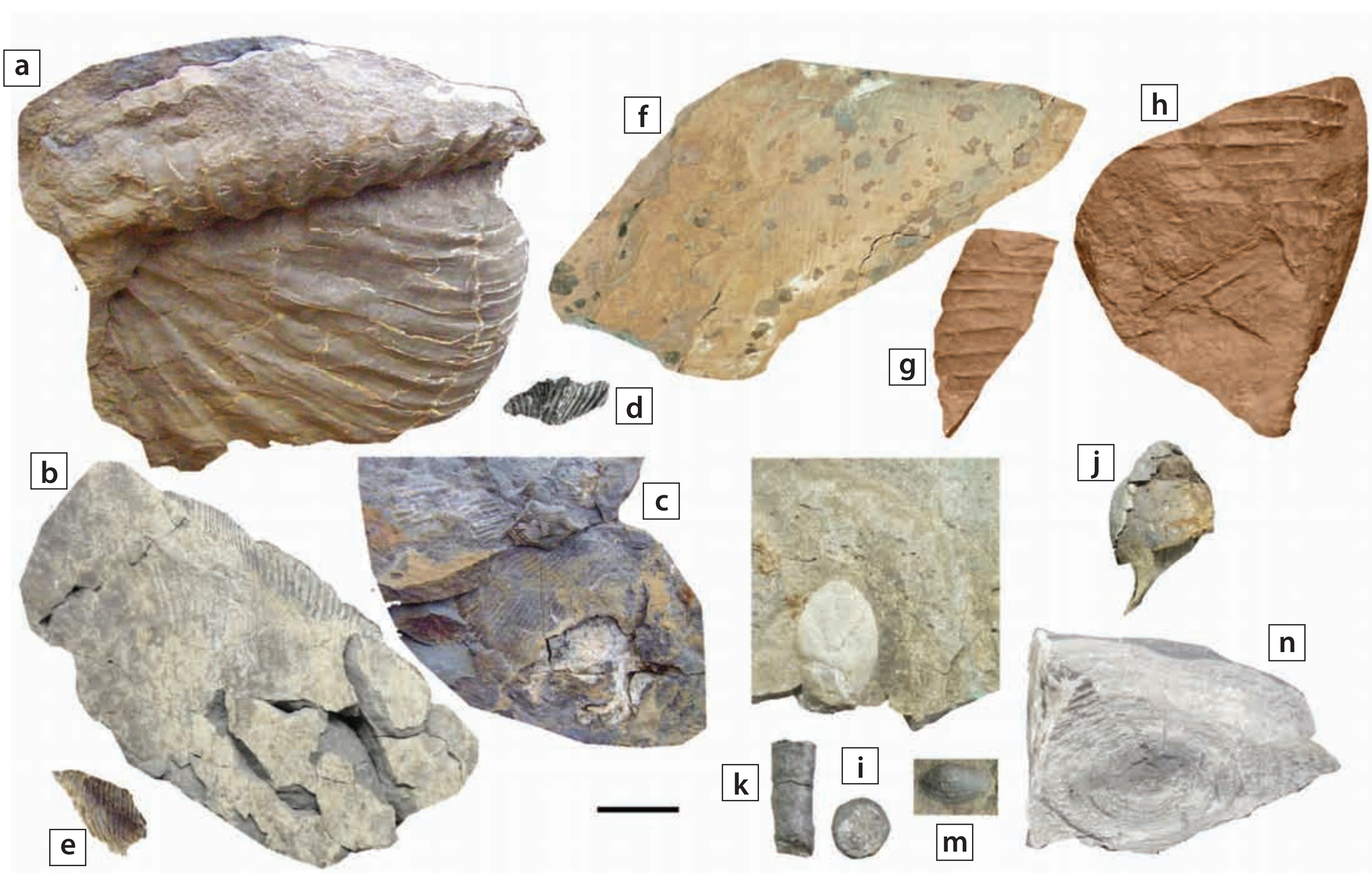

Figure 9: Policarpo Formation, mudstone-dominated member. *Grossouvrites* sp. (a), *Maorites* sp. (b-c), and Kossmaticeratidae indet. (d); Gaudryceratidae indet. (e); Phylloceratidae indet. (f) (all internal mould fragments; and partial shell preservation in d and f). *Diplomoceras* sp. (g-h; two views, same specimen; collapsed internal mould fragment). Irregular equinoid (i). Gastropoda indet. (j, internal mould). Belemnite fragment (k-l; two views, same specimen). *Panopea* sp. (m; internal mould). Shark vertebral disc (n). Localities: Cerro Fumando: a,c,d,g,h,m; Río Claro lower valley: b,i; Quebrada de Apen: f,j,k-l,n; Cerro Apen: e (scale = 1 cm valid for k-l, m; f x 0.25; rest x 0.5).

1996, Crame and Luther 1997, Olivero *et al.* 2003), and later, and almost massively, around the early-late Maastrichtian boundary in low latitudes (MacLeod *et al.* 1996; and the references therein).

The Policarpo Formation is younger than the Río Rodríguez Formation, although there is no information concerning their contact relationships. A sharp unconformity at the base of the Cerro Apen Beds marks the upper contact of the Policarpo Formation (Fig. 8a; Martinioni *et al.* 1999a, Martinioni 2010). With exposures in the interior of the island and north of the Fagnano Transform System, the Policarpo Formation is the tectonically displaced extension of the outcrops of Peninsula Mitre, south of the sinistral strike-slip major fault (Torres Carbonell *et al.* 2008; see also Olivero and Malumian 1999, Olivero *et al.* 1999a, 2002, 2003, 2007, Olivero 2002). These age equivalent sedimentary rocks of the two geographic domains of the island have an averaged similar petrographic composition (Fig. 8e; compare with data in Olivero 2002). However, it is worth to note that in the east the proportion of quartz seems to be slightly lower and that of plagioclase higher, with a predominance of lithics of andesitic volcanics (Olivero 2002, Olivero *et al.* 2002, 2003), which was not generally observed in central Tierra del Fuego. In Sierra de Apen the lower horizons of the Policarpo Formation could correlate with the late Campanian-early Maastrichtian? Bahía Thetis Formation of Península Mitre that has a higher proportion of quartz and a lower proportion of lithic volcanics than the Policarpo Formation (Olivero *et al.* 2003).

The Policarpo Formation has typical Upper Cretaceous *Zoophycos* ispp. (Fig. 10a-d). In Chile, the upper part of the Río García and Cerro Matrero formations (without record of inoceramids; Hünicken *et al.* 1975; see also Hromic 1988, Macellari 1988a, Riccardi 1988, Klepeis 1994) is a partial equivalent of Policarpo Formation. Cerro Cuchilla Formation, which covers transitionally (Riccardi 1988, Table17) the above mentioned Chilean units, could be related to the upper sandstone-dominated member of Policarpo Formation. In the subsurface of Austral Basin the equivalent units are the succession of the Arcillas Fragmentosas (upper part of Cabeza de León Formation) and the lower part of the Zona Glauconítica (Flores *et al.* 1973, Natland *et al.* 1974, Biddle *et al.* 1986, Robbiano *et al.* 1996), *i.e.* partially corresponding to the succession of the Riescoian-Germanian local stages of Natland *et al.* (1974). In Malvinas Basin it is partly equivalent with the upper part of the Upper Inoceramus and the lower part of the Zona Glauconítica (Yrigoyen 1989, Galeazzi 1996, 1998).

At an intercontinental scale, there is a good correlation with the upper part of López de Bertodano Formation (Maastrichtian-Danian), Seymour Island, Antarctica (Palamarczuk 1982, Palamarczuk *et al.* 1984, Askin 1988). In the Chilean Magallanes Province, to the northwest of the study area, palinological data from the well El Ganso Nº 1 record an important thickness of Maastrichtian sedimentites with evidence

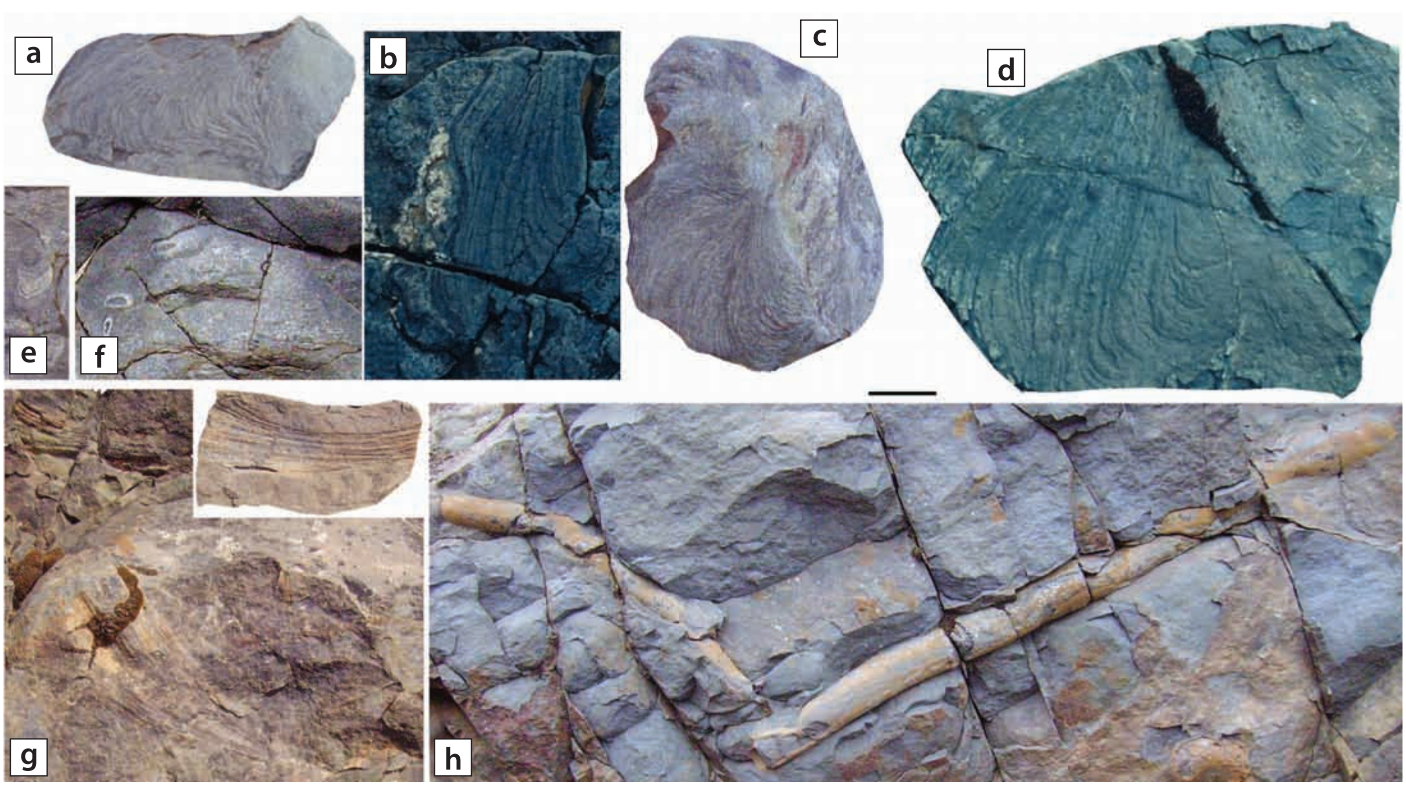

Figure 10: Policarpo Formation, mudstone-dominated member. *Zoophycos* isp. (a-d, plan view). Undetermined teichichnid (e, vertical view). *Schaubcylindrichnus* isp. (f). Possible *Paradictyodora* isp. (g, vertical view). *Thalassinoides* isp. (h). Localities: Sierra de Apen: a,c,e,f,h; Bahía Guanaco, Lago Fagnano: b,d; (scale = 1 cm valid for f; a-d,f,h x 0.25; e x 0.5; detail in g x 0.2).

of the passage to the Danian (Troncoso and Doubinger 1978). The compositional similarity of the dinocysts of these deposits with the groups of species herein described is very small, which raises some paleobiogeographic questions. The assemblage of *Areoligera senonensis* and related species, characteristic of the late Maastrichtian in Neuquina Basin (Palamarczuk 2004), is also present for that age in the well El Ganso Nº 1. This assemblage was not identified further south, being absent in the Maastrichtian of Tierra del Fuego and Antarctica (Martinioni *et al.* 1999a). Consequently, there is a difference in the assemblages concerning the geographic distribution of the Maastrichtian and Danian dinocysts to the north of the mentioned well location, even if other records of localities in Patagonia are compared with those of Sierra de Apen and Antarctica (Palamarczuk *et al.* 1998). An explanation could be based on the possible existence of a latitudinal provincialism; however, it remains unsolved why this difference even persists between two areas that are relatively close, like the well El Ganso Nº 1 and Sierra de Apen, having dissimilar associations at the southern end of the American continent (Palamarczuk *et al.* 1998).

Paleoenvironmental interpretation: The macro- and micropaleontological data together with the sedimentological characteristics indicate a marine origin for the Policarpo Formation. Some elements, like the prevailing fine-grained epiclastic sedimentites, the relatively poor, marine invertebrate fossil association, and the recurrent intercalation of graded tabular sandstone beds with a general coarsening-thickening upward trend are interpreted as sedimentation in an environment at a depth below the wave base level with occurrence of density currents. The density flows might have derived from emerged nearby areas, according to the presence of fossil plant remains and fresh water palynomorphs. The general environmental energy and/or oxygenation conditions are interpreted to have fluctuated during the deposition of these beds, since the trace fossils within the mudstone-dominated member are abundant in some horizons of the unit in contrast with portions of massive or laminated black mudstone with almost no bioturbation or without it.

Paleocurrent indicators based on cross-lamination and flute casts point to the northwest, to the northeast, and to the east, depending on the localities (Martinioni *et al.* 1999a, Martinioni 2010). The clastic composition of the sandstone of the whole Policarpo Formation, *i.e.* of sandstone beds from both members, suggests that the provenance of the sediments derived mainly from the erosion of older units, like Lemaire and Beauvoir/Yahgan formations (Upper Jurassic - Lower Cretaceous) that might have been exhumed to the south and west, according to the paleocurrent dispersal. The subtle compositional difference between the Policarpo Formation's sandstone petrographic samples of Sierra de Apen (Fig. 8e) and those with a slightly higher plagioclase content and a predominance of andesitic volcanic lithic fragments of Península Mitre (Olivero 2002), enables to speculate that the later could have accumulated closer to major emission centres of volcanic and pyroclastic material than the those in Sierra de Apen, since the principal components are present in both units. The occurrence of the characteristic Albian-Cenomanian palynomorph *Endoceratium* in association with the Maastrichtian dinocysts assemblage of the Policarpo Formation adds evidence to the age (and provenance) of the resedimented components of the unit (Martinioni *et al.* 1999a). The succession of Policarpo Formation has a gradual increase of sandstone intercalations with $T_{a\text{-}c}$ Bouma divisions and a general coarsening-thickenning upwards trend that is interpreted as prograding turbiditic lobe deposits, generated after incipent and progressive orogenic uplift pulses in a deep-marine ramp system.

CONCLUDING REMARKS

In summary, the geological and sedimentological observations in the marine, mudstone-dominated, Cretaceous units exposed north of Lago Fagnano, as well as their body and trace fossils, the biostratigraphic information, some isotopic dates of related igneous rocks, the preliminary structural observations, and the evaluation of the stratigraphic relationships among them, allowed for the construction of the first, fairly complete stratigraphic column of the Cretaceous in the area (Table1, Fig. 2). Thus, the mudstone-dominated succession of Sierra de Beauvoir can be grouped in two distinct tectono-stratigraphic packages (*cf.* Martinioni 2010), being represented at least by four lithostratigraphic units (Table1; Figs. 2, 12). The older and more deformed unit is the Beauvoir Formation that is largely mud-rock dominated with a subtle metamorphic imprint. The younger package, involving the Arroyo Castorera, Río Rodríguez and Policarpo formations, is less deformed, though folded and faulted, and has a gradual increase in coarser grained constituents towards the upper unit, becoming sandy, and even conglomeratic, at the youngest Cretaceous horizons (Fig. 12; see Martinioni *et al.* 1999a, Martinioni 2010).

Cretaceous Stratigraphic evolution of the Fuegian Andes north of Lago Fagnano

Lower stratigraphic package: The Beauvoir Formation (Aptian-Albian *s.s.*) correlates in Tierra del Fuego with the Yahgan Formation to the south and with the Hito XIX Formation to the north. The horizons of the Beauvoir Formation that contain *Aucellina euglypha* (Olivero and Medina 2001) crop out disconnected to the east in Cerro Heuhuepen, south of the Fagnano Transform System (Fig. 1). If restored to the position prior to the Cenozoic sinistral displacement along the main Fagnano fault of *ca*. 50 km (Torres Carbonell *et al.* 2008), these beds of the Beauvoir Formation in Cerro Heuhuepen might have been adjacent to its counterpart of Sierra de Beauvoir between the present positions of Cerro Kranck and Bahía Guanaco (Fig. 2). In an idealized S-N transect, three localities involving parts of the lower package (Fig. 12, Lower Cretaceous; Aptian-Albian) appear now separated by distances of approximately 40 km from each other (Canal Beagle, Sierra de Beauvoir, and Hito XIX in Fig. 1b). The southern position represented by the Yahgan Formation (Fig. 12, Y) is located between Canal Beagle and Lago Fagnano, and corresponds to the domain of the deep axis of the marginal basin (Olivero and Martinioni 1996a, b, 2001, and references therein). There, the sedimentation continued until the latest Early Cretaceous in the deep-marine trough setting according to the presence of a diagnostic Late Albian marine fossil invertebrate assemblage of *Inoceramus carsoni* and *Actinoceramus concentricus* in the Yahgan Formation (Olivero and Martinioni 1996a). The central composite column is constituted by the Beauvoir Formation (Fig. 12, B), *i.e.* the lower stratigraphic package of Sierra de Beauvoir focused herein with the addition of the exposures recorded for the unit in Cerro Heuhuepen (*cf.* Olivero and Medina 2001).

The Beauvoir Formation is also host rock of two plutonic bodies, at Cerro Kranck and Cerro Heuhuepen, and igneous dykes, at Cerro Rodríguez (Olivero *et al.* 1999a, 2007; see also Martinioni *et al.* 1999b, González Guillot *et al.* 2012). The later cut across deformed strata of the Beauvoir Formation with marine Aptian-Albian fossils suggesting a minimum pre-latest Albian age for part of these sedimentary rocks (Martinioni *et al.* 1999b), and the igneous intrusions at Cerro Kranck, with a late Cenomanian age (Cerredo *et al.* 2011a), and at Cerro Heuhuepen, with an oldest early Turonian age (Acevedo *et al.* 2000), both postdate the deposition of the youngest horizons ascribed to the Beauvoir Formation (Late Albian; Olivero and Medina 2001). These plutonic intrusions constrain the onset of deformation and folding of these beds, which might thus be attributable to initial stages of the closure and inversion of the marginal basin during the earliest Late Cretaceous.

The northern position represents the stratigraphic section of the Hito XIX Formation (Fig. 12, H) exhumed by the Vicuña thrust sheet, with Lower Cretaceous beds thrusted over younger rocks of the Upper Cretaceous and Paleogene (Álvarez-Marrón *et al.* 1993, Martinioni *et al.* 1998). At this last position there is an increase of sandstone and the presence of marls, as well as a larger amount of marine invertebrate fossil fauna, with diagnostic bivalves of the genus *Aucellina* also recorded in the two other locations. A schematic S-N block-diagram illustrates the suggested relative positions of the three units for the late Early Cretaceous (Aptian-Albian, Fig. 12; see also Fig. 4 in Olivero and Martinioni 2001). Based on the evaluation of the few available structural studies with palinspastic reconstructions and balanced cross sections the central column might have been closer to the northern than to the southern position at the time of the active sedimentation in their respective domains. Minimum estimates about the Albian distances are ~275 km, between the southern and cen-

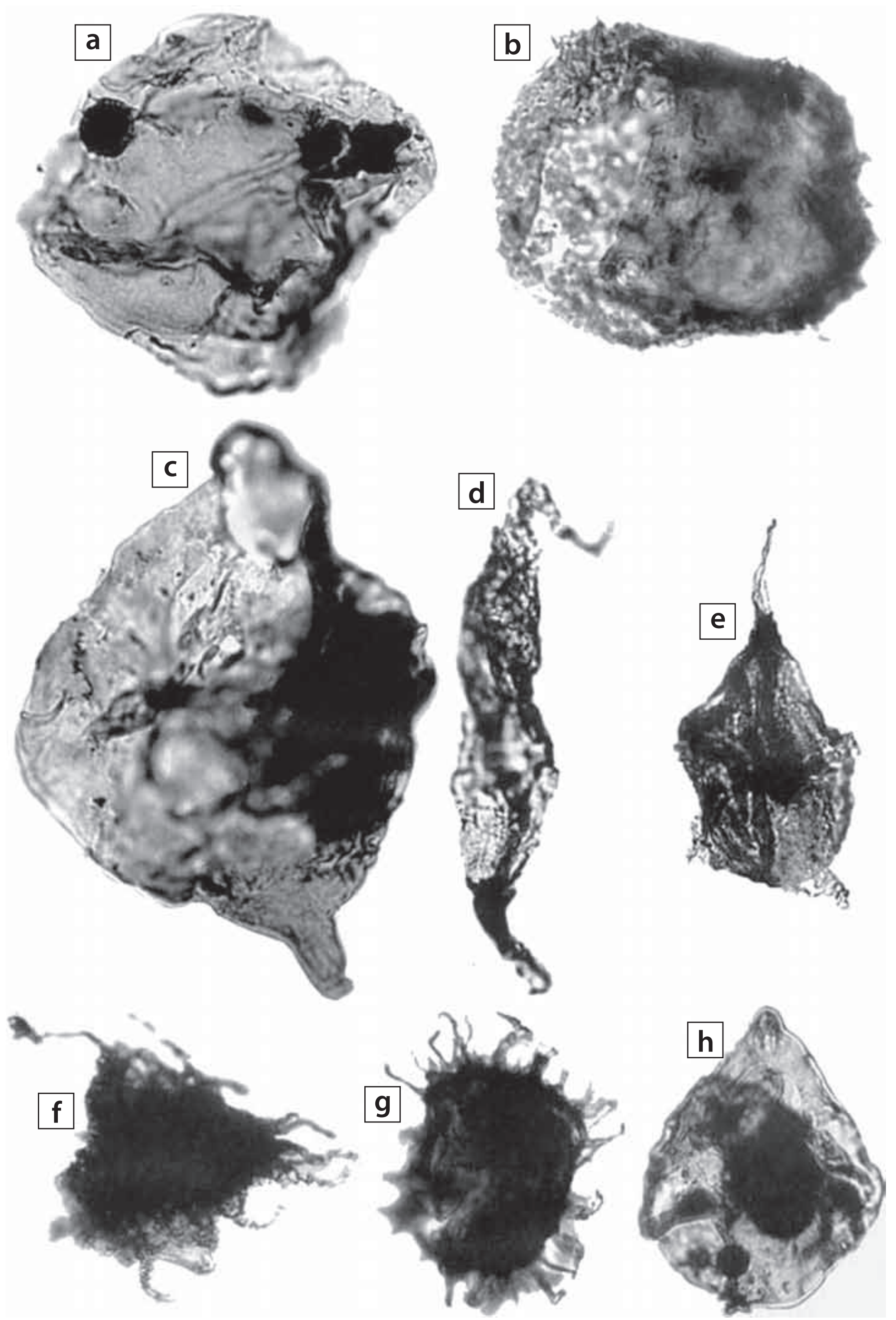

Figure 11: Policarpo Formation, mudstone-dominated member Maastrichtian palinological assemblage. *Manumiella seelandica* (a), *Operculodinium azcaratei* (b), *Manumiella* sp. (c), *Paleocystodinium granulatum* (d), *Cerodinium* sp. (e), *Azolla* sp. (f), *Fibrocysta* sp. (g), *Manumiella* sp. (h) (a-c, x 750; d-h, x 390).

tral positions (according to Kraemer 2003), and ~120 km, between the central and northern positions (Álvarez-Marrón *et al.* 1993, Klepeis 1994, Kraemer 2003). The southern Yahgan Formation accumulated behind the volcanic arc in the deep trough domain of the marginal basin that begun its closure and inversion with deformation and significant shortening during the earliest Late Cretaceous (*cf.* "mid Cretaceous" in Kraemer 2003, Fig. 5). The sedimentites of the central column might have started to get deformed during the latest Early Cretaceous, only if the isotopic date of the Cerro Rodríguez igneous dykes is confirmed and accepted as an age constraining element. The deformation of the Hito XIX Formation might have occurred later, according to its location further away from the propagation direction of the contraction (*cf.* Winslow 1982, Álvarez-Marrón *et al.* 1993, Klepeis 1994).

Upper stratigraphic package: This group of units can be roughly described as a thick and subtle coarsening- and thickening-upward succession accumulated as a response to the progressive sediment input related to ongoing stages of orogenic uplift. The mudstone-dominated Arroyo Castorera Formation is followed by the more lithologically varied thicknesses of alternating mudstone and siltstone of the Río Rodríguez Formation, and then capped by the mudstone to very fine-grained sandstone (to some extent medium-grained sandstone) of the mudstone-dominated member of the Policarpo Formation, which in turn is overlain by the sandstone-dominated member that includes up to coarse-grained conglomeratic sandstone and scattered sandy granule conglomerate. In this case a composite stratigraphic column involving the Upper Cretaceous units (Fig. 12; Turonian-Coniacian, Maastrichtian) is constructed after the sections recorded in the northern watershed of the Sierra de Beauvoir and neighbouring areas located within and approximately 50 km away from the northern leading edge of the folded and thrusted belt (Fig. 1). The Arroyo Castorera and Río Rodríguez formations have their type localities between the divide of Sierra de Beauvoir and its northern limit given by the east-southeast oriented structural depression of the Río Claro valley. They both correspond to the mudstone-dominated lower portion of the Upper Cretaceous sedimentary package and their stratigraphic arrangement is founded on its diagnostic fossil content. The oldest Arroyo Castorera Formation has a Turonian inoceramid fossil assemblage, including inoceramids from the *Inoceramus hobetsensis* and *I. lamarcki* groups, and the Río Rodríguez Formation has forms attributable to *Cremnoceramus* spp. of Coniacian age with the occurrence of a possible *I. andinus* in the upper horizons. The youngest Upper Cretaceous sedimentary unit is the Policarpo Formation, which is represented by the Cretaceous portion of the stratigraphic section measured in Cerro Apen, Sierra de Apen, located just north of the depression of the Río Mio valley. Diagnostic dinocysts and ammonites helped in constraining its Maastrichtian age, and its upper contact with the Cerro Apen Beds is an erosional surface (see Martinioni *et al.* 1999a, Martinioni 2010). Regarding data of outcrops of the Policarpo Formation in surrounding areas it is not completely ruled out that the unit might have an extension to the Danian.

Paleoenvironmental evolution of the area of Sierra de Beauvoir

The upper Mesozoic sedimentary rocks of the area of Sierra de Beauvoir accumulated after the last, rhyolitic phases of the Late Jurassic volcanism related with the Gondwana break-up (see Uliana *et al.* 1985). In the area the volcanism was submarine (Kranck 1932, Hanson and Wilson 1991, Wilson 1991) and coeval with the initiation of a marginal basin with sea-floor spreading (Rocas Verdes marginal basin; Dalziel *et al.* 1974) behind an active volcanic arc at this edge of the supercontinent.

The lower stratigraphic package (Fig. 12, Aptian-Albian) forms part of a sedimentary wedge located behind the andesitic volcanic arc of the "Pacific" margin of the South American plate. The wedge had its major sediment accumulation in positions adjacent to the arc. This was the depositional environment of the deep-marine sediments of the Yahgan Formation with its arc facing counterpart represented by the Hardy Formation (Olivero and Martinioni 1996b, Olivero and Malumián 2008, and references therein). A significant thickness reduction occurs in a northward direction away from the arc (see also Fig. 4 in Olivero and Martinioni 2001). The tectonic inversion of the marginal basin at the latitude of Canal Beagle occurred certainly after the Late Albian, according to the presence of diagnostic fossils of that age preserved in sedimentary rocks with material derived from the volcanic arc while the back-arc basin was still active (Olivero and Martinioni 1996a, b, 2001). The closure at the latitude of Lago Fagnano might have finally taken place during the earliest Late Cretaceous after considering the late Albian fossil records of Beauvoir Formation at Cerro Heuhuepen (see Olivero and Medina 2001, Olivero *et al.* 2009) together with the findings presented herein. This older, lower package of meta-sedimentary rocks that could roughly be attributed as a whole to the Lower Cretaceous might exceed the estimation of 450 m in thickness in Sierra de Beauvoir, being largely constituted by clayey to silty mudstone with scattered and thin very fine-grained sandstone. The bioturbated and/or *in situ* fossil bearing horizons, as well as thin bioclast (inoceramid shell fragments) accumulations, are very scarce. These beds, comparable with distal turbiditic lobe facies, are interpreted to be deposited in hemipelagic deep-marine environments with periods of oxygen deficient or depleted conditions at the basin-floor, based on the important thicknesses with no hints of organisms or organism traces that alternate with bioturbated and/or fossiliferous horizons.

The upper stratigraphic package is entirely Upper Cretaceous and has a more than 1,500 m thick composite section with two distinctive parts, a lower mudstone-dominated group of units and an upper unit with a gradually increasing amount of sandstone intercalations. The initial lower part is constituted by two units that, respectively, exceed the 300 m in thickness (Fig. 12, Turonian-Coniacian). The older Arroyo Castorera Formation has an almost exclusively mudstone succession with just a few, very thin and scattered very fine-grained sandstone layers, and the younger Río Rodríguez Formation is

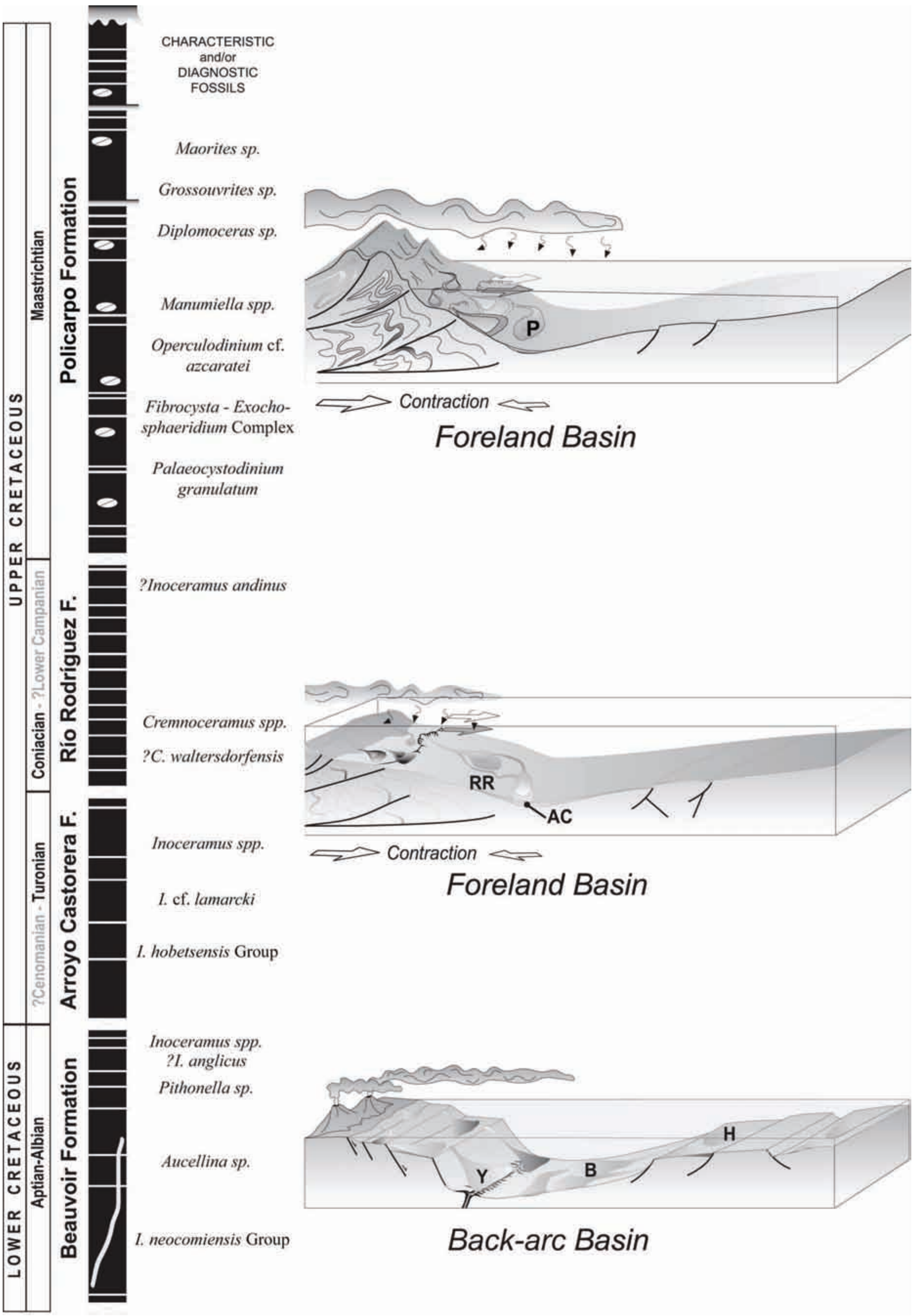

Figure 12: Cretaceous marine mud-rocks of central Tierra del Fuego. Composite and schematic stratigraphic column involving the four sedimentary units recorded for the area of Sierra de Beauvoir with their principal paleontological information. Block-diagrams reflect an idealized paleoenvironmental reconstruction and the depositional environment location of the different units for the Aptian-Albian, the Turonian-Coniacian, and the Maastrichtian. **Y**=>Yahgan, **B**=>Beauvoir, and **H**=>Hito XIX formations; **AC**=>Arroyo Castorera, and **RR**=>Río Rodríguez formations; **P**=>Policarpo Formation (no scale).

constituted by coarsening and thickening upward packages of sandy mudstone to coarse siltstone - fine-grained sandstone. Both units preserve some diagnostic inoceramids, among other fossil remains, and exhibit a low to mode- rate degree of bioturbation at certain horizons or restricted stratigraphic intervals. The inoceramids of the Arroyo Castorera Formation are Turonian. The inoceramid fragments of the Río Rodríguez Formation belong to Coniacian forms, with a possible extension to younger beds (*cf.* Buen Suceso Strata, Olivero and Medina 2001), based on one fragmentary element, but not as young as the early Late Campanian, when inoceramids appear to be extinct at these southern latitudes (*e.g.* Antarctic Península, Olivero and Medina 2000; and Tierra del Fuego, Olivero *et al.* 2003). The initial part of the upper stratigraphic package is interpreted to comprise hemipelagic to distal turbiditic deposits accumulated in a deep-marine, basin-floor to base-of-slope, depositional environment. The inference is consistent with the *in situ* faunal records and with the kind and slightly increased amount of bioturbation. It is suggested that the Arroyo Castorera Formation could have accumulated right after the beginning of the marginal basin's tectonic inversion, representing the transition from extensional to foreland basin tectonic style (see also Fig. 3 in Olivero and Martinioni, 2001). Regarding its characteristics, the unit may be interpreted as the passive fill of a starved, progressively deeper flexural basin (Natland *et al*. 1974, Biddle *et al*. 1986). In this context, the subsequent gradual and recurrent accumulation of coarsening- and thickening upwards successions of the Río Rodríguez Formation, considered as the piling-up of turbiditic lobe deposits, could also be interpreted as a clear sedimentological indicator of the tectonic inversion of the marginal basin in the stratigraphic succession and the incipient progress of the foreland basin development (*cf.* Martinioni 1997, 2010, Olivero and Martinioni 2001). According to this assumption, the sedimentation of the Río Rodríguez Formation might have evolved in an "early" ramp paleoenvironment located in front of a rising orogen, but, allegedly, still mainly submerged (see Fig. 7 in Covey 1986). The overall coarsening upward trend of the upper stratigraphic package becomes self evident in the youngest upper unit that has an up-section passage from mudstone to sandstone-dominated beds (Fig. 12, Maastrichtian). The uppermost Cretaceous Policarpo Formation has a lower member constituted by prevalent mudstone and intercalations of normally graded sandstone beds. The cross-bedding and flute cast paleocurrent measurements point in an average to the north. Diagnostic Maastrichtian dinocysts and ammonites, like a wider variety of ichnofossils, show up associated with the mudstone-dominated member of the unit that also includes an Albian-Cenomanian redeposited cyst. In Cerro Kooholjsh the unit ends with the sandstone-dominated member and, according to the dinocysts assemblage, it could not be ruled out that it may reach the Danian. The Policarpo Formation with its upward increasing amount of sandstone beds intercalation, up to its dominance, corresponds to prograding turbiditic lobe sedimentation generated in the foreland basin by tectonic pulses within a ramp setting, with an already emerged and growing Andean orogen. The progressive uplift with new tectonic pulses reactivates the depositional system enabling the development of erosion surfaces and accumulation of younger coarse clastic successions over such unconformable surfaces. These progradational systems erode and/or cover with their new deposits the older strata, as it happens with the Cerro Apen Beds over the Policarpo Formation (see Martinioni 1997, 2010, Martinioni *et al.* 1999a). The Austral foreland basin, based on the information of Sierra de Beauvoir (Martinioni 1997, 2010), was already active during the early Late Cretaceous (Cenomanian?-Turonian) and, according to the records of Canal Beagle (Olivero and Martinioni 1996a) and at Cerro Heuhuepen (Olivero and Medina 2001, Olivero *et al.* 2009), it did not exist prior to the latest Early Cretaceous (Late Albian).

It is suggested that the tectono-sedimentary evolution of the marine basins of southern South America, regarding the paleoenvironmental interpretation of the beds north of Lago Fagnano, implies that the deep-marine deposits of the Lower Cretaceous represent the post-rift sedimentation with a main source area located to the north, where the stable cratonic shelf of the Deseado massif was having the advances of the Springhill Formation successions (Thomas 1949a, b, Flores *et al.* 1973, Natland *et al.* 1974, Biddle *et al.* 1986, Galeazzi 1998), while the coeval sedimentation south of that domain was presumably occurring in the deeper marine environment of the Rocas Verdes marginal basin (Fig. 12, Aptian-Albian). Conversely, the Upper Cretaceous turbiditic deposits accumulated in ramp systems represent the sedimentation related to the initial stages of evolution of the Austral foreland basin, after the tectonic inversion of the marginal basin. This evolution might have started with an initially still submerged topographic high and an "early" ramp stage associated with a fine-grained clastic wedge (Fig. 12, Turonian-Coniacian). This stage was followed by successive northward migration phases of the ramp and the accumulation of progressively coarser grained clastic wedges, produced by the emergence and continued uplift of the orogen (Fig. 12, Maastrichtian; continuing through the Paleogene, see Martinioni 1997, 2010, Martinioni *et al.* 1998, 1999a).

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