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Mesozoic-Cenozoic stratigraphy of the Fuegian Andes, Argentina

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ABSTRACT

The stratigraphy of the Argentinean Fuegian Andes reveals contrasting Mesozoic-Cenozoic tectonic regimes. The Lemaire Formation, submarine complex of bimodal volcanites, breccias, and sedimentary rocks; the Yahgán Formation, volcaniclastic apron of deep-marine andesite-rich turbidites and mudstones; and the Beauvoir Formation, slope mudstones, all evidence late Jurassic-early Cretaceous extension and consequent origination of the Rocas Verdes Marginal Basin. The basal late Cretaceous ductile deformation, isoclinal folding, and metamorphism of these rocks indicate a compressional tectonic regime that resulted in the closure of the marginal basin. The Fuegian Andes were uplifted by the late Campanian; subsequent propagation of the compressional deformation and subsidence by tectonic loading along the northern orogenic margin originated the Austral and Malvinas foreland basins. The Turonian-lower Campanian "Estratos de Buen Suceso" represents the final stages of the closure of the marginal basin and/or the beginning of the foreland basins. During the late Campanian to mid Miocene, the foraminiferal assemblages allow precise dating of the main tectonic events and with the associated trace fossils and sedimentary facies, the general characterization of the depositional settings. The thrust and fold belt of the Austral/Malvinas basins includes three depocenters: 1) the Bahía Thetis (upper Campanian-Maastrichtian), Policarpo (upper Maastrichtian/Danian), and Tres Amigos (upper Paleocene) Formations, mostly turbidite settings with cosmopolitan agglutinated foraminifers; 2) the Río Claro Group, upper Paleocene-lower Eocene; and 3) the La Despedida Group, representing the extended upper mid Eocene-upper Eocene transgression with endemic foraminifers. A fourth depocenter, the Oligocene-mid Miocene Cabo Domingo Group mostly deposited below the calcite compensation depth and characterized by widespread agglutinated foraminifers, represents the last and deepest foredeep, originated just north of the fold belt during the waning compressional phase. Reduced exposures of mid Eocene bryozoan limestones, the Río Bueno Formation, and fluvial upper Eocene-lower Oligocene, the Punta Cactus and Sloggett Formations, conform reduced exposures within the fold belt. The late Miocene-Pliocene, shallow marine "estratos de la María Luisa" and Irigoyen Formation, the latter with foraminifers suggesting an Atlantic-Pacific connection, record Cenozoic transcurrency and pull-apart basins.

KEYWORDS | **Fuegian Andes. Stratigraphy. Mesozoic. Cenozoic.**

INTRODUCTION

This review attempts to synthesize the Mesozoic-Cenozoic stratigraphy of the Fuegian Andes. It is based on an early work (Olivero and Martinioni, 2001) with the addition of published data worked out during the last five years and not yet published results of studies in progress. An abridged version of the geologic map of the Isla Grande de Tierra del Fuego is also enclosed (Olivero et al., in press; Fig. 1).

The stratigraphy of the southernmost part of South America has been controlled since the Mesozoic by a series of dramatic changes due to contrasting tectonic regimes, represented by late Jurassic-early Cretaceous extension, late Cretaceous-Paleogene compression, and Cenozoic transcurrency (Katz, 1972; Dalziel et al., 1974; Kohn et al., 1995).

Mid to late Jurassic crustal strechting resulted in an extensive rifting phase, associated with a regional volcanic field that covers a large area of Patagonia (Bruhn, 1979; Hanson and Wilson, 1991). Continuation of the extensional regime during the late Jurassic-early Cretaceous opened in southern Patagonia the Rocas Verdes Marginal Basin, which is partially floored by ophiolites (Katz, 1972; Dalziel et al., 1974). The regional late Albian transgression that covers a large area of the Austral and Malvinas basins is related to subsidence during a sag phase. In the northern parts of the Austral and Malvinas basins (Fig. 1), the Aptian to Maastrichtian strata representing platform, slope, and deep basinal settings are thought as originated during an interval of tectonic quiescence (Biddle et al., 1986; Galeazzi, 1998). Conversely, in the southern Rocas Verdes Marginal Basin, the basal upper Cretaceous marks the inception of a compressional tectonic regime, which originated the ductile deformation, isoclinal folding, and metamorphism that characterize the Paleozoic to Mesozoic rocks of the southern Fuegian Andes. Peak metamorphism, reaching the amphibolite grade was attained between 100 and 90 Ma (Kohn et al., 1995; Olivero and Martinioni, 1996a). The closing of the Rocas Verdes Marginal Basin was completed around 70 Ma (Kohn et al., 1995) and the Fuegian Andes were already uplifted by the late Campanian (Olivero et al., 2003).

From the late Campanian up to the Oligocene, the northern propagation of the compressional deformation originated three main depocenters, which are located within the thrust and fold belt of the Austral and Malvinas basins. These depocenters include thick marine successions of upper Campanian-Maastrichtian/Danian, upper Paleocene-lower Eocene, and upper middle Eocene-upper Eocene that are distributed along the inner, central, and outer parts of the folded belt, respectively (Olivero and Malumián, 1999; Olivero et al., 2002a, 2003). A fourth depocenter, which consists mainly of uppermost Eocene /lower Oligocene-mid Miocene subhorizontal sedimentary rocks, is located just north of the folded belt. It represents the filling of the last foredeep of the Austral and Malvinas Basin formed during the waning stages of the compressional deformation.

The transcurrent tectonic regime is associated with the activity of the left-lateral Magallanes-Fagnano fault system, which presently defines the boundary between the South America and Scotia plates. In Argentinean Tierra del Fuego, transcurrency probably started in the Oligocene-Miocene and it is associated with small pull-apart basins (Ghiglione, 2002, 2003; Ghiglione and Ramos, 2005). One of these basins is located within the folded belt and it is filled with late Miocene-Pliocene shallow marine deposits (Malumián and Olivero, 2005a).

In summary, the Mesozoic-Cenozoic stratigraphy of the Fuegian Andes reveals the different tectonic regimes. Accordingly, the following stratigraphic description is grouped in: basement rocks; marginal basin, marginal basin-foreland basin transition; inner, central, and outer, folded belts of the foreland basin; subhorizontal foreland; and pull-apart basins strata.

BASEMENT ROCKS (UPPER PALEOZOIC-MID JURASSIC)

Highly deformed schists, greenstones, and amphibolites are exposed in Cordillera Darwin and westernmost Argentinean side of the Beagle Channel (Kranck, 1932; Fig. 1). The highest metamorphic grade, with staurolite, kyanite, and sillimanite is in Cordillera Darwin, and there is a continuous decrease in the metamorphic grade towards the NE and W, and an abrupt change towards the S.

In the Tierra del Fuego National Park, strongly cleaved, polyphase deformed schists, with abundant refolded quartz veins are exposed between Ensenada and Lapataia bays (Metamorfita Lapataia, Borrello, 1969; Caminos et al., 1981). Dominant rocks are fine-grained quartz-sericite-garnet schists; less common are quartz-biotite schists and amphibolites (Olivero et al., 1997).

An unconformity separates the basement from the Lemaire Formation. However, as peak-metamorphism was reached during the mid-late Cretaceous, basement and cover rocks are difficult to separate in the field (Dalziel, 1982; Kohn et al., 1995; Olivero et al., 1997). The metasedimentary and metavolcanic rocks of the basement are interpreted as an accretionary prism on the Pan-

thalassic margin of Gondwana, older than mid-Jurassic (Hervé et al., 1981 and this issue).

ROCAS VERDES MARGINAL BASIN (UPPER JURASSIC-ALBIAN)

Lemaire Formation, upper Jurassic

Their main outcrops are distributed in a discontinuous WNW belt stretching from Seno Almirantazgo in Chile to Isla de los Estados in Argentina (Fig. 1).

The Lemaire or Tobífera Fm conforms a submarine volcanic-sedimentary complex that includes epiclastic rocks (originally, turbidites, conglomerates, chert, and black radiolarian and carbonaceous mudstones); acidic volcanic and volcaniclastic rocks (rhyolitic lava, pyroclastic flows, breccias, tuffs, and accretionary lapilli; subvolcanic quartz porphyries); and basaltic spillites (Hanson and Wilson, 1991). In Bahía Ensenada, Sierra de Alvear, and Sierra de Sorondo, the Lemaire Fm consists of a complex association of these rocks with the addition of massive sandstones (Olivero and Martinioni, 1996b; Olivero et al., 1997). Massive sandstones of the Lemaire Fm are distinguished from similar Yahgán sandstones by their acidic petrographic components (Olivero and Martinioni, 1996b). In Península Brunswick, Chile (Fuenzalida and Covacevich, 1988), and Argentino Lake, Argentina (Feruglio, 1949/50), similar acidic volcaniclastic rocks preserves late Jurassic fossils.

The Lemaire rocks are strongly deformed and a penetrative cleavage has completely obliterated the original stratification in the fine-grained facies (Bruhn, 1979; Olivero et al., 1997). The contact with the Yahgán Fm is dominantly tectonic but in the less deformed areas in the subsurface of the Austral Basin the contact with lower Cretaceous rocks is unconformable (Biddle et al., 1986; Galeazzi, 1998). The stratigraphic relationships of the Lemaire Fm with the Tortuga Ophiolite and rocks of the volcanic arc (Hardy Fm) remains unclear (Suárez et al., 1985; Miller et al., 1994).

The Jurassic rhyolitic volcanism in Patagonia represents regional extension during initial break-up of Gondwana (Ramos, 1996). In northern Tierra del Fuego and extra-Andean Patagonia this volcanism developed in subaerial settings. In contrast, the silicic-basaltic volcanism of the Lemaire Fm is restricted to a narrow, deep-marine volcano-tectonic-rift (Hanson and Wilson, 1991). Continued extension during the latest Jurassic-early Cretaceous resulted in the opening of the Cretaceous Rocas Verdes marginal basin, partly floored by the oceanic rocks of the Tortuga Ophiolite (Katz, 1972; Dalziel et al., 1974).

Yahgán Formation, lower Cretaceous-?uppermost Jurassic

Kranck (1932) established the Yahgán Fm for the slates and andesitic-rich greywackes typically exposed in Monte Olivia and Ushuaia. It is also exposed along the northern Beagle Channel, from Ushuaia to Bahía Sloggett (Fig. 1); and in Hoste, Navarino, Nueva, Lennox, and Picton islands (Dott et al., 1977; Winn, 1978; Suárez et al., 1985). Northwards it is laterally replaced by black mudstones of the Beauvoir-La Paciencia Fms and southwards it grades to the volcanic rocks of the Hardy Fm in Chile (Suárez et al., 1985; Miller et al., 1994).

The Yahgán Fm consists of coarse breccias and conglomerates, sandstones, sandy and silty turbidites, black tuffaceous mudstones and tuffs, intruded by basaltic rocks of tholeiitic-calc-alkaline and spillitic affinities. The coarser rocks, restricted to the Chilean archipelago, bear Aptian-Albian corals and bivalves (the Tekenika beds of Dott et al., 1977) and Tithonian-Neocomian ammonites and belemnites (Suárez et al., 1985). In Navarino Island, mudstones and sandy turbidites bear poorly preserved inoceramids and ammonites (Suárez et al., 1985). Along the northern margin of the Beagle Channel, the Yahgán Fm includes three main facies: a) black mudstones, fine-grained turbidites and tuffs, b) classical turbidites, and c) massive to graded sandstones (Olivero and Martinioni, 1996b).

Fossils are very scarce; a few horizons have trace fossils, and one horizon bears the late Albian inoceramids *Inoceramus carsoni* and *Birostrina concentrica* (Olivero and Martinioni, 1996a, b).

Tight, isoclinal folds with a penetrative, axial planar cleavage characterize the fine-grained rocks. The metamorphic grade reaches the lower greenschist facies (chlorite-sericite-quartz-albite-epidote); and a widespread prehnitization affected the original rocks (Caminos et al., 1981). In the less deformed coarser facies the clastic composition is remarkably uniform, with abundant andesitic fragments (Winn, 1978; Suárez et al., 1985; Olivero and Martinioni, 1996b). The fossils of the Yahgán Fm suggest a Tithonian-Neocomian basal part and a late Albian upper part (Olivero and Martinioni, 1996a). Post-main deformation granitic-dioritic rocks are isotopically dated between 70-90 Ma (Halpern and Rex, 1972; Suárez et al., 1985; Kohn et al., 1995).

The Yahgán Fm is interpreted as the volcaniclastic filling of the Rocas Verdes marginal basin located between a Pacific andesitic arc and the South American continent (Katz, 1972; Dalziel et al., 1974). The clastic-wedge geometry of the Yahgán rocks suggests a volcaniclastic

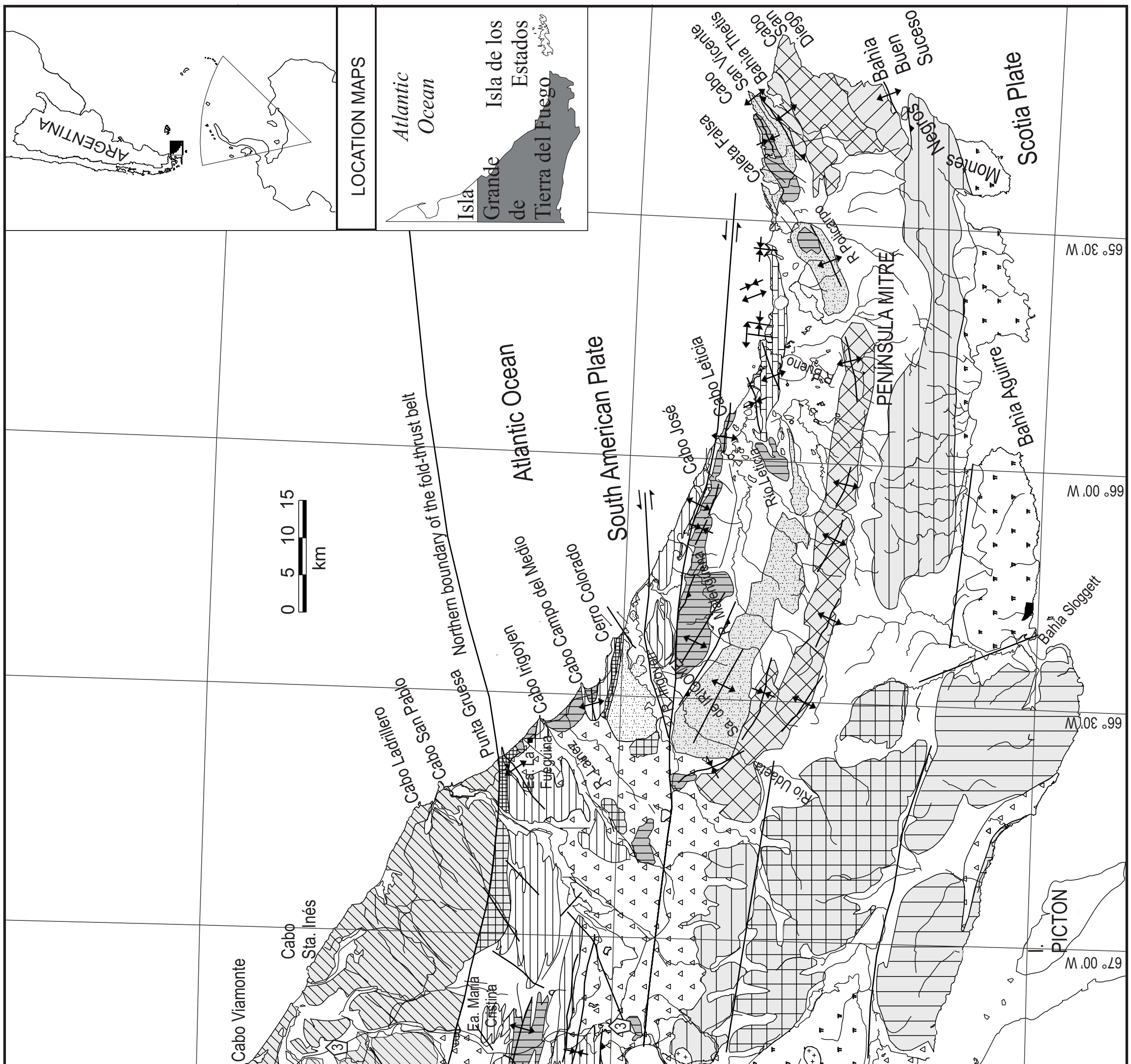

FIGURE 1 | **Geologic map of Tierra del Fuego, Argentina. After Olivero et al. (in press).**

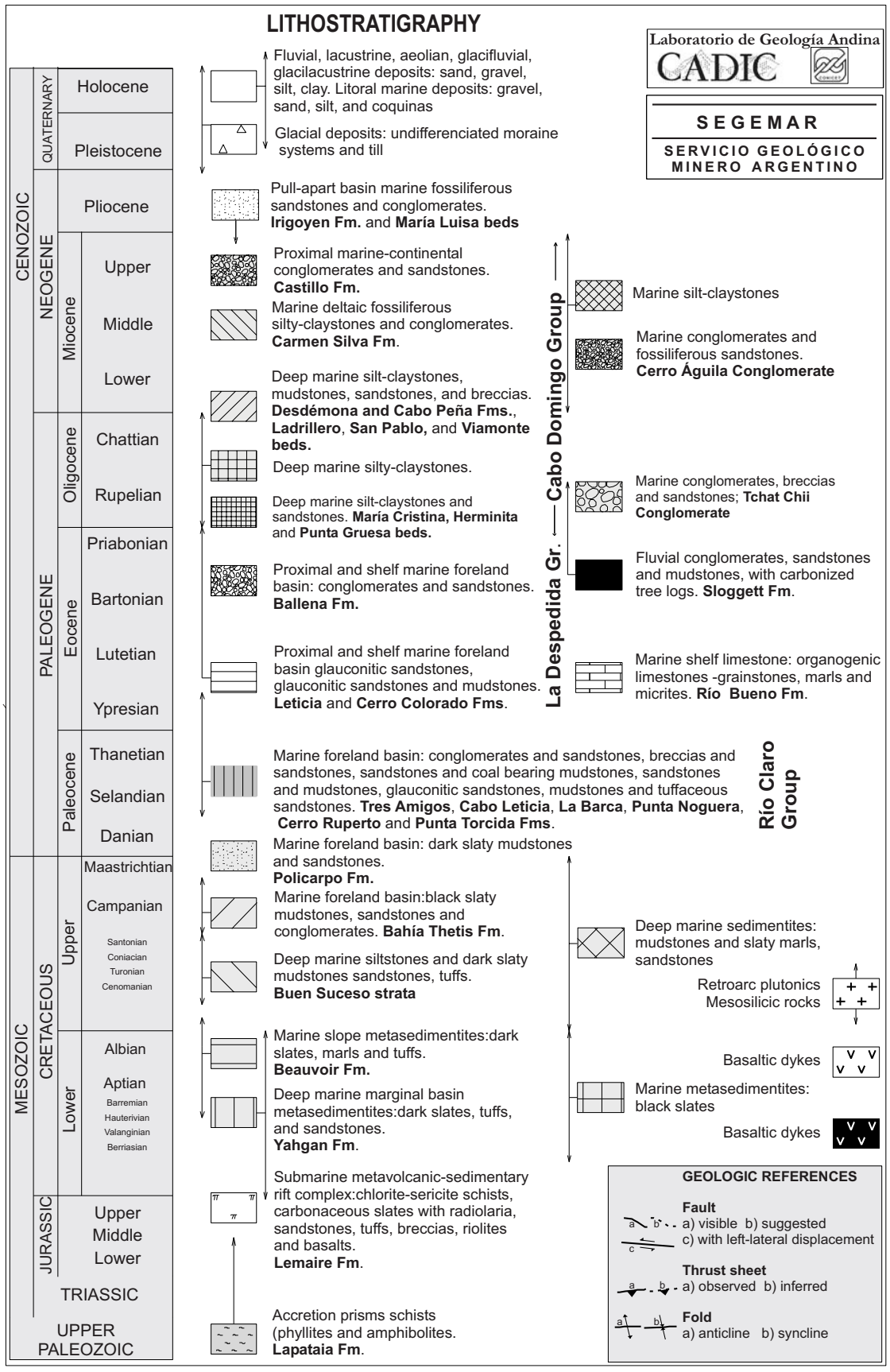

FIGURE 1 | **Legend**

apron adjacent to the Pacific magmatic arc (Fig. 2; Olivero and Martinioni, 2001).

Beauvoir Formation, lower Cretaceous

The Beauvoir Fm was established for the black slates exposed in Sierra de Beauvoir (Camacho, 1967). Provisionally, the fossiliferous marlstones near the Hito XIX (Macellari, 1979) and the belt of black slates extended from eastern Lago Fagnano to Buen Suceso Bay are also included in the Beauvoir Fm (Fig. 1).

The Beauvoir Fm consists of homogeneous, massive to faintly laminated dark slates and gray tuffs, with scarce rhythmites of sandstones and mudstones. The strata are involved in trust-sheets and often form asymmetrical folds, with subvertical axial planar cleavage.

In Sierra de Beauvoir, intrusions of basaltic dykes gave an Albian isotopic age (Martinioni et al., 1999a). Megafossils are generally scarce; however, a few horizons bear a rich mollusk fauna, including *Aucellina andina*, *A. radiatostriata*, and belemnites (Aptian-Albian), and *A. euglypha* and *Inoceramus* cf. *urius* assigned to the late Albian-basal Cenomanian (Macellari, 1979; Olivero and Medina, 2001).

The original black mudstones of the Beauvoir Fm represent outer shelf sedimentation below the wave base in northern Tierra del Fuego and deeper, slope and basin plain settings to the south, where it laterally grades to the Yahgán Fm (Olivero and Martinioni, 1996a,b). In the subsurface it corresponds to the Nueva Argentina Fm, early-middle Albian, and the overlying Arroyo Alfa Fm, late Albian (Flores et al., 1973; Malumián, 1990) from the southern stable platform and in Chile to the La Paciencia or Vicuña Fms from the folded belt.

MARGINAL BASIN-FORELAND BASIN TRANSITION (TURONIAN-LOWER CAMPANIAN)

Estratos de Buen Suceso

This unit includes two fine-grained, Turonian-Coniacian and Santonian-lower Campanian, fossiliferous successions exposed in the Buen Suceso Bay (Fig. 1).

The Turonian-Coniacian beds dominated by slaty micritic limestones and marly mudstone bear abundant specimens of *Inoceramus madagascariensis*. The Santonian-lower Campanian consists of well stratified slaty, black mudstones with the bivalves *Inoceramus* (Platyceramus) sp. and *Sphenoceramus* sp.; gray tuffs; and dark gray, silty sandstones. The latter bears some fully bioturbated horizons with the ichnogenera *Zoophycos*, *Planolites*, *Palaeophycus*, *Chondrites* and *Rhizocorallium* (Olivero and Medina, 2001).

The strata are gently folded and involved in trust-sheets; they bear faint traces of slaty cleavage, and are cut by a dense joint system associated with a profuse inyection of quartz veins. They represent outer shelf to slope settings developped partly during the final stages of the closure of the marginal Rocas Verdes Basin and/or partly the beginning of the foreland basin. These strata are correlated with the Cabeza de León Fm/"Inoceramus Superior" in the subsurface of the Austral Basin (Olivero and Medina, 2001).

FORELAND BASIN: INNER FOLDED BELT (UPPER CAMPANIAN- UPPER PALEOCENE)

Bahía Thetis Formation, upper Campanian?-lower Maastrichtian

The dominantly black slaty mudstones and greywackes of Bahía Thetis (Fig. 1), previously included in the "Series de Beauvoir" or "Estratos de Bahía Thetis" (Furque and Camacho, 1949) were recently studied by Olivero et al. (2003).

The Bahía Thetis Formation (>250 m thick) consists of hard, highly deformed, dark, organic-rich, laminated mudstone and tuff with incipient cleavage; turbidite sandstone; resedimented conglomerate and pebbly mudstone. The conglomerate bears large clasts of radiolarian slates and foliated rhyolites, derived from the Beauvoir-Yahgán and Lemaire Fms, respectively. The base is not exposed and its upper part is thrusted over the Policarpo Fm.

Trace fossils and megafossils are absent or very scarce. The dark mudstones bear abundant radiolaria. The foraminifera are restricted to an extended horizon and comprise low diversity agglutinated assemblages typical of dysoxic environments, and they are characterized by *Rzehakina epigona*, *R. lata* and *R. fissistomata* (Caramés and Malumián, 2006).

The Bahía Thetis Fm represents deep-water channel-levee (turbidites-conglomerates) and dysoxic-anoxic basin plain settings (dark, laminated mudstones). Provenance of conglomerate clasts indicates that the Fuegian Andes was already uplifted by the late Campanian. The Bahía Thetis Fm is correlated with the Cerro Cazador Fm (Santa Cruz Province), and part of the Cabeza de León Fm in the Fuegian subsurface.

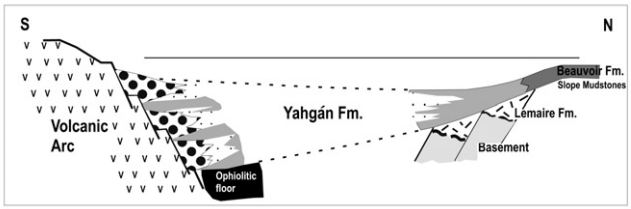

FIGURE 2 | **Paleogeographic scheme during deposition of the Yahgán Formation (heavy stippled: conglomerate; light stippled: sandstone; light gray: mudstone). After Olivero and Martinioni (2001).**

Policarpo Formation, Maastrichtian-Danian

The type area is located along the Atlantic shore of Peninsula Mitre, between Caleta Falsa and San Vicente Cape (Furque and Camacho, 1949; Olivero et al., 2002a, 2003). It also includes the NW belt of strata exposed in Sierra de Irigoyen and Sierra de Apen (Fig. 1).

The Policarpo Fm (minimum 350 m, and probably >700 m thick) consists of bioturbated, tuffaceous, monotonous organic-rich, dark gray sandy mudstones and silty sandstones. It is highly deformed, with relatively open folds and associated thrusts. The Fm is covered in angular unconformity by the Tres Amigos Fm and equivalent upper Paleocene rocks or by the lower middle Eocene Río Bueno Fm (Martinioni et al., 1999b; Olivero et al., 2002a, 2003).

A distinctive feature is the high degree of bioturbation. The Maastrichtian part bears rare solitary corals, echinoids, scaphopods, gastropods, bivalves, ammonites and dinocysts. Agglutinated cosmopolitan forms that include the oldest record in the Austral Basin of *Spiroplectammina spectabilis* dominated the foraminifera.

Depositional settings include outer shelf and/or slope. Dominance of agglutinated foraminifera suggests corrosive and turbiditic settings. The abundance of fresh pyroclastic fragments indicates coeval volcanic activity. In the subsurface it is correlated with the Maastrichtian Arenas Glauconíticas (Galeazzi, 1998) and the upper part ("Fragmentosa") of the Cabeza de León Fm (Flores et al., 1973). In Chile it is equivalent to the Rocallosa Fm and the Riescoian Stage. The outcrops in the Sierra de Apen are correlated with the upper part of the Cerro Matrero Fm (Martinioni et al., 1999b).

Tres Amigos Formation, upper Paleocene

The type area is located W of San Vicente Cape, nearby the Tres Amigos hut (Olivero et al., 2003). To the N of Fagnano Lake it is correlated with the conglomerates of the Sierra de Apen (Martinioni et al., 1999b) and Cerro Pirámide (Fig. 1). It consists of well-bedded alternating intervals of indurate, gray and dark gray conglomerates, coarse sandstones and rhythmic alternations of fine sandstones and mudstones. Clast composition is dominated by altered andesites and foliated acidic metavolcanites, plutonic rocks are scarce. The thickness in the type area is >50 m and in the Sierra de Apen >200 m. The base overlay in angular unconformity the Policarpo Fm, the top is not exposed.

The fossil content is scarce. This Fm was probably deposited in submarine fan-delta systems.

Punta Cactus and Sloggett Formations, upper Eocene/lower Oligocene

They are only known in its type area located in Sloggett Bay, northern Beagle Channel (Fig. 1) and constitute the only Paleogene continental beds in the Fuegian Andes (Caminos et al., 1981; Zanettini and Zappettini, 1988; Olivero et al., 1998).

The Punta Cactus Fm consists of yellowish and reddish fanglomerate and conglomerate (125 m). The Sloggett Fm (95 m) includes two members: the basal, dark gray Gris Member (40 m), formed by massive and carbonaceous mudstone with lenses of conglomerate and pebbly sandstone; and the upper, yellowish Bayo Member (55 m), which consist of a complex of lenticular conglomerate and sandstone, grading laterally and vertically to heterolithic mudstone and coal measures, including large trees, and channeled conglomerate. They are exposed in a small tectonic window below a thrusted block of the Lemaire Fm and the clastic composition of both formations is exclusively of foliated acidic volcanites.

The recorded beech, podocarpaceous, and protaceous pollen; fern and fungal spores; and fresh-water algae from the Sloggett Fm and the absence of typical Oligocene-Neogene palynomorphs suggest most probably a late Eocene age. Both formations are interpreted as part of the same fluvial basin with a point source in the thrusted block of the Lemaire Fm, grading from proximal deposits of an alluvial fan (Punta Cactus Fm) to distal braided/anastomosed channel complex and associated floodplain deposits (Sloggett Fm).

FORELAND BASIN: CENTRAL FOLDED BELT (UPPER PALEOCENE-LOWER EOCENE)

Río Claro Group, upper Paleocene-lower Eocene

The Group includes in part the Río Claro "Series" established for the sandstones exposed E and N of Fag-

nano Lake (Furque and Camacho, 1949) and the Cabo Leticia (Paleocene), La Barca (upper Paleocene), Punta Noguera (uppermost Paleocene and/or-lowermost Eocene); Punta Torcida (upper Paleocene/lower Eocene), and Cerro Ruperto (lower Eocene) Fms (Olivero and Malumián, 1999; Olivero et al., 2002a; Malumián and Caramés, 2002). It is well exposed along the Atlantic shore between the Río Bueno and Irigoyen Cape; to the NW, and up to the Chilean border, the Group define a discontinuous belt exposed above the timber line and cuts along the roads (Fig. 1).

In the Río Bueno area the Group includes four formations. The Cabo Leticia Fm c. 150 m thick, consists of gravity flows deposits: breccias; conglomerates; and massive, tuffaceous sandstones, with abundant shell fragments.

La Barca Fm, c. 220 m, includes two members: LB1, tuffaceous sandstones and intercalated carbonaceous siltstones; and LB2, black mudstones. The La Barca Fm is dominated by low diversity agglutinated foraminifera assemblages and it is marked primarily by the abundance of *S. spectabilis*; in contrast, a restricted horizon of the lower member bears a mostly cosmopolitan Midway Type assemblage dominated by buliminids; the assemblage includes the dominant *Bulimina karpatica*, and exceptional endemic species such as *Buliminella isabelleana procera* Huber and *Antarcticella* sp., both known from Antarctica and very common and widespread in Patagonia. According to the high organic content, the infaunal morphotypes are dominant in all the formation indicating disoxic to anoxic environmental conditions (Malumián and Caramés 2002; Malumián, in press).

The Punta Noguera Fm c. 380 m thick, consists of glauconitic gravity flows deposits, including massive, tuffaceous sandstones, and rhythmically interbedded classical turbidites. The very shallow-water foraminiferal assemblage of the Punta Noguera Fm is dominated by *Elphidium* and *Cribrorotalia* suggesting a postPaleocene age; but it also has the last records of *Rzehakina* spp., *Alabamina creta* and *Charltonina acutimarginata,* which are elsewhere restricted to preEocene ages (Morkhoven et al., 1986; *cf.* Hornibrook et al., 1989). Its endemic character is revealed with some species apparently confined to the Austral Basin such as *Antarcticella ceccioni* and *Conolagena argentina*. Several benthonic species, belonging to the genera *Cribrorotalia*, "*Remaneica*" and similar to *Praepararotalia* are new and apparently endemic. The only recorded planktonic species belong to the genus *Chiloguembelina*. The epifaunal morphotypes and attached test are dominant in concordance with the strong glauconitic formation.

In general, the assemblage is characterized by the oldest record of the genera *Elphidium* and *Cribrorotalia* and by the dramatic turnover respect to the cosmopolitan late Paleocene assemblage of the La Barca Fm. This turnover seems to be the shallow water high latitude equivalent of the dramatic change at the Paleocene/Eocene boundary in the deep ocean. The radiolaria, suggest a late Paleocene age, equivalent to the upper RP5 of the New Zealand zonation of Hollis (1997), according to Jannou (2007).

The Cerro Ruperto Fm, 200 m, consists of glauconite rich, silty very fine sandstones and siltstones.

In the Punta Torcida-Irigoyen Cape area only the Punta Torcida Fm, including the members PTa, PTb, PTc, and unnamed strata, is exposed (Olivero and Malumián, 1999; Jannou and Olivero, 2001). The lower PTa member (> 74 m) is composed of dark gray mudstones with thin sandstone beds; the PTb member (58 m), mudstones with small sandstone lenses, both members include levels with high radiolarian content; and the PTc member (83 m) mudstones (Olivero and Malumián, 1999). The upper unnamed strata (ca. 200 m) consist of turbidites and tuffaceous mudstones (Olivero and López, 2001; Olivero et al., 2002b, 2004).

The formation contains abundant ostracods (Jannou, in press) and foraminifera. Most of the benthic foraminifera were described from the Agua Fresca Fm in the pioneer work in Austral Basin of Todd and Kniker (1952) and include common endemic species such as *Antarcticella ceccioni*. Planktonic foraminifera indicate and early Eocene age an the benthonic ones are mostly dominated by agglutinated forms typical of turbiditic settings (Olivero and Malumián, 1999).

The rocks of the Group are folded and involved in thrust sheets. The base is not exposed and the top is covered in angular unconformity by the Río Bueno Fm, to the S, and by the Leticia Fm, to the N. The succession defines an overall regressive megasequence, with relatively deep-water turbidite systems at the base (Cabo Leticia to Punta Noguera Fms; Punta Torcida Fm) and shallower, shelfal deposits at the top (Cerro Ruperto Fm). The abundance of fresh pyroclastic material indicates an important volcanic activity during the deposition of the Group (Olivero, 2002) and the abundance of organic matter and ostracods, suggests estuarine circulation.

Río Bueno Formation, lower middle Eocene

It is only known in the type area located near the Río Bueno (Furque and Camacho, 1949; Fig. 1).

This Fm, 60-80 m thick, includes two members: RB1, rhythmically bedded grainstones; and RB2, alternation of

grainstones, bioturbated marls, and micrites (Malumián and Olivero, 1998; Olivero et al., 2002a).

The RB1 member is a bryozoan dominated limestone with scarce planktonic and a diverse benthic foraminiferal assemblage. Endemic species known from the Danian of Patagonia, such as *Lagena archangelski* and *Buliminella* ex gr. *isabelleana* have their last occurrence in this assemblage, giving to the RB1 member an older aspect than that of the RB2 member. Besides, other southern mid-high latitude endemic species such as *Planorotalites australiformis, Antarcticella ceccioni*, and *Elphidium aguafrescaense* have their oldest occurrence in this assemblage, which also includes very distinct endemic species of the Austral Basin such as *Astacolus skyringense* (Malumián, in press).

The RB2 member, without record of planktonic foraminifers, is characterized by *Elphidium saginatum*.

The Río Bueno Fm is gently folded. The RB1 member rests in angular unconformity on the Policarpo, La Barca, Punta Noguera, or Cerro Ruperto Fms. The limestones represent shallow shelf deposits.

FORELAND BASIN: OUTER FOLDED BELT (UPPER MID EOCENE-UPPERMOST EOCENE)

La Despedida Group, upper middle Eocene-lowermost Oligocene

This group includes the La Despedida Fm exposed in the northern Menéndez River (Codignotto and Malumián, 1981; Malumián, 1988); the Leticia and Cerro Colorado Fms (partly the "Estratos de Leticia" of Furque and Camacho, 1949) exposed in the Atlantic shore, near Campo del Medio Cape (Malumián et al., 1994; Olivero and Malumián, 1999); and the discontinuous NW belt of strata connecting the former localities (Fig. 1).

At Campo del Medio Cape, the Leticia Fm (upper middle Eocene, 520 m thick) consists of gray and greenish fine, bioturbated, glauconitic, tuffaceous or lithic sandstones with minor fine conglomerates and mudstones. Large channels with sandstone fillings characterized its basal and upper parts; fine-grained sandstones in its middle part bear abundant fossil mollusks, vertical crinoid stems, penguin bones (Clarke et al., 2003), and microfossils (Malumián et al., 1994; Olivero and Malumián, 1999).

The benthonic foraminifera are of accentuated high southern latitude endemism (Malumián, in press), which includes big nodosarids associated to abundant crinoids reflecting a retrograde community (Malumián and Olivero, 2005a). The Leticia Fm represents shallow marine environments at the onset of a transgressive sequence. It records the last acarininids, suggesting the last evidence of temperate waters.

The Leticia Fm is equivalent to the subsurface Glauconitico B in Tierra del Fuego. In the N of the Austral Basin, is correlatable with the Man Aike and Río Turbio Fms. In western Tierra del Fuego, near Hito XIX (Fig. 1), marine, coarse conglomerates with minor, interbedded mudstones, equivalent to the Ballena Fm in Chile, bear mid Eocene palynomorphs similar to those of the Leticia Formation (Martinioni et al., 1998).

The Cerro Colorado Fm (upper middle to upper Eocene, 855 m thick) consists of a vertical stacking of four informal members: CCa, CCb, CCc, and CCd, respectively. Each member is composed of dark gray mudstones at the base, regular intercalation of mudstones and light gray or greenish sandstones at the mid part, and thick gray or yellowish sandstones and pebbly sandstones at the top. Sandstone beds consist mainly of plagioclase crystals, fine schists, acidic volcanic rocks, and andesitic fragments, and quartz in the CCa and CCb Mbrs.; and fine schists, foliated acidic volcanic rocks, quartz, and feldspars in the CCd member. CCa member contains mollusks, crinoids, and echinoids. Scarce, similar fossils were also recorded in CCb and CCc members. Members CCa, CCb, and CCc are correlated with the upper member of the La Despedida section of Malumián (1988) at the Menéndez River, partially with the Man Aike and Río Turbio Fms, and in the subsurface of Tierra del Fuego with the "Margosa Media". The upper CCd member seems to be missing in the rest of Tierra del Fuego Island.

The rocks of the La Despedida Group are folded and thrusted. The Leticia Fm rests on angular unconformity over lower Eocene rocks, and presents internal progressive and syntectonic intraformational unconformities (Ghiglione et al., 2002). An unconformity separates the top of the Group from Oligocene sandstones at Cerro Colorado and coarse conglomerates at Cerro Tchat Chii (Malumián, 1988; Malumián and Olivero, 2006).

The Cerro Colorado Fm grades upward from lower inner shelf to upper outer shelf settings. In the latter, the foraminiferal benthic assemblages reflect cooling waters by replacement of the species known in the Leticia Fm by species of typical genera of temperate-cool water or south polar origin such as *Ammoelphidiella*, *Antarcticella*, and *Buccella*.

SUBHORIZONTAL FORELAND STRATA (UPPERMOST EOCENE-LOWER MID MIOCENE)

Cabo Domingo Group, Oligocene-Miocene

Studies on the stratigraphy of the upper part of the Cabo Domingo Group are still in progress by the authors,

thus its description is preliminar. This Group (Malumián, 1999) includes the mostly subhorizontal beds exposed along the Atlantic coast from Punta Gruesa to Cabo Domingo and to the N of the frontal fault that defines the northern boundary of the Fuegian fold and thrust belt (Fig. 1). To the S, includes the folded, unnamed strata located above the Cerro Colorado Fm (Malumián and Olivero, 2005b), the La María Cristina beds, mudstones located near to the María Cristina Farm, and the subhorizontal strata between Punta Gruesa and Viamonte Cape (Olivero et al., 1999). In the N, includes the "Capas de La Herminita"; Cabo Peña Formation, Cerro Aguila and Tchat Chii Conglomerates; and the Carmen Silva and Cerro Castillo Fms (Codignotto and Malumián, 1981).

The basal part of the Cabo Domingo Group consists of gently folded beds of varied lithologies. In the Cerro Colorado and Punta Gruesa areas the lower to upper Oligocene (?basal Miocene) strata consists of folded conglomerate, sandstone, and mudstone that bear mostly a residual agglutinated foraminiferal assemblage, indicating conditions below the calcite compensation depth. They rest on a subtle parallel unconformity over upper Eocene rocks (Malumián and Olivero, 2005b). Similar settings are interpreted for the homogenous mudstones exposed near the frontal fault of the Fuegian fold belt, in particular for the La María Cristina and La Herminita beds (Fig. 1).

The upper part of the Group is characterized by shallow marine and deltaic mudstones of the Carmen Silva Fm and by mostly fluvial deposits of the Cerro Castillo Fm (Codignotto and Malumián, 1981).

The unconformity at the base of the Cabo Domingo Group separates gently folded Oligocene beds cropping out near the boundary of the Fuegian fold and thrust belt from uppermost Eocene strata. This unconformity represents the final stages of the compressional deformation in the fold belt and was followed by a marked deepening that represents the deepest foredeep in the Austral Basin. During the early Oligocene-middle early Miocene the foredeep was filled with deep-marine mudstones and sandstones and during the middle to late Miocene the filling was completed with shallow marine, deltaic, and fluvial strata.

PULL-APART BASINS (MIOCENE-PLIOCENE)

"Estratos de La María Luisa"/ Irigoyen Formation, upper Miocene Pliocene

The upper Miocene Pliocene rocks include horizontal strata exposed within the folded belt in the Río Irigoyen type area (Figs. 1 and 3; Malumián and Olivero, 2005b; Giglione, 2003).

The "estratos de La María Luisa" (>50 m thick, upper Miocene-?Pliocene) consist of basal fine conglomerates and coarse sandstones, with reworked Eocene microfossils, followed by brown, carbonaceous claystones, with few planktonic foraminifera. The base of these strata rest unconformably on Oligocene beds to the S of Cerro Colorado. They represent shallow marine, inner shelf settings.

The Irigoyen Fm (> 50 m thick; uppermost Miocene?-Pliocene) consists of glauconitic, fine sandstones, interbedded sandstones and siltstones, and channelized, fossiliferous conglomerates. The base of this formation probably rests in unconformity over the "estratos de La María Luisa" and the top is not exposed. Some horizons bear abundant gastropods, bivalves and echinoids. The microfauna is characterized by abundant benthic foraminifera of outstanding Pacific aspect, in particular *Nonion hancocki* is dominant in certain levels. The Irigoyen Fm was deposited in restricted, shallow marine-estuarine settings.

The location within the fold belt of these shallow marine, upper Miocene-Pliocene deposits of contrasting subhorizontal structure, support previous interpretation as the filling of a pull-apart basin related to the Magallanes-Fagnano fault system (Lodolo et al., 2002, 2003; Ghiglione, 2003). The Pacific aspect of the foraminiferal assemblage of the Río Irigoyen Fm suggests a direct connection between the Atlantic and Pacific coasts, probably located along the structural depression of the Magallanes-Fagnano fault system (Malumián and Olivero 2005b; Malumián and Scarpa, 2005).

CONCLUDING REMARKS: THE UPPER CRETACEOUS-CENOZOIC CLASTIC WEDGES OF THE FORELAND BASIN

A North-South schematic cross-section from the cratonic area (Santa Cruz Province) to the orogenic area (Fuegian Andes-North Scotia Ridge) illustrated the gross architecture of the late Cretaceous-Cenozoic strata of the foreland Austral-Malvinas basins (Fig. 3; Olivero and Malumián, 2002).

In the northern cratonic area (SC2 well, Fig. 3) four major sedimentary cycles are recognized: a) Maastrichtian-Danian; b) late middle Eocene; c) late Oligocene; and d) latest Oligocene-early Miocene. They consist of fine-grained, shallow marine platform deposits with minor intercalation of terrestrial beds. Total thickness is about 900 m and the bases of cycles b), c), and d) are marked by major unconformities (Malumián, 1999, 2002; Malumián and Náñez, 2002). The general coincidence in the timing

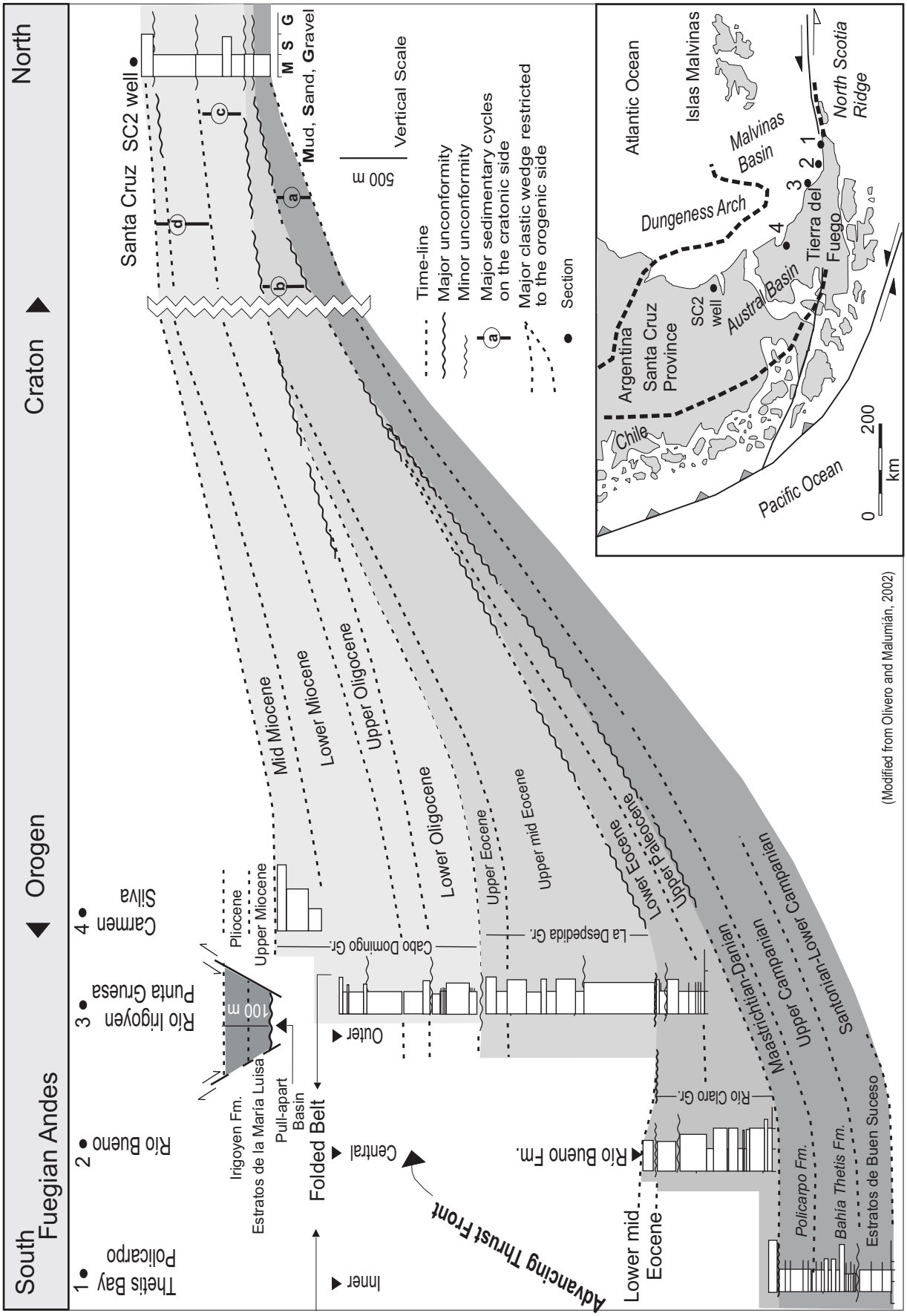

FIGURE 3 | **Simplified North-South cross section depicting the basin-fill geometry and the stratigraphic correlation between the cratonic and orogenic areas of the Austral-Malvinas basins. After Olivero and Malumián (2002).**

of sedimentation and erosion with high and low sea-level conditions, respectively, suggests eustacy as the main control on the development of these four sedimentary cycles (Malumián, 2002).

In the southern orogenic area a contrasting pattern of very thick, deformed clastic wedges, originated in relatively deep-water settings and with complex stratigraphic arrangements, characterizes the upper Cretaceous-lower Miocene deposits (localities 1, 2, and 3, Fig. 3). The composite stratigraphic column (ca. 3,500 m of aggregate thickness) is relatively complete and includes the following intervals separated by major, intervening unconformities: upper Campanian-Maastrichtian/Danian; upper Paleocene-lower Eocene; upper middle Eocene-upper Eocene; and lower Oligocene-middle Miocene (Olivero and Malumián, 1999; Olivero et al., 2002a, 2003). The northern propagation of the thrust front controlled the generation and migration of successive depocenters in the inner, central, and outer fold belt, as well as the marked thinning of the clastic wedges towards the cratonic side and the opposite pattern of merging and fanning-out of major unconformities toward the craton and the orogen, respectively. The lower middle Eocene shallow water limestones (Río Bueno Fm) probably represent deposition on syntectonic structural highs, disconnected from the main sites of clastic supplies and deposition (Fig. 3; Malumián and Olivero, 1998; Olivero and Malumián, 2002). During the latest Eocene-earliest Oligocene, the final compressional stage originated the deepest foredeep, which was initially filled by mudstones and claystones mostly deposited below the calcite compensation depth (La María Cristina, La Herminita, and La Desdémona beds). Coarse grained, shallow marine and fluvial deposits (Carmen Silva and Cerro Castillo Fms) represent the uppermost sedimentary filling.

Shallow marine, upper Miocene-Pliocene strata within the folded belt were deposited in pull-apart basins originated along the Magallanes-Fagnano Fault (Figs. 1 and 3, Lodolo et al., 2002, 2003; Ghiglione, 2003; Malumián and Olivero, 2005b).

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