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Patagonia: where does it come from?

Victor A. Ramos*, Maximiliano Naipauer

Laboratorio de Tectónica Andina, Instituto de Estudios Andinos Don Pablo Groeber (Universidad de Buenos Aires – CONICET), Intendente Güiraldes 2160, Ciudad Universitaria, C1428EGA, Buenos Aires, Argentina

e-mail addresses:andes@gl.fcen.uba.ar (V.A.R., Corresponding author); maxinaipauer@hotmail.com (M.N.)

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Abstract

Based on the recent finding of archeocyathids in molassic middle Cambrian to Early Ordovician age-sequences of northern Patagonia the relationships between this southern part of South America and East Antarctica need to be re-examined. The early Cambrian age of the archeocyathids, and their derivation from the Shackleton Limestones, open several alternatives that are evaluated based on the lithology and the U-Pb zircon ages of the different metamorphic sequences of Patagonia and the Transantarctic Mountains. Based on these data, it is proposed that the Somuncurá Massif of northern Patagonia is the conjugate margin of the Pensacola Mountains in East Antarctica. The main episodes of deformation within the Cambrian-Ordovician Ross Orogeny are correlated, as well as the passive margin setting during the Silurian-Devonian, which indicate that the lower section of the Beacon Supergroup of Antarctica corresponds to the Sierra Grande Formation in Patagonia. These facts show that the Patagonian terrane may have been situated as the conjugate margin of the Transantarctic Mountains from Southern Victoria Land to the Pensacola Mountains. The rifting of Patagonia from Antarctica and the beginning of subduction along western Patagonia, are correlated among different terranes, showing a robust coherent evolution through early Paleozoic times among these blocks. The final amalgamation of Patagonia with Western Gondwana occurred in late Paleozoic times, but is not analyzed in the present contribution.

Keywords: Archeocyathids, Shackleton Limestones, Early Paleozoic, Orthogneisses, Ross Orogeny

Resumen

Sobre la base de hallazgos recientes de arqueociátidos en depósitos molásicos de edad cámbrica media a ordovícica temprana del norte de la Patagonia, las relaciones entre esta parte del sur de Sudamérica y Antártida Oriental necesitan ser reexaminadas. La edad cámbrica temprana de los arqueociátidos y su derivación de las Calizas Shackleton abren varias alternativas que son evaluadas sobre la base de la litología y las edades U-Pb en circones de diferentes secuencias metamórficas de la Patagonia y de las Montañas Trasantárticas. Sobre la base de estos datos se propone que el Macizo de Somuncurá del norte de la Patagonia fue el margen conjugado de las Montañas Pensacola de Antártida Oriental. Los episodios principales de deformación son correlacionados dentro del orógeno Ross del Cámbrico-Ordovícico, así como el ambiente de margen pasivo durante el Silúrico y el Devónico que indica que la sección inferior del Supergrupo Beacon de Antártida se corresponde con la Formación Sierra Grande de Patagonia. Estos datos muestran que el terreno Patagonia podría haber estado situado como el margen conjugado de las Montañas Trasantárticas desde el sur de la Tierra Victoria hasta las Montañas Pensacola. El rifting de Patagonia de Antártida y el inicio de la subducción a lo largo del oeste de la Patagonia se correlacionan entre diferentes terrenos mostrando una evolución coherente y robusta a lo largo del Paleozoico temprano entre estos bloques. El amalgamiento final de la Patagonia con el Gondwana Occidental se produjo en el Paleozoico tardío, pero no es analizado en la presente contribución.

Palabras clave: Arqueociátidos, Calizas Shackleton, Eopaleozoico, Ortogneises, Orogenia de Ross

1. Introduction

The recent discovery of archeocyathids in the Somuncurá Massif of northern Patagonia has produced a plethora of studies dealing with the origin and provenance of Patagonia (González *et al.*, 2011 a,b,c, 2013; Rapalini *et al.*, 2010; López de Lucchi *et al.*, 2010; Chernicoff *et al.*, 2013; Tomezzoli, 2012; Ramos and Naipauer, 2012; Tomezzoli *et al.*, 2013). These studies attempt to decipher the geological history of Patagonia, and propose several alternatives for its original location, based on new geochronological, paleomagnetic, and paleontological data. Two leading hypotheses, which have the higher consensus, will be evaluated. The first hypothesis considers all Patagonia, including the Somuncurá Massif, to be allochthonous with respect to Western Gondwana during Paleozoic times (see Ramos 1984, 2008 for a review of these studies). The second hypothesis considers northern Patagonia to be autochthonous, and only the Deseado Massif located in southern Patagonia, to be allochthonous (Pankhurst *et al.*, 2006; Martínez Dopico *et al.*, 2011). Some intermediate alternatives regard Patagonia as a paraautochthonous terrane, detached from Western Gondwana and reamalgamated during late Paleozoic times (Rapalini, 2005; López de Lucchi *et al.*, 2010; Rapalini *et al.*, 2010; Tomezzoli *et al.*, 2013). A few other studies consider all Patagonia to be autochthonous (Gregori *et al.*, 2008; Rapalini *et al.*, 2013, among others).

The objective of the present study is to evaluate the provenance of the Patagonian basement based on the large U-Pb data-base that is available, to compare it with the Transantarctic Mountains basement, and to incorporate the occurrences of the archeocyathids and the geological evolution of these potential areas to further constrain the possible location of Patagonia in Eastern Gondwana. In order to evaluate the different potential scenarios the data-base has been divided in two broad time intervals, the pre-Silurian and the Silurian-Devonian, both in Patagonia and in the Transantarctic Mountains.

The present location of Patagonia is indicated in figure 1, as well as the late Paleozoic suture with the rest of South America and the early Paleozoic continental margin of the Transantarctic Mountains in East Antarctica. This continental margin is associated with the carbonate platform of the Shackleton Limestone of early Cambrian ages as indicated by Stump (1995), among others.

2. Pre-Silurian Geology of Patagonia

We have adopted for the present analysis the northern boundary of Patagonia as the one accepted by the *Servicio Geológico Argentino*, based on structural, geophysical, and other geological on-land features, combined with the data available on the offshore platform in the Atlantic side (see details in Ramos *et al.*, 2004).

The northern boundary is outlined by the Huincul Ridge (Fig. 2), a basement feature inherited by the collision of Patagonia that splits the Neuquén Basin in two distinct depocenters as proposed by Bettini (1984), Franzese and Spalletti (2001), Mosquera and Ramos (2006), among others. Along the offshore, this boundary has been identified by the Tona magnetic anomaly by Ghidella *et al.* (1995), Max *et al.* (1999), and Pángaro and Ramos (2012).

Metamorphic and igneous rocks of Cambrian and Ordovician age are only known along the eastern margin of Patagonia which can be divided in three sectors, Sierra Grande in the north, Deseado Massif in the centre, and the subsurface of Tierra del Fuego to the south.

The best known exposures are in the northeast near Sierra Grande and east of El Jagüelito Fault (Fig. 2). There are widespread exposures of Late Carboniferous to Permian granitoids that intrude Cambrian–Ordovician metamorphic rocks (López de Lucchi *et al.*, 2010; Martínez Dopico *et al.*, 2011). In the area west of Sierra Grande there are highly deformed porphyritic granodiorite-biotite monzogranites, as the Tardugno Granodiorite, which in its type locality yields an age of 528.5 ± 3.5 Ma (U-Pb SHRIMP data, Rapalini *et al.*, 2013). The metaclastic units of the Nahuel Niyeu Formation with some levels of metavolcanic rocks broadly related with an active margin environment yields detrital zircons older than 515 Ma (Pankhurst *et al.*, 2006) for the lower grade rocks near Puesto Naverrete (Fig. 2). The studies of Martínez Dopico *et al.* (2011) provided Sm-Nd isotopic data, which yielded T_{DM} ages of 1.7 Ga and epsilon Nd of -5.07 calculated for the deposition time of the fine grained schists. These data are consistent with sialic Mesoproterozoic basement that was recycled during younger (Cambrian) magmatic activity. Recent studies of Chernicoff *et al.* (2013) in this area have also shown an old basement inheritance in the late Paleozoic granitoids.

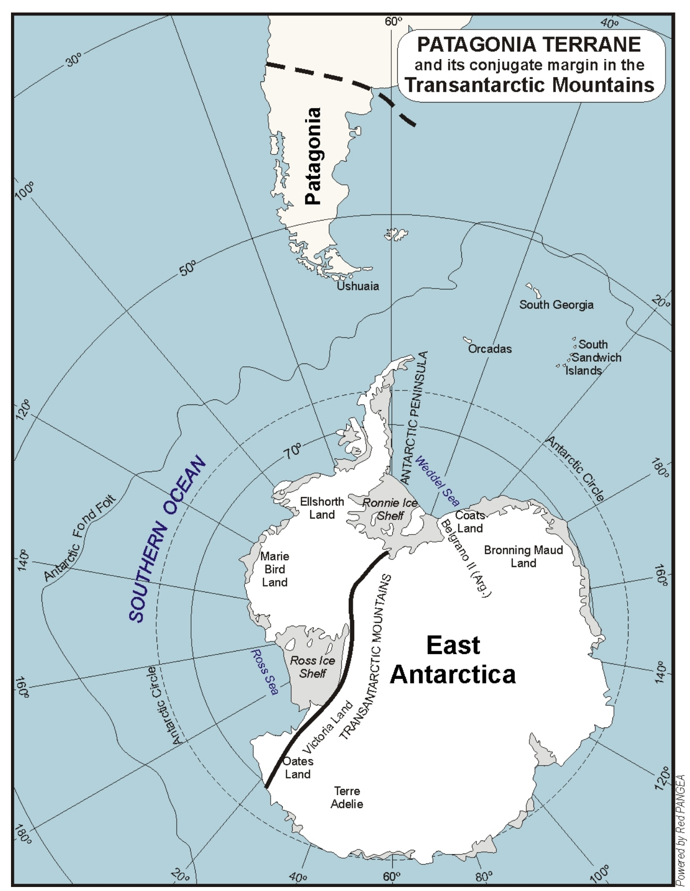

Fig. 1.- Present location of Patagonia, its late Paleozoic suture with the rest of South America (after Ramos, 2008), and the outline of the early Paleozoic continental margin of the Transantarctic Mountains in East Antarctica (after Stump, 1995).

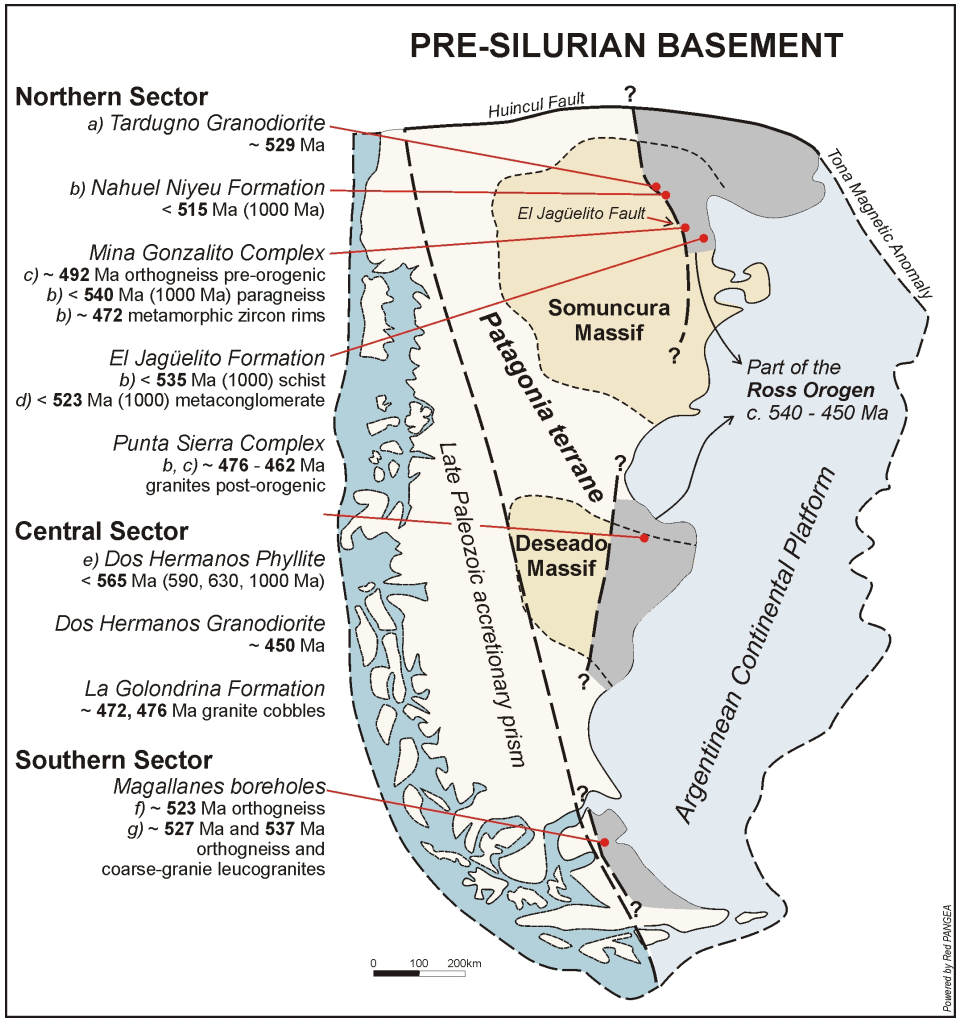

Fig. 2.- Main exposures of the pre-Silurian metamorphic and igneous basement known in Patagonia. Ages are based on the following sources: a) Rapalini *et al.* (2013); b) Pankhurst *et al.* (2006); c) Varela *et al.* (2011); d) Naipauer *et al.* (2010); e) Pankhurst *et al.* (2003); f) Söllner *et al.* (2000) and g) Hervé *et al.* (2008).

Further to the east near Sierra Grande (Fig. 2), the Mina Gonzalito Gneiss (Ramos, 1975) yielded a maximum age of 540 Ma with older zircons around 1,000 Ma (Pankhurst *et al.*, 2006). This paragneiss has a metamorphic age obtained by U-Pb SHRIMP from zircon rims of ~ 472 Ma (Pankhurst *et al.*, 2006). González *et al.* (2008a) identified in the Mina Gonzalito Gneiss two belts of rocks in tectonic contact outlined by a ductile shear zone. The eastern belt has dominant paragneisses and has been studied by Pankhurst *et al.* (2006). The western belt is characterized by a high grade metamorphism that affected pre- and syntectonic granitoids (González *et al.*, 2008 a). A pre-tectonic granodioritic orthogneiss of this belt has been dated by U-Pb SHRIMP in zircons at *ca.* 492 Ma (Varela *et al.*, 2011).

The El Jagüelito Formation, a unit correlatable with the Nahuel Niyeu Formation, outcrops to the south around Sierra Grande, and is mainly composed of slates, phyllites and metawackes, metasandstones and minor intercalations of metaconglomerates, felsic-to-mafic metavolcanic rocks and metaignimbrites (Naipauer *et al.*, 2010; González *et al.*, 2011a, b). Youngest detrital zircons yields ca. 535 Ma for a fine grained meta-sandstone (Pankhurst *et al.*, 2006) and ca. 523 Ma for a meta-conglomerate (Naipauer *et al.*, 2010). Further to the east along the Atlantic cost, there are some post-tectonic granitoids that yield ages around 476-462 Ma in Punta Sierra (Pankhurst *et al.*, 2006; Varela *et al.*, 2008). The schists of El Jagüelito Formation have interbedded meta-conglomerates with limestone clasts bearing well preserved archeocyathids. These fossils were studied by González *et al.* (2011a), who were able to correlate these archeocyathids with those typical from the Shackleton Limestone of the Transantarctic Mountains of late lower Cambrian age. This finding confirms that the protolith of these schists should be younger than 523 Ma and older than 476 Ma, the age of the granites emplaced in the unit (middle Cambrian-Lower Ordovician). As emphasized by several authors, the endemism of the archeocyathids within Gondwana precludes correlation between these austral Antarctic forms with the northern archeocyathids of northern Africa and Spain.

The central sector comprises the exposures of the Deseado Massif (Fig. 2). The metamorphic rocks of this area have a maximum protolith age of 565 Ma, based on the youngest detrital zircons obtained from Dos Hermanos Phyllite, and a minimum age of 450 Ma, which is the age of a granitoid emplaced in the schists (Pankhurst *et al.*, 2003). The pattern of detrital zircon ages of the phyllite is characterized by peaks at ca. 590, 630, 865, 1060, and 2000 Ma.

Several authors proposed the southern extension of the Cambrian Pampean orogeny along Patagonia and correlated this deformation with the Ross Orogeny in Transantarctic Mountains (Aceñolaza and Miller, 1982). More recent studies from borehole data of the southern sector obtained a U-Pb TIMS age of 523 Ma for orthogneisses in extra-Andean Tierra del Fuego (Fig. 2, Söllner *et al.*, 2000). Hervé *et al.* (2008) have studied basement samples of several wells along the Magellan Strait that constrained by U-Pb SHRIMP in zircons the age of orthogneisses between 527 and 537 Ma.

3. Pre-Silurian-Devonian Geology of the Transantarctic Mountains

The Ross Orogen as described by Stump (1995) is characterized by a passive margin as the result of Rodinia break-up during the Neoproterozoic, which includes the lower Cambrian Shackleton Limestone. This broad carbonate shelf of unknown width extends as an almost continuous belt of 1200 km from the Argentine Ranges in northern Pensacola Mountains, up to south of the Byrd glacier (Rowell *et al.*, 1992). This carbonate sequence is unconformably overlain by the Douglas Conglomerate, which is an expression of the first intense deformation that occurred along the orogen during the middle Cambrian (Rowell *et al.*, 1992; Stump, 1995), which is in turn followed by the final late Cambrian - Early Ordovician Ross deformation. The early deformation is recognized from the Pensacola and Queen Maud Mountains to further north in the Central Transantarctic Mountains (Goodge *et al.*, 2004).

The close similarity between the archeocyathids of East Antarctica and the forms found in the clasts of El Jagüelito Formation indicates a probable derivation from this region (González *et al.*, 2011a,c). These authors favored a provenance from the Shackleton Limestone, which is unconformably covered by the Douglas Conglomerate (Goodge *et al.*, 2004 and references therein). This metaconglomerate contains clasts of the underlying limestones and is petrographically quite similar to the El Jagüelito Formation metaconglomerate (González *et al.*, 2011a). It is evident that the Transantarctic Mountains limestones were the source of limestone blocks and erratics for a very long time, as has been proposed for the fossiliferous Permo-Carboniferous tillites from Antarctica (Debrenne and Kruse, 1986), South Africa (Debrenne, 1975), the Malvinas Islands (Keidel, 1916; Stone and Thomson, 2005), the Sierra de la Ventana tillites (González *et al.*, 2013), as well as for recent moraines (Hill, 1965).

Although the Shackleton Limestone may be the source of the clasts found in Patagonia, the large extension of this platform makes it important to analyze and evaluate the different metamorphic rocks associated with the limestones. Some of these metamorphic rocks may correlate with the pre-Ordovician rocks of Patagonia previously described. The main metamorphic and igneous units of the different sectors will be briefly analyzed in order to compare the lithology and the potential correlations with the Transantarctic Mountains (Fig. 3).

The Pensacola and the Thiel Mountains are located at the northern extreme of the Transantarctic Mountains and are characterized by reduced and isolated outcrops of basement rocks. The lithology and detrital zircon patterns of this region are similar to the northern sector of Patagonia. Low-grade metamorphic sequences of the Pensacola Mountains consist of metasandstones and slates of the Hannah Ridge and Patuxent Formations, the Nelson Limestone, and volcanic rocks of Gambacorta Formation (Stump, 1995; Curtis *et al.*, 2004). The detrital zircon patterns of Patuxent Formation have a dominant frequency peak of 530 Ma, and secondary peaks of 670, 1050, and 1185 Ma (Fig. 4). That pattern is very similar to the detrital zircon age populations of El Jagüelito Formation (González *et al.*, 2011a,c) (Fig. 4). In the Thiel Mountains, exposed porphyries (493 Ma; Rb-Sr whole rock), Reed Ridge granites (ca. 491 Ma; Rb-Sr whole rock), and small stocks with cross-cutting relations with the porphyries occur, as well as the coeval Mount Walcott Formation, a volcanosedimentary sequence of *ca.* 480 Ma (Rb-Sr whole rock, Pankhurst *et al.*, 1988). Although there is not an exact equivalent of these rocks in Patagonia, the Reed Ridge Granite has similar ages to the pretectonic orthogneisses of Mina Gonzalito Formation dated by Varela *et al.* (2011) in *ca.* 492 Ma by U-Pb in zircons. The Mount Walcott Formation may be correlated with the siliciclastic metasedimentary rocks and interbedded siliceous metavolcanic rocks of El Jagüelito Formation, as suggested by the presence of similar trace fossil assemblages consisting of *Planolites* and *Chondrites* in the clastic sequences (Pankhurst *et al.*, 1988; González *et al.*, 2002).

The Queen Maud and Horlick Mountains characterized the northern Transantarctic Mountains formed by the Queen Maud-Wisconsin Range batholith between the Shackleton Glacier and the Reedy Glacier (Fig. 3). These rocks are part of the Granite Harbour Intrusives (lower Cambrian to Ordovician) that extend to Victoria Land as part of the Ross magmatic arc. The country rock in this sector is composed by volcanosedimentary low-grade metamorphic rocks, where the oldest unit is the La Gorce Formation with metagraywackes and slates similar to the Goldie Formation of the central Transantarctic Mountains (see below). Above the La Gorce Formation in tectonic and intrusive contact, it is the Liv Group (Wyatt and Ackerman formations) that according to Warenham *et al.* (2001). The Wyatt and Ackerman formations are dominated by lavas of dacitic composition with ages *ca.* 525 Ma (U-Pb; Encarnación and Grunow, 1996); the rest of the Liv Group (Taylor, Fairweather, and Leverett formations) consists of a succession of low-grade metasedimentary and metavolcanic rocks of bimodal composition, mainly rhyolites and basalts with ages *ca.* 515 Ma (U-Pb; Encarnación and Grunow, 1996). Although El Jagüelito Formation

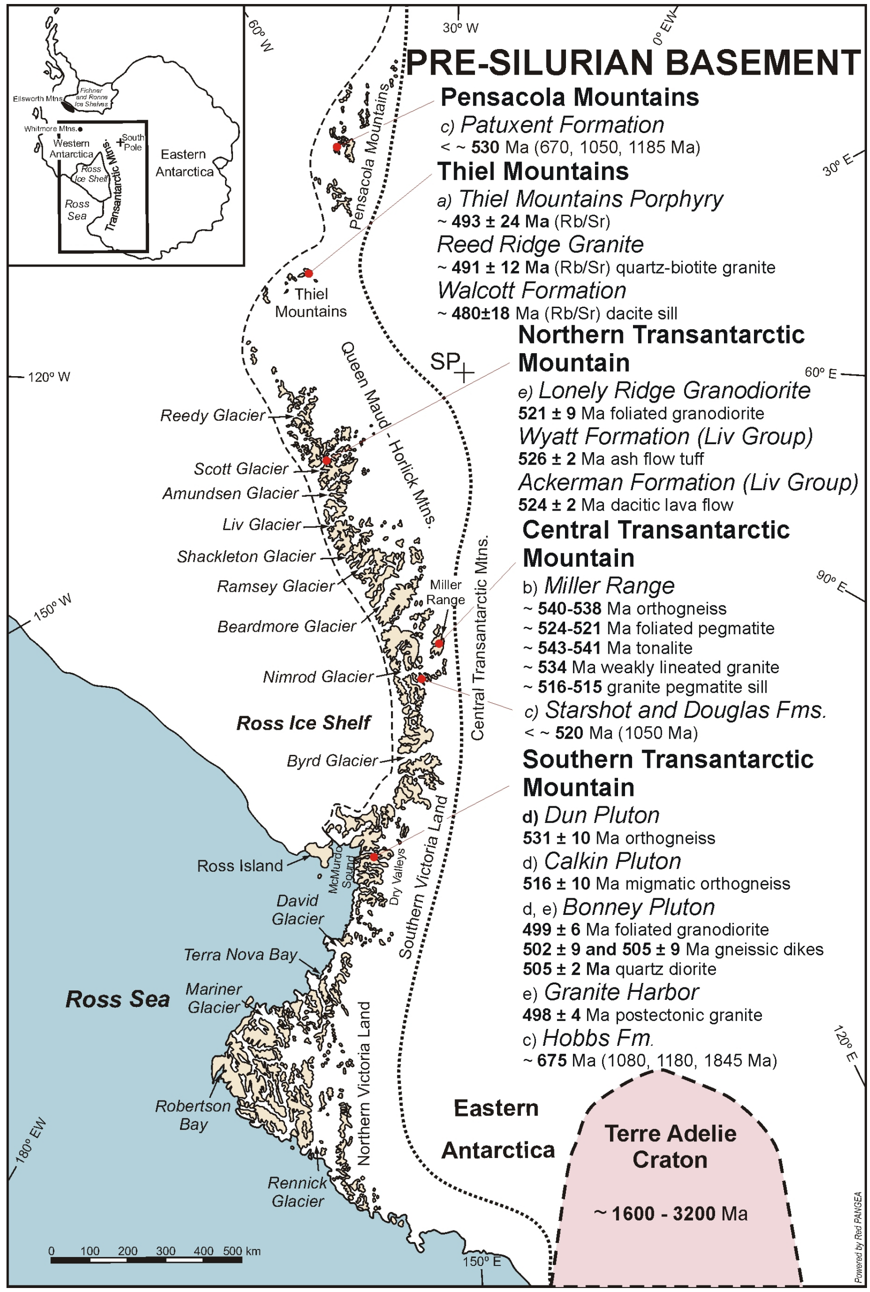

Fig. 3.- Main basement provinces of the Transantarctic Mountains with dominant ages. Based on: a) Pankhurst *et al.* (1988); b) Goodge *et al.* (1993b); c) Goodge *et al.* (2004); d) Alibone and Wysoczanski (2002) and e) Encarnación and Grunow (1996).

is described as a metaclastic sequence, several authors have identified interbedded metavolcanic rocks of felsic to mafic composition (De Alba, 1964; Naipauer *et al.*, 2010; González *et al.*, 2011a,b), which have not yet been dated. In the Queen Maud and Horlick Mountains, as part of the Granite Harbour Intrusives are small pretectonic stocks with U-Pb ages between 521 and 531 Ma (Encarnación and Grunow, 1996). Along the eastern border of Patagonia, there are orthogneisses with similar ages to the Tardugno metagranodiorite in the north and the Magallanes boreholes in the south (Fig. 2). There are also clasts of orthogneisses in the El Jagüelito Formation as described by González *et al.* (2008b). These orthogneisses could be considered to be associated with the early arc stage of the Ross magmatic arc (Fig. 3), emplaced prior to the final deformation.

The Central Transantarctic Mountains have more complex lithological variations with igneous and sedimentary protoliths, but of different ages. The oldest units, the Nimrod Group, contains sedimentary protoliths and some orthogneisses, and mafic and ultramafic rocks that have been metamorphosed to amphibolite facies. The Nimrod Group is exposed only in the Miller Range (Fig. 3) where it yields ages ranging from Archean to Paleoproterozoic (Goodge *et al.*, 1993a). Rocks as old as the Nimrod Group are not known in Patagonia, although some zircon cores from orthogneisses with inherited Archean ages have been reported (Rolando *et al.*, 2002; Chernicoff *et al.*, 2013). The unconformably overlying Neoproterozoic to Cambrian Beardmore Group, composed by the Cobham and Goldie formations is comprised of a thick low grade metamorphic sequence of sandstones, slates, carbonates, diamictites with minor intercalations of volcanic rocks (Goodge *et al.*, 2002, 2004). The Goldie Formation is intruded by Neoproterozoic gabbros and U-Pb detrital zircon ages indicate Mesoproterozoic to Archean cratonic sources (Goodge *et al.*, 2004).

González *et al.* (2011a,b) correlated the El Jagüelito Formation of northern Patagonia with the Goldie Formation, because in the Herradura del Salado in northern Patagonia, metapelites and metawackes were emplaced by diabases and microgabbros. However, the detrital patterns of El Jagüelito Formation and the Goldie Formation are not comparable. The basement of the Transantarctic Mountains ends with the sedimentary rocks of the Byrd Group, which is in tectonic contact with older rocks. This group begins with the Shackleton Limestone that contains lower Cambrian archeocyathids (Myrow *et al.*, 2002). Above the limestones, the Holyoake and Starshot formations and the Douglas Conglomerate are conformably deposited. The Starshot Formation contains pelites, sandstones and some interbedded conglomeratic horizons, whereas the Douglas Conglomerate has coarse conglomerates with clasts of folded Shackleton Limestone, together with clasts of quartzites, felsic volcanic rocks, gneisses, and granites (Goodge *et al.*, 2004). The U-Pb detrital zircon ages have a dominant *ca.* 525 Ma population, a secondary ca. 1050 Ma peak, with subordinates 1500 and 3000 Ma peaks.

Based on the similar lithological composition of the Byrd Group and mainly on the characteristics of the Douglas Conglomerates, several recent studies have compared these units to the El Jagüelito Formation of northern Patagonia (González *et al.,* 2011a,b). Naipauer *et al.* (2010) found similar detrital zircon patterns of the interbedded conglomerates in the El Jagüelito Formation with those in the Douglas Conglomerate. However, in contrast with all the pre-Ordovician units of northern Patagonia, the Byrd Group is characterized by the presence of different Mesoproterozoic and Archean peaks (Fig. 4). Another first order difference is the absence of volcanic rocks in the Byrd Group which are an outstanding component in the El Jagüelito Formation.

The Southern Victoria Land has some strongly deformed metamorphic rocks and consists of Early Cambrian to Ordovician calcalkaline and alkaline rocks that predate the Granite Harbour intrusions. The high grade metamorphic rocks are assigned to the Neoproterozoic, and based on crosscutting Granite Harbour plutons a minimum age of 550 Ma was given (Goodge *et al.*, 2004). Some detrital zircons from Hobbs Formation, one of the principal units of this sequence yielded Meso- and Paleoproterozoic ages that are very different from the sources detected in Patagonia (Fig. 4).

Based on these descriptions, it is probable that the middle Cambrian - Lower Ordovician ash-flow tuffs, lavas, volcanic breccias, and agglomerates of rhyolitic and dacitic composition known in the Neptune Ranges in central Pensacola Mountains (Stump, 1995) could be the sources of the detritus found in El Jagüelito Formation, a hypothesis that is reinforced by the detrital sequence distribution as seen in figure 4.

All these metamorphic successions are folded and deformed beneath the lower Beacon Supergroup, a flat-lying shallow marine clastic sequence of Early Devonian to Triassic age, preserved from the Pensacola Mountains to the Southern Victoria Land (Bradshaw, 1991). The Beacon Supergroup is developed throughout most of the Transantarctic Mountains, with the only exception of Northern Victoria Land. Quartzose sandstones were deposited in an epicontinental marine environment during Early Devonian times, although in the Pensacola Mountains sedimentation started earlier. Similar rocks are exposed in the Ellsworth Mountains but with deeper marginal facies. If these mountains are restored to a Paleozoic position, the Ellsworth facies would indicate a marginal environment similar to deposits of the same age in South Africa (Bradshaw, 1991) and in Sierra de la Ventana (Ramos, 2008). In the Ohio Range, located south of the Pensacola Mountains, typical Malvinokaffric faunas of Devonian age are similar to the South American faunas.

4. Silurian-Devonian Geology of Patagonia

The eastern margin of Patagonia records an important sedimentary sequence that unconformably overlies the deformed pre-Silurian basement near Sierra Grande (Fig. 5). The Sierra Grande Formation, a quartzose clastic shallow water succession, contains a poorly preserved Malvinokaffric fauna of brachiopods and trilobites of lower Silurian to Lower Devonian age (Manceñido and Damborenea, 1984; Limarino *et al.*, 1999). The U-Pb detrital zircon analyses show a maximum sedimentation age of ca. 428 Ma (Uriz *et al.*, 2011) for the middle part of this 2,130m thick sequence.

Highly deformed quartzites west of Sierra Grande in the Nahuel Niyeu area were assigned to this unit by Von Gosen (2003). This deformation was attributed to the late Paleozoic collision of Patagonia. South of Sierra Grande several isolated outcrops of the Sierra Grande Formation were recognized by Cortés *et al.* (1984).

These outcrops may extend to the northeastern corner of the Deseado Massif, where the southernmost basement rocks are exposed in Cabo Blanco (47°19′S, 65°44′ W. Fig. 5) along the coast (Márquez and Navarrete, 2011). These authors assigned a probable Devonian age to these rocks, criteria previously proposed by Darwin (1846), who correlated these rocks with the Devonian quartzites of the Malvinas Island.

Metasedimentary deposits of Devonian age bearing Malvinokaffric fauna were described in the accretionary prism of Chile at 42º24'S latitude. A series of slates metamorphosed in the late Paleozoic known as the "Pizarras de Buill" and bearing trilobites were described by Fortey *et al.* (1992). These authors interpreted the slates to represent the western edge of a large shallow water platform with similar faunas found in Argentina, Bolivia and South Africa.

Along most of the western margin of Patagonia there is an oblique belt of calcalkaline magmatic rocks (Halpern, 1968, 1973), interpreted as a Paleozoic magmatic arc by Ramos

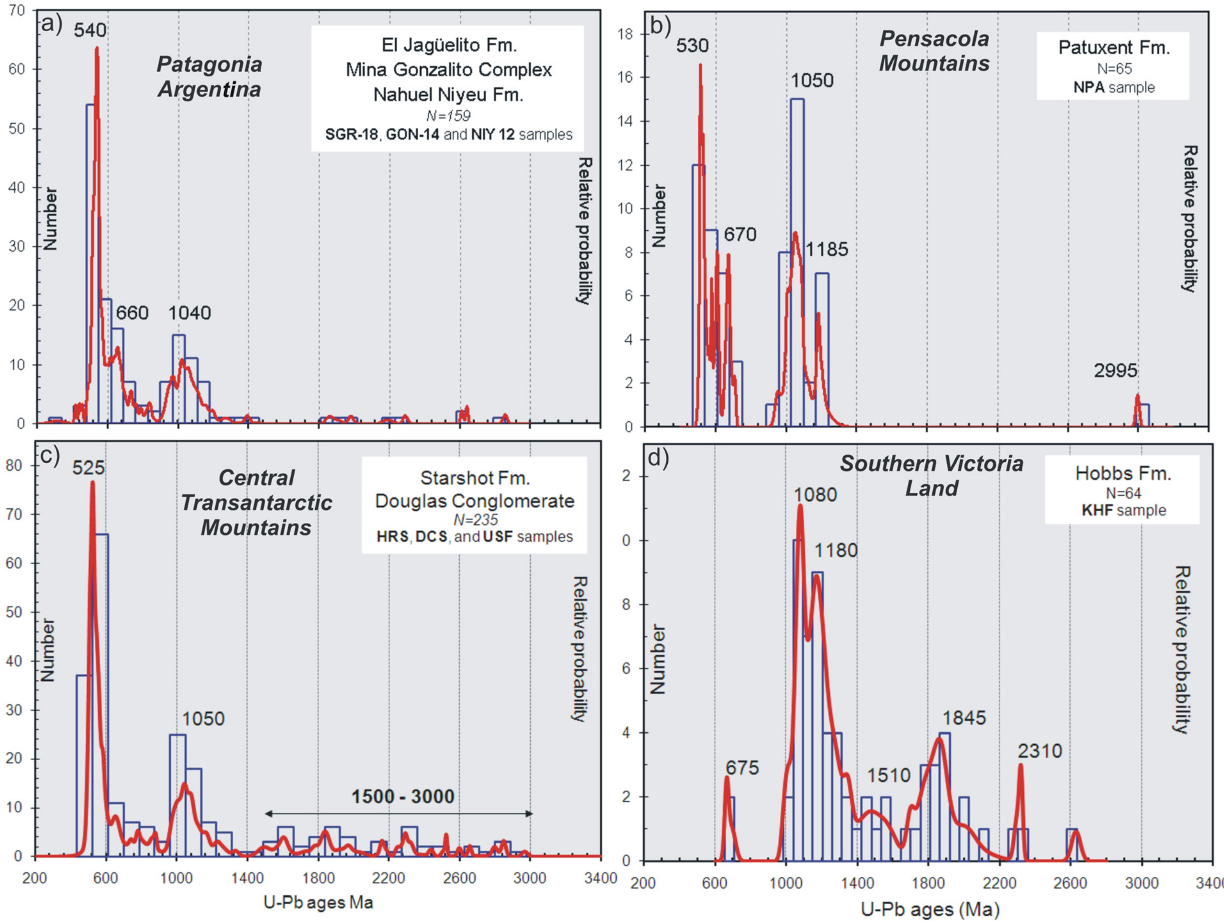

Fig. 4.- U-Pb detrital zircon age patterns to compare (a) the pre-Ordovician basement of northern Patagonia with (b) the Pensacola Mountains, (c) Central Transantarctic Mountains and (d) Southern Victoria Land (references in Fig. 3).

(1983). More recent studies identified this arc as exhumed during a collisional episode in late Carboniferous times (Pankhurst *et al.*, 2006).

The existing geochronological data presented in figure 5 indicate the development of a magmatic arc between late Silurian and Middle Devonian times. This belt is associated with schists and meta-quartzites described by Moreira *et al.* (2007) along the western side of the Deseado Massif, and interpreted as forearc deposits. This magmatic arc lasted until the late Carboniferous when the amalgamation of the Antarctic Peninsula block occurred at southern Patagonia (Ramos, 2008). All along the western margin of Patagonia a wide late Paleozoic – early Mesozoic accretionary prism is well preserved (Hervé *et al.*, 2003).

5. Discussion

The similarities in the basement of the Pensacola Mountains and northern Patagonia are quite striking. Both basements share a common pattern of detrital zircons (Fig. 4a, b), with frequency peaks in the Neoproterozoic and Grenville-age Mesoproterozoic, and gaps in the older zircons. The Patuxent Formation has common lithological features with El Jagüelito Formation, similar metamorphic grade, and interbedded conglomeratic lenses and volcanic rocks (Stump, 1995; Goodge *et al.*, 2004). The resemblance goes behind that fact, since the Shackleton Limestones is the most probable source for the carbonate clasts of the El Jagüelito Formation.

If this correlation is accepted as the best match, then Patagonia would be located as indicated in figure 6, a position somewhat similar to the one proposed by Aceñolaza *et al.* (2002). This location is further north of the one proposed by González *et al.* (2011a, c).

There are some striking features with this newly proposed position of Patagonia. The entire Patagonia is north of Northern Victoria Land, where some early Paleozoic terranes have been amalgamated with East Antarctica during the Ross Orogeny, as noticed since the early work of Bradshaw *et al.* (1985). The Bowers and Robert Bay terranes of Northern Victoria Land, accreted by the end of the late Cambrian, have a top-to-the present ocean vergence compatible with a previous subduction toward East Antarctica (Tessensohn and Henjes-Kunst, 2005). Those terranes still remain attached to East Antarctica.

From Southern Victoria Land to Pensacola Mountains there is evidence of metamorphism and collision, but the counterpart is missing. Besides, in southern Patagonia there are orthogneisses with ages between 527 and 537 Ma (Hervé *et al.*, 2008)

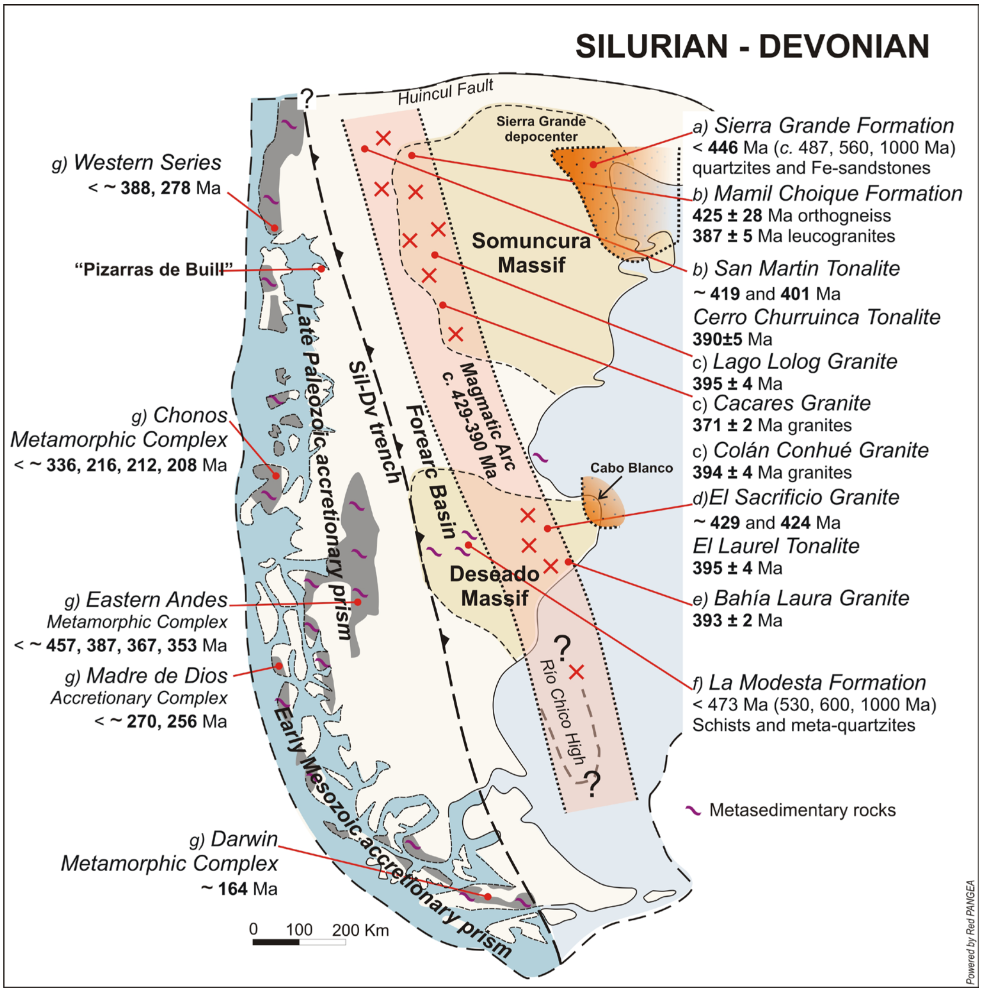

Fig. 5.- Paleogeographic reconstruction of Patagonia with the location of the proposed Devonian magmatic arc and the original subduction trench in Silurian – Devonian times prior to the development of the late Paleozoic accretionary prism (modified from Halpern, 1968; Ramos, 1983, and data from (a) Uriz *et al.*, 2011); (b) Varela *et al.*, 2005; (c) Pankhurst *et al.*, 2003; (d) Pankhurst *et al.*, 2006; (e) Guido *et al.*, 2005; (f) Moreira *et al.*, 2007 and (g) Hervé *et al.*, 2003).

in the basement. These ages are similar to the age of high-grade metamorphic and intrusive rocks of the Ross orogen described in the Queen Maud and Horlick Mountain by Paulsen *et al.* (2012) (see location in Fig. 3). There, two orthogneisses from the Bravo Hills near Shackleton Glacier, yielded igneous protolith crystallization ages of 535 ± 8.9 Ma and 517 ± 6.5 Ma, a similar range to the Magallanes orthogneisses described by Söllner *et al.* (2000) and Hervé *et al.* (2008). This clearly implies that eastern Patagonia was part of the Ross Orogeny. The southern sector has evidence of the early Ross deformation sensu Rowell *et al.* (1992) and Stump (1995), depicted by Paulsen *et al.* (2012) in the Queen Maud batholith.

The northern sector of Patagonia has younger deformation as indicated by the 492 Ma orthogneisses described by Varela *et al.* (2011). However, as noticed by Chernicoff *et al.* (2013), a number of units such as the Ordovician Arroyo Salado Granite (inheritance at 531–572 Ma), the Ordovician Sierra Grande Granite (inheritance at 502–506 Ma), the Permian Boca de la Zanja Granodiorite (inheritance at 511 Ma), the Permian Navarrete Granodiorite (inheritance at 514 Ma), as well as the youngest and predominant detrital zircon age peaks dated at *ca.* 535 Ma and 535–540 Ma yielded by the El Jagüelito Formation and the Mina Gonzalito Gneiss, respectively, have been interpreted as resulting from erosion from a nearby, coeval, and active magmatic arc (Pankhurst *et al.*, 2006). The analysis of the two conjugate continental margins shows that eastern Patagonia and the Transantarctic Mountains where affected by the Ross Orogeny as previously proposed by Chernicoff *et al.* (2013).

This interpretation means that Patagonia could have been accreted to East Antarctica during middle Cambrian times, and that the Patuxent, El Jagüelito and Starshot formations and the Douglas Conglomerate could represent the synorogenic deformation associated with the collision. On the other hand, after the collision an extensional regime led to the development of a passive margin represented by the Devonian lower section of the Beacon Supergroup. This supergroup was deposited on a regional unconformity surface well preserved from the Pensacola Mountains to the Southern Victoria Land, but it is absent in Northern Victoria Land as noticed by Bradshaw (1991). The accreted terranes in this latter region are still in place, and therefore this gap makes sense. The passive margin quartzites of the Sierra Grande Formation preserved in eastern Patagonia from the Somuncurá Massif to the Cabo Blanco, in the northern Deseado Massif (Fig. 5), could represent the conjugate margin sequence of the lower Beacon Supergroup. Both sequences share a common Devonian history, but the sedimentation was interrupted in Sierra Grande in late

Paleozoic times, whereas the Beacon Supergroup continued to the Triassic in a stable setting.

There are some other similarities as the Devonian Marie Bird granitoids, a calcalkaline suite (Siddoway and Fanning, 2009) associated with subduction of the Marie Bird Land terrane as proposed by Dalziel and Grunow (1985). This magmatic arc with similar polarity is seen in western Patagonia (Fig. 5), with similar ages.

Based on these facts, a tentative tectonic evolution is depicted in figure 7, which in its earlier stage follows the proposal of Goodge *et al.* (2004). The evolution starts with a Neoproterozoic passive margin developed during the Rodinia break-up prior to the inception of the Ross Orogeny (Fig. 7a). Subduction towards East Antarctica is recorded almost all along the Transantarctic Mountains by numerous calcalkaline orthogneisses described in the latest Neoproterozoic to Cambrian times. A carbonate platform represented by the Shackleton Limestones was widely distributed from Argentine Ranges in northern Pensacola Mountains to Victoria Land, and developed as a forearc platform bearing a distinctive fauna Early Cambrian archeocyathids. Parts of these rocks are preserved in eastern Patagonia as described in the Somuncurá and Deseado massifs and in the Magallanes Strait boreholes. These suites of orthogneisses were formed during the early Ross Orogeny, produced by the accretion of Patagonia and other Northern Victoria Land terranes in the middle – late Cambrian.

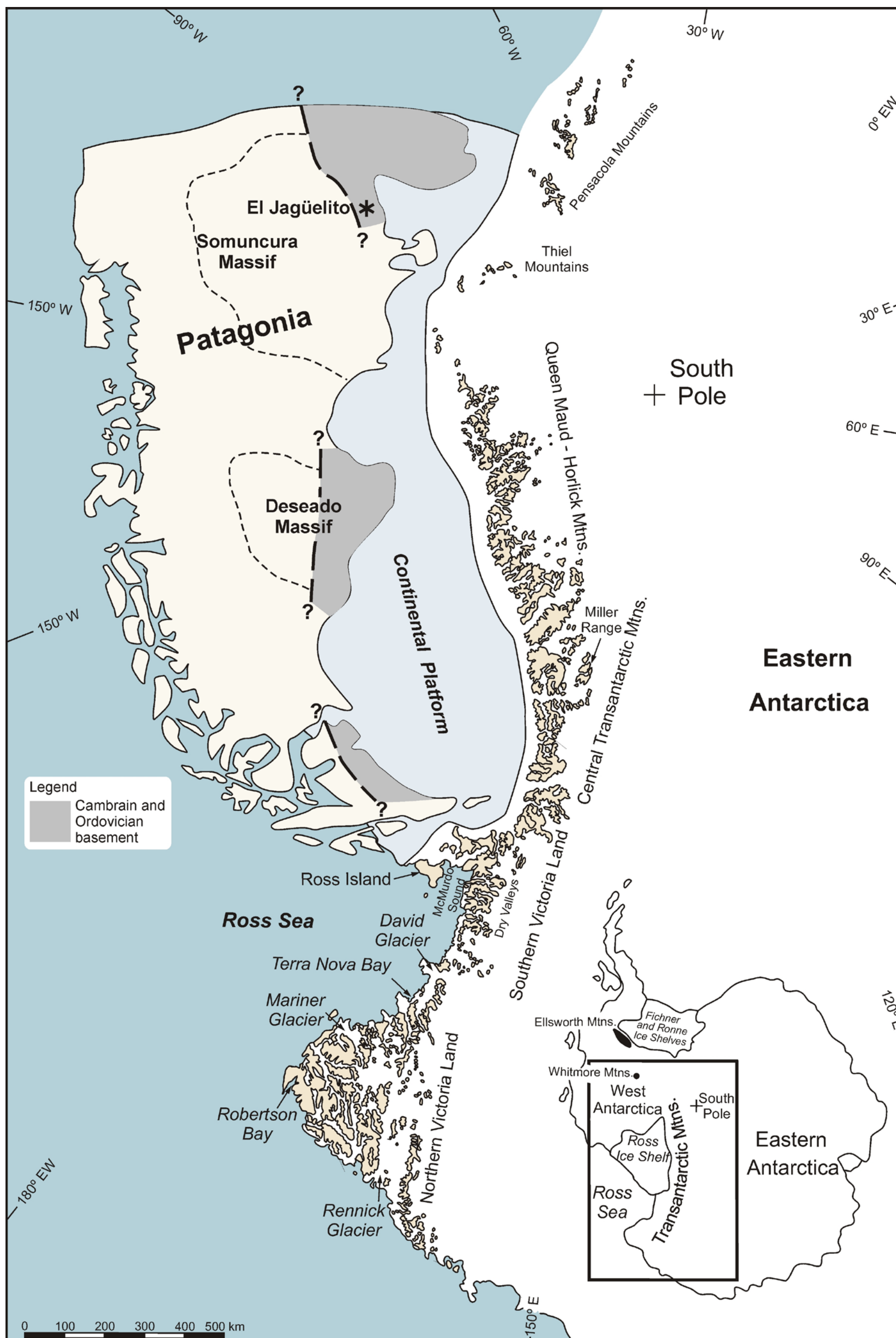

Fig. 6.- Proposed location of Patagonia as conjugate margin of the Transantarctic Mountains. Note that this match implies that the Pensacola Mountains basement should be correlated with the pre-Ordovician basement of the Somuncurá Massif. The Patagonian continental platform includes the Malvinas plateau previous to the Jurassic stretching associated with the opening of the South Atlantic Ocean.

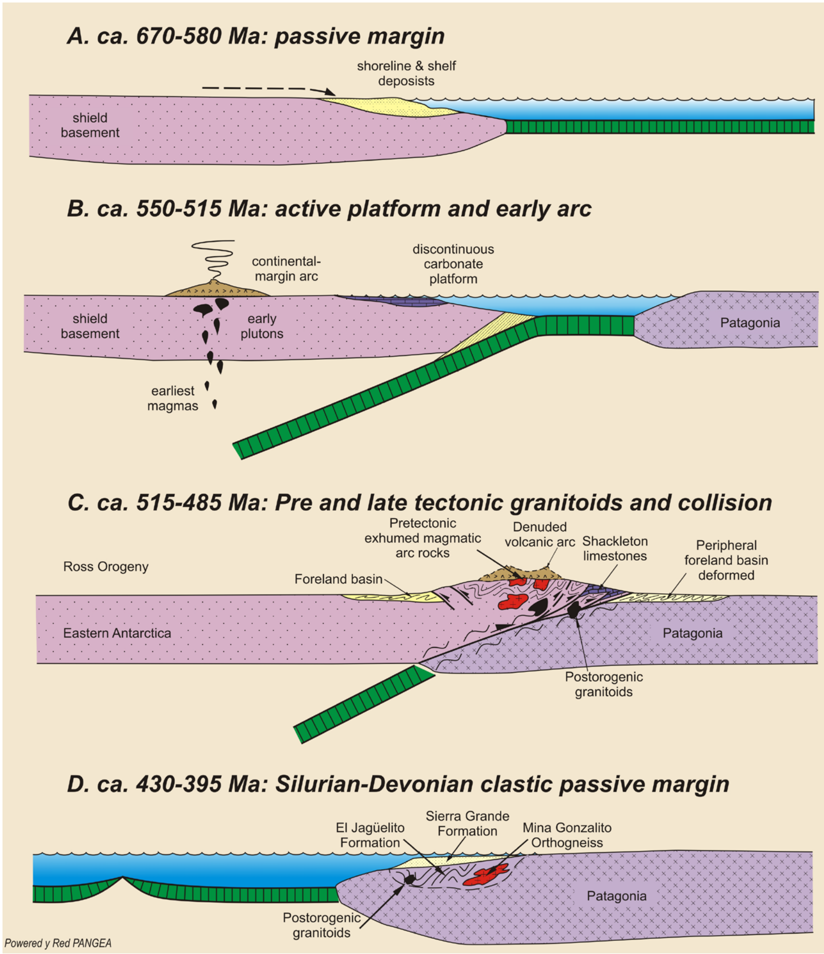

Fig. 7.- Interpretation of the Transantarctic Mountains-Patagonia relationships during Neoproterozoic and early Paleozoic times (modified from Goodge *et al.*, 2004 and Ramos and Naipauer, 2012).

The accretion was not coeval and could be younger to the north. Deformation produced a series of molasse basins where El Jagüelito Formation was deposited in middle-late Cambrian to Early Ordovician times. Erosion of the carbonate platform produced the archeocyathid-bearing clasts of the Shackleton Limestone, as well as clasts of granitoids and volcanic rocks in the conglomerates, whereas some volcanic and pyroclastic lenses were interbedded in this unit (Fig. 7c). The deformation lasted until mid-Ordovician times as part of the main deformational phase of the Ross Orogeny.

During the Late Ordovician and Silurian, post-tectonic granitoids were emplaced in the deformed rocks and rifting and extension led to the final separation of part of the collided block as present Patagonia (Fig. 7d). Sierra Grande Formation quartzites, as well as the lower section of Beacon Supergroup, are the clastic passive margin sequences of these new conjugate margin.

The drift stage of Patagonia in the Devonian is associated with a magmatic arc along its western margin, coeval with the Marie Bird terranes granitoids. Subsequent late Paleozoic collisions amalgamated the northern part of Patagonia to the Western Gondwana as described by several authors (see Ramos, 2008 and cites therein).

6. Concluding remarks

The analysis of the metamorphic rocks in the Transantarctic Mountains and their ages show a close correlation of northern Patagonia basement with the Pensacola Mountains. Southern Patagonia basement have many geological features in common with remaining basement of East Antarctica, mainly south of Southern Victoria Land. Both facts together with the occurrence of archeocyathids point out the potential connections of Patagonia with Eastern Gondwana during early Paleozoic sharing in common the Ross Orogen.

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