THE HESPERIDES BASIN: A CONTINENTAL-SCALE UPPER PALAEOZOIC TO TRIASSIC BASIN IN SOUTHERN GONDWANA

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**ABSTRACT**

The late Palaeozoic to Triassic sedimentary record of the central Argentinean offshore was analysed through the integration of data from exploratory wells and 2D seismic lines. Our interpretations were combined with existing ones in Argentina, Uruguay, Brazil and South Africa for their analysis in the late Palaeozoic south-western Gondwana context. The mapped upper Palaeozoic-Lower Triassic stratigraphic record offshore Argentina bears a thickness of +7.000 m south of the Colorado basin and encompasses the time span between Pennsylvanian and Lower Triassic; this means that it triples that of the Sierras de la Ventana of Argentina and involves a far larger time span. On the basis of seismic stratigraphic interpretations in localities near the coast, we interpret that a strong denudation process removed a

great portion of the stratigraphic record in the Sierras de la Ventana, the surrounding plains and the Tandilia system of Buenos Aires. The seismic stratigraphic configuration of the late Palaeozoic succession shows continuous and parallel reflections in a wide sediment wedge extending for more than 1.000 km between the Gondwanides orogen core to the south and offshore Uruguay to the north. Two salient aspects of this sedimentary wedge are that no flexural depocentre was observed at the Ventania fold belt front, and that deformation in the orogenic front is post-Lower Triassic. The original westwards extent of the basin is interpreted to have encompassed the whole of Buenos Aires province in continuity with the Chacoparaná basin; to the east continuity and a straightforward correlation with the Karoo basin was interpreted. The name of Hespérides Basin (1) is proposed herein to refer to a Pennsylvanian to Lower Triassic basin mainly controlled by dynamic subsidence that encompasses and exceeds the area of the Sauce Grande and Colorado basins and the Claromecó fore-deep in Argentina. The Hespérides basin is interpreted to have been in lateral continuity with the Kalahari, Karoo and Chacoparaná basins of Africa and South America forming a +3,000,000 sq. km depocentre.

Page footer: (1) Hespérides is one of the sons of Zeus, as Adamastor (the Neoproterozoic Ocean) and Atlantis (the Meso-Cenozoic Ocean), all them consecutive basins that opened in the Present South Atlantic.

## 1. INTRODUCTION

### 1.1 Foreword and objectives

The Argentinean continental shelf between 35° and 42° S has a width ranging from 300 to 560 km that has represented a wide blank in the south-western Gondwana reconstructions; recent interpretations based on gravimetric and seismic data provide a comprehensive basement block configuration and tectonic evolution of the area integrated with both onshore Argentina and South Africa (Pángaro & Ramos 2012; Pángaro 2013). However, upper Palaeozoic sedimentary rocks known on the Argentinean continental shelf since the early 80s through exploratory drilling and 2D seismic interpretation (Uliana & Biddle 1987; Archangelsky 1996; Juan *et al.* 1996), have received little effort to integrate them into the south-western Gondwana context. The aim of this paper is to make use of all the available information on the fragmented record of pre-Mesozoic strata, which lie deeply buried underneath the Mesozoic-Cenozoic sedimentary cover, to unravel the stratigraphy and subsidence history of a new sedimentary basin that evolved ahead of the collisional orogen of Patagonia and south-western Gondwana between late Palaeozoic and early Triassic (Ramos 1984, 2008; Rapalini 2005; Rapalini *et al.* 2010; Pángaro & Ramos 2012; Pángaro 2013).

The study area is situated on the eastern margin of the South American plate and extends both onshore and offshore central Argentina between 35° S and 42° S (Fig. 1). The interpretations on the upper Palaeozoic record arising from this study are integrated over 1,000,000 sq. km; however, they were focused in the offshore area thanks to the availability of a dense seismic grid covering 250,000 sq. km. Due to the scale of this analysis, and the distance of several hundreds of kilometres between onshore Argentina localities and the areas covered by seismic data, the Karoo basin of South Africa was included by reason of its proximity in pre-breakup reconstructions.

### 1.2 Methodology and database

In order to interpret the late Palaeozoic to early Triassic stratigraphy of the central Argentinean offshore, selected boreholes were analysed to identify key regional stratigraphic surfaces to calibrate the 2D seismic-stratigraphic interpretations. Thanks to the remarkable lateral continuity of the Palaeozoic record, well-to-seismic calibrations that were extrapolated across hundreds of kilometres led to high confidence interpretations in areas devoid of previous interpretations on the Palaeozoic stratigraphy. This allowed the construction of a 480,000 sq. km sub-unconformity map that helped delineating the pre-Mesozoic units' distribution. Gathered information was integrated in palaeogeographic and palaeoenvironmental maps of the upper Palaeozoic and Lower Triassic, and used for calculating tectonic subsidence curves of the upper Palaeozoic to present time span.

Our well database included wireline logs, cuttings, core descriptions and biostratigraphic data (Archangelsky 1996; Balarino 2009, 2012) from two wells that drilled circa 3,000 m of upper Palaeozoic sedimentary rocks. Data from a series of wells that drilled only a few tens of metres of pre-Mesozoic rocks provided extra tie points. The seismic database comprised 2D lines of highly variable quality acquired through more than 40 years of exploration. Onshore data features published interpretations of the upper Palaeozoic of the Sierras de la Ventana of Buenos Aires (Andreis & Cladera 1992; Andreis & Archangelsky 1996; López Gamundí *et al.* 1995), the Carapacha and San Rafael basins in western central Argentina (López Gamundí *et al.* 1994; Melchor 1999; Azcuy *et al.* 1999; Kleiman & Japas 2009; Pazos *et al.* 2013), the Cuenca Norte of Uruguay (De Santa Anta *et al.* 2006), the Chacoparaná and Paraná basins of north-eastern Argentina and southern Brazil (Zalan *et al.* 1990; Winn & Steinmetz 1998; Milani & Zalan 1999; Azcuy *et al.* 2007; Milani & De Wit 2008) and the Karoo and Kalahari basins of South Africa (Smith *et al.* 1993; Veevers *et al.* 1994; Catuneanu *et al.* 1998; Johnson *et al.* 2006; Lindeque *et al.* 2011; Flint *et al.* 2011).

## 2. REGIONAL SETTING

In order to integrate our interpretations in the south-western Gondwana context, a comprehensive regional stratigraphic and tectonic scenario was set-up on the basis of previously published interpretations from Argentina and South Africa; this section aims to highlight the most relevant features of the upper Palaeozoic to Lower Triassic Gondwana geology that will provided a framework to situate our observations. Upper Palaeozoic stratigraphic evolution of the area was intimately linked to that of the south-western Gondwana convergent margin which was the locus for terrane accretion between Devonian and Triassic (Milani & De Wit 2008). The accretion of Patagonia (Ramos 1984, 2008; Rapalini 2005; Rapalini *et al.* 2010; Pángaro & Ramos 2012; Ramos & Naipauer 2014) and its possible extension into the South African Agulhas plateau (Lindeque *et al.* 2008) was the last collisional event to affect the area and resulted in the evolution of a vast foreland basin, encompassing the present day Karoo basin in South Africa, and the Claromecó (or Sauce Grande – Colorado), Carapacha and San Rafael basins in South America. Patagonia was recently interpreted by Ramos & Naipauer (2013) as a microplate detached from Antarctica and accreted to southern Gondwana between Carboniferous (Ramos 2008) and late Lower Triassic times (Pángaro & Ramos 2012). However, some authors hold different opinions about the allochthonous character of Patagonia and interpreted it as para-autochthonous (Rapalini *et al.* 2010) or even as autochthonous (Rapalini *et al.* 2013; Pankhurst *et al.* 2014).

The regional distribution and tectonic characteristics of late Palaeozoic basins was analysed by Limarino & Spalletti (2006) who recognised three main groups; including intra-cratonic basins, peripheral basins, and active continental-margin basins ("proto-pacific basins") (Fig. 1).

The Claromecó basin (Kostadinoff & Font de Affolter 1982; Ramos 1984; Ramos & Kostadinoff 2005) or Sauce Grande – Colorado basin (Andreis 1984; Azcuy 1985) are terms proposed to refer to the Palaeozoic sedimentary rocks outcropping in the Sierras de la Ventana of Buenos Aires province, and underlying the Cenozoic sedimentary cover to the north (Furque 1965; Lesta & Sylwan 2005). Offshore, these terms include upper Palaeozoic rocks documented by exploratory wells (Archangelsky 1996 and references therein). This basinal extension was interpreted to be partially restricted to the Colorado basin area; however, Permian sedimentary rocks have been interpreted in seismic lines to the north in the Salado basin area (Tavella & Wright 1996) and drilled further north in the pre-rift stage sedimentary record offshore Uruguay (Veroslavsky *et al.* 2003).

Correlation of upper Palaeozoic sedimentary rocks of the Sierras de la Ventana with the Karoo basin and the existence of the trans-continental Gondwanides orogen, were first proposed by Keidel (1913, 1916) and confirmed by du Toit (1927), whose maps envisaged the continuity of the Ventana – Cape fold belt into the Argentinean continental shelf and the extension of the upper Palaeozoic basin (Fig. 1).

The upper Palaeozoic to Triassic stratigraphic record in the studied portion of south-western Gondwana

starts with regionally distributed diamictites and glacigenic deposits related to the peak of the Late Palaeozoic Ice Age (Isbell *et al.* 2012) during late Pennsylvanian to Sakmarian; these are represented in eastern Argentina by the Sauce Grande Formation and in South Africa by the Dwyka Group and equivalent units (Harrington 1947, 1980; Vissier 1987, 1997; Andreis & Torres Ribeiro 2003) (Fig. 2). Above these lie low energy subaqueous deposits bearing the characteristic *Eurydesma* fauna that were referred to as the '*Eurydesma* Transgression' (Smith *et al.* 1993); these include the Piedra Azul Formation in Argentina (Harrington 1947, 1980) and the Prince Albert Formation in South Africa (Johnson *et al.* 1997). In Argentina these transgressive deposits were assigned to the Cisuralian (298.9–272.3 Ma) based on the presence of *Eurydesma* fauna, on the presence of *Malanzania nana* (Morel & Gutierrez 2000) and on recent palynological determinations within the Sauce Grande Formation (Di Pasquo *et al.* 2008). In South Africa and Namibia, detailed U-Pb SHRIMP juvenile zircon dating led to placing the transgression in the latest Sakmarian (290.9±1.7 Ma, Stollhofen *et al.* 2008) (based on the International Commission on Stratigraphy chart 2013).

In South Africa this transgression is overlain by some 200 m of low energy sediments of the Prince Albert, Whitehill and Collingham formations (Aarnes *et al.* 2011) spanning 17 Ma. The Whitehill Formation constitutes a key south-western Gondwana regional marker since it contains *Mesosaurus* fauna that allowed early correlations with the Iratí Formation of the Paraná basin of Brazil, and the El Mangrullo Formation of northern Uruguay (Milani & De Wit 2008 and references therein). This unit has no equivalent in onshore Argentina where the *Eurydesma* transgression is present on top of the glacigenic deposits in the Sierras de la Ventana of Buenos Aires; in this locality a much thinner succession of shales, siltstones and fine-grained sandstones is overlain by a sand-prone marginal marine to continental succession topped by an erosive unconformity (Andreis & Archangelsky 1996).

Above the Whitehill Formation a general regressive trend is interpreted by several authors (e.g. Johnson *et al.* 1997); this is represented in SW South Africa by the upper units of the Ecca Group, namely the Collingham, Vischkuil, Laingsburg, Fort Brown and Waterford formations. On top of these the continental Beaufort Group, whose age was traditionally considered upper Permian, completes the general regression trend. U-Pb SHRIMP age determinations of the underlying Ecca Group by Fildani *et al.* (2009, 2011) suggest a Lower Triassic age for the basal Beaufort Group at 20º E. While newly published results by Rubidge *et al.* (2013) state an uppermost Guadalupian to Lopingian age for the basal Beaufort Group at 25º E, allowing to re-situate it in the upper Permian, the analysis presented by Fildani *et al.* (2011) suggests that continental facies of the Beaufort Group and submarine fan facies of the Laingsburg Formation might have coexisted during the Lopingian (259.8 - 251.2 Ma).

The tectonic evolution of the Karoo basin, traditionally considered a classic foreland basin (Smith *et al.* 1997; Catuneanu *et al.* 2002), has been recently reviewed as having evolved under a rather different scenario (Tankard *et al.* 2009; Flint *et al.* 2011; Lindeque *et al.* 2011; Fildani *et al.* 2011). The classic

interpretations relied heavily on early dating of metamorphic minerals by Hälbich (1983) suggesting a Permian development of the Cape fold belt, hence leading to a foreland scenario with a flexural depocentre (Catuneanu *et al.* 2002 and references therein). On the other hand, new evidence indicates a basin that evolved alongside a collisional orogen, but located farther southwest than previously envisaged. This was earlier proposed by Pysklywec & Mitrovica (1999) who, based on the basin's depocentre wavelength and slope configuration, concluded that only dynamic subsidence was required to account for the origin of the Karoo basin. Evidence supporting the dynamic subsidence model between the Pennsylvanian and Lower Triassic were later provided by several authors; this included the seismic configuration of the Cape fold belt foreland as interpreted by Lindeque *et al.* (2011), stratigraphic interpretations presented by Prélat *et al.* (2009) and Flint *et al.* (2011) suggesting an autocyclic control on the stratigraphic architecture rather than the tectonic influence of a nearby orogen, and also sandstone provenance analysis published by Van Lente (2004) that suggest a North Patagonian massif source for the Upper Ecca Group sediments rather than a Cape fold belt origin.

Due to the reduced area of the Sierras de la Ventana outcrops and intense deformation during the Gondwanides orogeny, analysis of the late Palaeozoic in eastern onshore Argentina relied upon sparse information when compared to its South African counterpart. Westwards, in the La Pampa and Mendoza provinces, isolated outcrops provide insights into the evolution during upper Palaeozoic (Azcuy *et al.* 1999; López Gamundí *et al.* 1994) (Fig. 3). The consequence of the nature of the Argentinean outcrops when compared to the Karoo basin is that in the former the number of studies, was extremely limited: only in recent years were zircons from the outcropping sequence in the Sierras de la Ventana dated (Alessandretti *et al.* 2010; López Gamundí *et al.* 2013; Ramos *et al.* 2013). Despite all this, several authors recognised in Sierras de la Ventana the existence of a circa 2,400 m thick succession initially correlated with the South African Dwyka and Ecca Groups (Keidel 1913) (Fig. 2). This succession shows near reversal of palaeocurrent direction, from N-S to SW-NE, during late Carboniferous to Permian (Andreis *et al.* 1989); Ramos (1984, 2008) interpreted this as the consequence of slope modification during the accretion of Patagonia to south-western Gondwana. Provenance studies suggest that these sedimentary rocks were deposited proximal to an active volcanic arc and an orogen to the south (Andreis & Cladera 1992; López Gamundí *et al.* 1999; López Gamundí 2006; Ramos *et al.* 2013). Immediately to the north, beneath the Cenozoic sedimentary cover of Buenos Aires Province, lies the Claromecó basin (Kostadinoff & Font de Affolter 1982; Ramos 1984) which was previously considered as a foreland basin, in part due to the interpretation by some authors of a Permian age for the deformational event that folded the Sierras de la Ventana (López Gamundí *et al.* 1995; Tomezzolli & Vilas 1999). Subsurface data allows clear correlation with the outcrops of the Sierras de la Ventana (Lesta & Sylwan 2005). Recent thermal maturity determinations in the Paragüil x-1 well, in levels correlated with the youngest rocks that crop out in the Sierras de la Ventana, led to interpreting the erosion of approximately 2 km of overburden (Arzadún *et al.* 2013) probably during the Cretaceous and Cenozoic (Pángaro 2013).

Further west, a series of Upper Carboniferous to Lower Triassic sedimentary and volcanic rocks crop out (López Gamundí *et al.* 1995; Azcuy *et al.* 1999; Kleiman & Japas 2009) (Figs. 2 & 3). The most complete stratigraphic record of this area is represented by the Upper Carboniferous to Lower Permian El Imperial Formation in the San Rafael area of the Mendoza province (López Gamundí *et al.* 1995; Azcuy *et al.* 1999; Henry *et al.* 2014) which is a succession of marine, deltaic and fluvial environment deposits with a glacial-related intercalation that has been correlated to the Glacial Episode II of Bashkirian age (López Gamundí & Buatois 2010 and references therein). This unit shows a basal transgression beneath open marine to deltaic environment sedimentary rocks; in turn overlain by a 300 m glacially-influenced succession (Henry *et al.* 2014 and references therein). Above these lie open marine to shallow marine sedimentary rocks grading into fluvial deposits according to Espejo (1996 in Azcuy *et al.* 1999), while Pazos *et al.* (2013) envisage a persistent subaqueous marine environment.

One regionally significant characteristic of this succession is that it shows a change in palaeocurrents from a SSW direction during Pennsylvanian to a NE direction during upper Pennsylvanian to Cisuralian. The youngest age determined for the El Imperial Formation is lower Cisuralian (297.2±5.2 Ma) (Rocha-Campos *et al.* 2011); its upper contact is an angular unconformity capped by the Cochicó Group, a subduction-related succession (Kleiman & Japas 2009) dated by U-Pb SHRIMP of juvenile volcanic zircons as 281.1 ± 2.5 Ma (upper Cisuralian) (Rocha-Campos *et al.* 2006). The top of the Cochicó Group is marked by another angular unconformity dated 265±2.6 Ma (Guadalupian) (Rocha-Campos *et al.* 2006). These stratigraphic relationships led several authors to interpret the San Rafael orogenic phase, affecting the area roughly between 280 and 260 Ma. (Kleiman & Japas 2009; López Gamundí *et al.* 2013). At the top of the arc-related magmatic units, a Lower Triassic extension-related volcanic unit marks the end of compressive deformation associated with the Gondwanides orogeny (Kleiman & Japas 2009 and references therein). Between the San Rafael and the Sierras de la Ventana localities lies the Carapacha basin of the La Pampa province, the only local remnant of upper Palaeozoic sedimentary rocks, where the 4,000 m thick Carapacha Formation is characterised by two main units separated by an angular unconformity. The lower one bearing fine-grained sediments interpreted as deposited in a lacustrine environment, and an overlying one characterised by coarser grained arkosic sedimentary rocks interpreted as deposited in a braided fluvial environment (Melchor 1999). The age of the lower member was interpreted as Lower Permian on the basis of the presence of *Gangamopteris* flora (Archangelsky *et al.* 1980), while the upper member was dated as Lopingian (259.8 – 252.2 Ma) by Melchor (1999) on the basis of plant remains. Regional interpretations on the upper Carboniferous to Permian palaeogeography suggest that the San Rafael and Carapacha basins were part of a system of foreland basins related to an advancing deformation front from the south west during upper Pennsylvanian to Cisuralian (López Gamundí *et al.* 1994; Kleiman & Japas 2009).

By integrating the Palaeozoic stratigraphy and pre-existing models, a northwards and eastwards advancing orogenic front between Pennsylvanian and Lower to Middle Triassic is interpreted. Early evidence of this is the 180° rotation in sediment source area documented in both central Argentina and

southern South Africa (Andreis & Cladera 1992; Andreis & Archangelsky 1996; Johnson *et al.* 1997; Azcuy *et al.* 1999). From west to east an advance of the orogenic front can be inferred by integrating compressive deformation in the San Rafael block with the pre-orogenic nature interpreted by Flint *et al.* (2011) for the lower Ecca Group units. The Sierras de la Ventana of Buenos Aires, for which there are no solid models to date to account for strong Permian compressive deformation, lie in between these two localities. Mild deformation was interpreted through palaeomagnetic studies (Tomezzolli & Vilas 1999) and the interpretation of growth strata (López Gamundí et al 1995). South of this region deformation was recently dated at 261.3±2.7 Ma (late Guadalupian) by the U-Pb SHRIMP method in gneisses of the North Patagonian Massif (Chernicoff *et al.* 2013).

Offshore Buenos Aires, Pángaro & Ramos (2012) and Pángaro (2013) used 2D seismic data to interpret that the whole Pennsylvanian to Lower Triassic succession was folded in one single compressive tectonic event. This interpretation is in phase with those of the South African Karoo basin that envisage a post-Ecca Group and probably a post-Beaufort Group evolution of the Cape fold belt. However, Flint (personal communication) on the basis of the presence of quartzite material in the Upper Beaufort Group, and the thickness of this unit compared to the underlying Ecca Group, interprets that the Cape Fold Belt became active during the Triassic overimposing a flexural load to the dynamic subsidence. This situation was not proved offshore Argentina due to the Mesozoic denudation of the Lower Triassic record south of the Ventana Fold belt front, but an analogue situation to that proposed by Flint cannot be disregarded.

## 3. THE UPPER PALAEOZOIC IN THE CENTRAL ARGENTINEAN OFFSHORE

The upper Palaeozoic – Lower Triassic stratigraphy in the offshore area was reconstructed on the basis of the data provided by the Puelche x-1 and Cruz del Sur x-1 wells (Figs. 3 & 4), which drilled more than 3,000 m of upper Palaeozoic sedimentary rocks. The former drilled through 1,400 m of sedimentary strata dated as Pennsylvanian to Guadalupian (223.2 - 259.8 Ma) based upon recognition of *Potoniesporites-Lundbladispora*, *Striatites* and *Cristatisporites* biozones (Archangelsky 1996); while the Cruz del Sur x-1 drilled 1,600 m of sedimentary rocks of Cisuralian-Guadalupian to Lopingian age (approximately 280 to 252 Ma) (Balarino 2009, 2012). Integrating these wells shows that the offshore stratigraphic record encompasses a longer time period than the onshore Sierras de la Ventana region, where U-Pb SHRIMP zircon dating in the uppermost units provided ages of 274.3±4.8 Ma and 280±1.9 (upper Cisuralian) (Alessandretti *et al.* 2010; López Gamundí *et al.* 2013). Other exploratory wells drilled only a few tens of metres into the pre-Mesozoic strata; these include the Gaviotín x-1 well in offshore Uruguay in which Veroslavsky *et al.* (2003) documented Permian sedimentary rocks previously regarded as Mesozoic, the Pejerrey well north of the Colorado basin that drilled a series of hard hyaline quartz-rich sandstones devoid of any microfossils correlated to the Silurian-Devonian passive margin sedimentary rocks of south-western Gondwana (Pángaro 2013), and the Dorado x-1 and D.x-1 wells that allowed the calibration of seismic data to the north.

Apart from these pieces of data, dense 2D seismic coverage of the Argentinean offshore proved extremely valuable when calibrated with the wells. Hundreds of rotated downthrown blocks related to normal faults of the Jurassic and Cretaceous rift events (Pángaro & Ramos 2012) allowed the preservation of thousands of metres of Palaeozoic strata; even though these blocks are typically less than a few tens of kilometres long in dip direction, their combination allows valuable regional observations over hundreds of kilometres in areas without previous interpretation on the Palaeozoic stratigraphy.

### 3.1 Well data interpretation

The first step in reconstructing the Palaeozoic sedimentary record in the Argentinean offshore was to set up a well-controlled stratigraphic column and palaeoenvironmental interpretation. Due to the partial stratigraphic record present in the closest control localities in the Argentinean onshore (Pángaro 2013) the stratigraphic column of the western Karoo basin was chosen for correlation. The distance between the Argentinean outcrops of Sierras de la Ventana and the offshore wells is 330 km, comparable to the 350 km between these and the African pre-Gondwana break-up coast. The main support for the interpretations is the gamma ray log, calibrated through direct observation of borehole cores, sidewall cores and cuttings.

The Puelche x-1 well drilled three units that show distinctive gamma-ray profiles. The lowest unit spans over 460 m (Fig. 4) and comprises more than 95% of diamictites and minor silty shales and sandstones. Two well cores within this interval totalling 10.5 m, along with cuttings descriptions, enabled a straight forward lithological discrimination as well as valuable facies observations. The second unit bears a thickness of 290 m, its base marked by an abrupt increase of the gamma ray log values; this high gamma ray values and the abundant shaly and silty fragments observed in cuttings led to interpreting this unit as composed by low energy environment sedimentary rocks deposited above a flooding surface. The third unit, bearing a partial thickness of 840 m also shows a shift in gamma ray value at its base and is characterised by high frequency oscillations reflecting a layering in thin and rather discrete beds. Three well cores within this unit totalling 10.5 m allowed the recognition of a homogeneous package composed mainly of very fine to fine sandstones and siltstones in very thin beds and bed-sets, characterised by traction-related sedimentary structures such as ripples and micro-hummocks.

Biostratigraphic data available for the Puelche x-1 well (Archangelsky 1996) indicates that the upper 400 m belong to the *Striatites* biozone while the remaining drilled Palaeozoic interval - sections one, two and most of section three - belong to the *Cristatisporites* biozone, and that the lowermost portion of the well could contain the *Potoniesporites Lundbladispora* biozone. The presence of the latter in the bottom of the well indicates a Pennsylvanian to lower Cisuralian age for the diamictites. The *Cristatisporites* biozone present in most of the well is characteristic of the Gondwanaland Cisuralian (289.9 – 272.3 Ma)

sedimentary record while the *Striatites* biozone present in the upper part is indicative of upper Cisuralian to Guadalupian age (approximately 283 – 259 Ma).

The Cruz del Sur x-1 well, situated in the south eastern margin of Colorado basin, drilled a total of 1,600 m of upper Palaeozoic sedimentary rocks characterised by two prevailing lithologies: very fine to fine grained sandstones and feldspathic wackes interbedded with siltstones, and siltstones and shales with occasional very fine-grained sandstone intercalations (Table 1). The sand prone units occur in two sections of the well, the lower one with a thickness of +300 m and a sharp top surface, and the upper one with a thickness of 100 m and limited at top and bottom by sharp surfaces (Fig. 4). The top of the upper Palaeozoic section is marked by the Palaeozoic – Mesozoic unconformity that separates the pre-rift stage sedimentary rocks from the drift-stage Upper Cretaceous ones.

The revision of the available material for the Cruz del Sur x-1 well led Balarino (2009, 2012) to identify two biostratigraphic associations indicative of a Cisuralian - Guadalupian to Lopingian age for this unit (approximately 283 -252 Ma). This data allows a preliminary correlation of the Palaeozoic sedimentary rocks drilled in the Cruz del Sur x-1 well with the submarine fans of the Laingsburg Formation and equivalent units in the Tanqua and Laingsburg depocentres of south western South Africa according to the absolute ages provided by Fildani *et al.* (2007, 2009) (Fig. 2).

The integration of both wells led to the demarcation of a +3 km thick upper Palaeozoic sedimentary succession with remarkable similarities to that of the south-western Karoo basin. The diamictite prone unit correlates with the Dwyka Group, while the overlying fine-grained sediments were correlated with the Prince Albert, Whitehill and Collingham formations (Fig. 2). The uppermost silty to fine-grained section of the Puelche x-1 well was correlated to the Vischkuil and Tierberg formations which were interpreted in the southern Karoo basin as basin plain to outer basin floor fan deposits (Johnson *et al.* 1997; Flint et al. 2011 and references therein). Finally, the whole of the Cruz del Sur x-1 well Palaeozoic section was correlated with the submarine fans of the Laingsburg Formation on the basis of their lithology and palynological assemblages. Absolute age determinations in South Africa (Bangert *et al.* 1999; Werner 2006; Fildani *et al.* 2007, 2009; Rubidge *et al.* 2013) allowed a detailed reconstruction of the Palaeozoic stratigraphic column in the western Karoo basin which was considered as a reference to tie the Argentinean offshore data (Fig. 2).

### 3.2 Detailed stratigraphic and palaeoenvironmental interpretation

Based on the reconstructed +3 km thick stratigraphic column of Palaeozoic sedimentary rocks a detailed 1:500 to 1:200 log-based interpretation was carried out to further assess their depositional environments. The lack of modern-high resolution well logs led to relying heavily upon gamma ray,

resistivity and sonic logs with a maximum vertical resolution of about 1 ft. Calibration of the response of such logs was achieved through the correlation with cores, both of the vertical well and sidewall cores, cuttings descriptions, and geochemical analyses.

The basal portion of the Puelche x-1 well is composed of 460 metres of diamictites and minor amounts of intercalated siltstones and claystones with dropstones, and subordinate sandstones (Fig. 5). Two cores were obtained within this unit (Figs. 6 & 7); the lower one is exclusively composed of 5 metres of massive diamictites with pebbles reaching 8 cm in size. The gamma ray response for this core is rather constant with a value around 80° API; which is the value that characterises 95 % of the diamictite-bearing unit. The second core is composed of diamictites with shaly matrix and abundant intercalations of laminated siltstones and mudstones containing micro-dropstones. The most relevant piece of data to arise from the interpretation of this core is that it allows the calibration of one of three units of higher gamma ray values within the diamictite-bearing unit. Similar finer-grained intercalations have been described both in the Sauce Grande Formation in Argentina (Andreis & Torres Ribeiro 2003) and in the Dwyka Group in South Africa (Visser 1997) were they have been interpreted as deposited during the last stages of ice-retreat phases. The presence of shales and siltstones with micro-dropstones in these levels allows interpreting an analogue situation to that described by Vissier (1997) in which suspension settling coexists with rafted sediment supplied by icebergs. A third electrofacies characterised by low gamma ray values is present in the diamictite bearing unit and is interpreted as sand-prone intercalations detected during cuttings description. These could represent an analogue to sandstone intercalations described in both the Sauce Grande Formation and the Dwyka Group and forming part of the deglaciation sequences (Visser 1997). The vertical arrangement of the three lithofacies led to interpreting three deglaciation sequences that were tentatively correlated with the upper three sequences identified in South Africa by Vissier (1997) and Fielding *et al.* (2008).

Above the diamictite-bearing unit lies a package of low energy environment sedimentary rocks correlated with the Prince Albert, Whitehill and Collingham formations; this unit contains eight high gamma ray sections interpreted as organic rich layers that correlate with similar strata in the Karoo basin. The only age constraint for correlation of these rocks is the presence of the *Cristatisporites* biozone (Archangelsky 1996), which is indicative of a Cisuralian age. This, along with the straight forward litho-stratigraphic correlation with the Karoo basin, allows interpreting that the Whitehill Formation has its equivalent in the Argentinean offshore as suggested by enhanced total organic content values in coincidence with the high gamma-ray value units detected in the Puelche x-1 well.

The Cruz del Sur x-1 well drilled two sandy packages, a lower one with a thickness greater than 290 m and the upper one with a thickness of 100 m, both characterised by an intercalation of fine to very fine-grained sands with subordinate siltstones (Fig. 8). A third very fine sandstone to siltstone package 90 m thick was drilled towards the top of the Guadalupian to Lopingian section. Calibration for detailed

interpretation based mainly on gamma ray logs was possible through the correlation of gamma ray values with lithology from detailed petrographic studies (Table 1).

Our interpretation led to identifying hundreds of individual sandstone beds and bed sets that were analysed following the premises applied by Prélat *et al.* (2009) and Prélat *et al.* (2010) who provide a detailed interpretation of the Laingsburg and Tanqua depocentres' submarine lobes of the Ecca Group. These authors describe a system in which the initiation of the falling-stage systems tract leads to an increased sediment transport towards the deeper portions of the basin, while a relative rise of base level leads to coarser sediments being trapped in the coastal and shallow shelf environments. During highstands only minor amounts of turbiditic sands would reach the deeper portions, hence fall-out plumes would be the dominant process of sediment transport into the basin. The result of this evolution would typically be a series of sandstone-bearing packages deposited during falling stage and lowstand periods, interbedded with fine-grained sedimentation related retrogradational periods. When applied to submarine lobes, lateral compensation will also be a factor controlling high energy sediment distribution; as a consequence of this, a higher frequency control is to be expected. The result of these interactions led Prélat *et al.* (2009) to consider the thickness of the fine-grained intercalations as an indication of their hierarchy.

A similar approach was applied to the analysis of the Cruz del Sur x-1 well in which three submarine lobe complexes were identified (Fig. 8). The lower lobe complex was partially drilled between the well bottom and 3,980 m b.s.l. and is characterised by a progradational–retrogradational trend; the total thickness of this lobe complex was estimated in 420 m on the basis of seismic interpretation (Pángaro 2013). The uppermost 30 m show a progressive grain size decrease towards a rather abrupt surface that marks the abandonment of the submarine lobe complex. The second submarine lobe complex presents a smaller thickness and sharp bottom and top boundaries; internally it displays a more 'massive' aspect when compared to the lower complex, suggesting a system deposited by higher energy fluxes or a more axial position within the lobe complex. The uppermost lobe complex reflects a lower energy environment, probably due to having being drilled in a marginal position. One remarkable aspect of the lower lobe complex is its +300 m thickness, six times that of the average lobe complex measured in the Karoo basin (Prélat *et. al.* 2010).Considering the individual lobes which are in the range of a few to less than 10 m this might be an indication of a laterally compensating system in which several stacked lobes or even lobe complexes could occur. As will be discussed further, the integration of this interpretation with regional seismic mapping of the top and bottom boundaries of the main submarine lobe complex allowed the identification of regional-extension surfaces that can be traced over hundreds of kilometres basinwards.

### 3.3 Seismic interpretation

A regional seismic stratigraphic interpretation was carried out in order to extrapolate the data obtained from the two offshore wells analysed. However, due to the generally poor seismic data quality, only partial well-seismic correlation was possible in the drilled locations. A composite sonic log was constructed in order to generate dedicated synthetic seismograms for each seismic survey (Fig. 4), this provided a valuable tool for the prediction of the expected seismic response of the upper Palaeozoic stratigraphy as far as 400 km from the wells. East of the Pejerrey High a 2D seismic survey acquired by Digicom in 1994 achieved a very good imaging quality at pre-Mesozoic levels (Fig. 9), this survey encompasses 8,500 sq. km in the northern flank of the Colorado basin where Palaeozoic sedimentary rocks were preserved in rotated downthrown blocks.

Seismic-stratigraphic interpretation of the upper Palaeozoic to Lower Triassic succession over an area of 250,000 sq. km showed that this interval is characterised by a remarkable lateral continuity (Fig. 9). The results of this interpretation were that no onlap terminations against local or regional highs were detected, no thickness variations were evident at the scale of tens of kilometres, no sigmoidal reflections were visible and only the uppermost portion of the whole upper Palaeozoic to Lower Triassic stratigraphic record displays seismic facies indicative of a higher-energy continental sedimentary environment, as indicated by erosive features at the top of the section.

The integration of the composite well log derived from the Puelche x-1 and Cruz del Sur x-1 wells with the seismic data in the Digicom survey area allowed a one to one seismic characterization of the stratigraphic record (Fig. 10). The first aspect to be considered is the predicted seismic image of the diamictite bearing unit which is characterised by a well-defined positive reflection at the top and rather low-amplitude and discontinuous reflections within the package. The fine-grained intercalations that represent the top of each deglaciation sequence should be interpretable in some seismic surveys depending on their thickness and the frequency content of the data. Another characteristic feature of this unit is its erosion profile, which reflects the indurated massive diamictite layers; these resulted in the occurrence of buried hills throughout the Argentinean offshore that allow their straightforward identification (Pángaro 2013).

The overlying sedimentary rocks of the Sakmarian - Artinskian transgression (291 Ma) and low energy deposits of the highstand system tract show in the Digicom survey laterally continuous high-frequency and low-amplitude reflections with an extension of tens of kilometres; apart from this, the lower relative contrast in wave propagation velocity with the overlying Mesozoic sedimentary rocks results in a lower amplitude reflection at the Palaeozoic – Mesozoic unconformity. The general regression trend interpreted in the Puelche x-1 well is also interpretable in seismic data through the recognition of a transition from low amplitude reflections at the base of the post-glacial sequence, to an overlying

alternation of increasingly contrasting amplitude reflections that suggest an increase in frequency and thickness of sandy intercalations. Besides, the progressive increase in the amplitude of the Palaeozoic – Mesozoic unconformity reflects as well an increase in sand content since propagation velocity of the Mesozoic strata can be considered as laterally constant.

Overlying the described section, a regionally extensive negative high-amplitude reflection is interpreted to mark the base of the Guadalupian-Lopingian (272 – 252 Ma) submarine lobe complexes system documented in Cruz del Sur x-1 well. This interface is interpreted as an abrupt regional-scale surface that can be traced across hundreds of kilometres from the south of the Colorado basin up to the northern Salado basin area. One hypothesis to explain the regional extent of this surface is that it might be related to a sudden increase in sediment supply. Internally the submarine fan system package is characterised by high frequency parallel reflections with a lateral continuity of tens of kilometres in the interpreted sediment transport direction; our interpretation of this characteristic seismic facies is of a system of laterally compensating lobes of medium to small thickness in the range of a few tens of metres. These would preferably occur in a very low gradient basin, interpretation that also explains the extended major stratigraphic surfaces delimiting units with very small thickness variations. The submarine lobe complexes system is capped by the regionally continuous and abrupt Guadalupian – Lopingian retrogradational surface that was documented in the Cruz del Sur x-1 well and is characterised by a high amplitude positive reflection reflecting the decrease in sand content. Another diagnostic feature of the submarine lobes system and the overlying lower energy deposits is the amplitude of the Palaeozoic – Mesozoic unconformity which shows a decrease in amplitude reflecting the finer grained sedimentary rocks above the lobes system. Above the later a rather continuous progradation is interpreted on the basis of progressively higher amplitude seismic reflections that stand for more pronounced lithological contrasts, and an increasing amplitude in the pre-Mesozoic – Mesozoic unconformity.

Above the parallel-reflections unit is a 600 m thick package characterised internally by concave upwards erosive features in a laterally compensating array; since this unit has not been drilled in the Argentinean offshore only seismic data and regional correlations were available for its interpretation. Direct comparison with the Karoo basin allows correlation of this unit with the fluvial environment sedimentary rocks of the Adelaide and Tarkastad subgroups of the Beaufort Group. According to Johnson *et al.* (1997) the former is characterised by thinning upward cycles of a meandering fluvial system limited at their base by erosive surfaces carving from tens of centimetres to tens of metres, while the latter reflects a higher energy braided fluvial system. The lower Beaufort Group was recently revised by Wilson *et al.* (2014) who propose a system dominated by very fine sand and characterised by lateral and downstream accretion on several scales, with local variability controlled both by autocyclic and allocyclic factors. Correlation of the non-drilled units of the upper Palaeozoic to Lower Triassic in the study area with these is straightforward, hence allowing to point-out that in the Argentinean offshore the Beaufort Group has its equivalent in this post-lower Lopingian sedimentary rocks that were previously unknown in eastern central Argentina.

A similarly detailed interpretation was carried out over an area of 250,000 sq. km from the south of Colorado basin to the Punta del Este basin in Uruguay, and between the South American plate margin and the Argentinean coast. All the analysed localities share a series of characteristics that, despite being interpreted in rotated blocks with a remnant extension of Palaeozoic rocks of a few tens of kilometres in length at the maximum, are key for interpreting the regional configuration of the basin as a whole. The most remarkable of these characteristics is layer-cake seismic configuration of the basin fill devoid of onlap terminations, neither against local highs nor against a regional slope. Additionally, the thickness of each of the seismic units interpreted remains constant at the scale of observation of a few tens of kilometres; especially the seismic line displayed in Fig. 9 shows that this characteristic can be traced over distances of 75 km supporting the very low overall gradient of the basin as a whole.

Among the interpreted localities, of special interest are sites B and C (Figs. 11 & 12) which lie only 20 to 30 km away from the coast; at these the upper Palaeozoic to Lower Triassic sedimentary units retain the aforementioned characteristics allowing the interpretation of their continuity onshore. This aspect is particularly remarkable in the case of Locality B which shows a 4.5 km thick upper Palaeozoic to Lower Triassic sedimentary succession only 180 km away from the Sierras de la Ventana area, which is the only time equivalent outcrop to such rocks in eastern Argentina and where the stratigraphic record is very limited due to Mesozoic and Cenozoic erosion.

By integrating the seismic interpretation of the upper Palaeozoic to Lower Triassic, an 800 km long SSW-NNE cross section was constructed between a location some 60 km south of the Colorado basin and the southern Uruguayan offshore; this cross section can be considered parallel to the main sediment transport direction on the basis of palaeocurrent directions measured in the Sierras de la Ventana (Andreis & Cladera 1992) and in the Karoo basin (Johnson *et al.* 1997) (Fig. 13c). The results show that the present day dipping of the pre-Pennsylvanian basement is 0.5 degrees; however, when considering the Guadalupian regressive surface as a datum, this figure drops to 0.2 degrees and shows neither local increases nor hinge points over the mapped portion of the basin. A similar low-angle peneplain was described on the basis of good quality seismic lines by Lindeque *et al.* (2011) in the Karoo basin of South Africa. Another remarkable aspect of the Argentinean offshore upper Palaeozoic to Lower Triassic record is the continuity of the main stratigraphic surfaces, namely the Sakmarian post-glacial transgression and the base and top of the Guadalupian – Lopingian submarine lobes system.

The seismic stratigraphic analysis also suggests that the upper Palaeozoic-Lower Triassic section shows no thickness variations or presence of growth strata related to development of the offshore portion of the Ventana fold belt. This is consistent with previous seismic interpretations by Pangaro and Ramos (2012) that indicated compressive deformation resulting in the Venta fold belt was post-depositional and hence post-Lower Triassic.

**4. ORIGINAL AND PRESENT DAY DISTRIBUTION OF UPPER PALAEOZOIC TO LOWER TRIASSIC ROCKS: THE HESPERIDES BASIN.**

By integrating seismic and well data a detailed mapping of the rocks underlying the Palaeozoic + Lower Triassic – Mesozoic + Cenozoic unconformity was carried out. This interpretation was integrated with published data allowing the discrimination of Pennsylvanian to Lower Triassic sedimentary rocks, lower Palaeozoic sedimentary rocks, the crystalline basement, the full extension of the Ventana fold belt, the Permian orogenic core, and areas of undifferentiated Lower Palaeozoic and crystalline basement units. The resulting map (Fig. 13a) allows a series of high-impact observations regarding preservation potential of the pre-Mesozoic units. The first observation is that the present day distribution of the upper Palaeozoic rocks is a direct consequence of the Mesozoic and Cenozoic tectonic events, especially the Jurassic and Cretaceous rifting events (Pángaro & Ramos 2012). Rift-related denudation that resulted in the removal of as much as 7 km of section in some areas (Pángaro & Ramos 2011; Pángaro 2013), led to the preservation of three main stripes of upper Palaeozoic rocks in the axes of the Colorado and Salado basins, and in a corridor that parallels the South American plate boundary.

The present day distribution of the upper Palaeozoic sedimentary units with respect to their interpreted original thickness (Fig. 13a) suggests that the latter was controlled by factors and tectonic features different to those evident in the present day structural configuration. Most probably our offshore upper Palaeozoic to Lower Triassic thickness maps extend onshore with no significant variations. This is evident when considering Locality B (Fig. 11): although near the Argentinean shore, a parallel layer-cake configuration suggests that thickness changes are unlikely to occur in neither neighbouring areas nor the immediate onshore region. This interpretation of onshore continuity of the late Palaeozoic basin is consistent with an early proposal by Harrington (1962) of a large scale depocentre in front of the Gondwanides that encompassed most of the Buenos Aires province.

The regional integration of our thickness map with neighbouring Chacoparaná and Paraná basins faced the difficulty of these being affected by a similar process of Mesozoic denudation. In the case of the Paraná basin, its eastern boundary is deeply controlled by the Atlantic break-up-related uplift of the coastal range of southern Brazil (Zalan *et al.* 1990; Milani & Zalan 1999); while its western margin, in the vicinity of the Asunción arch, was also affected by Mesozoic and Cenozoic kilometre-scale erosion (Milani & Zalan 1999). In the case of the Chacoparaná basin no estimations of the eroded thickness are available.

Interpretations herein are consistent with a continuous Pennsylvanian to Lower Triassic basin extending into present-day eastern onshore Argentina with no significant thickness variations and with connections to the Chacoparaná basin to the west, the Parana basin to the north and the Kalahari and Karoo basins to the east. The name of Hesperides is proposed herein to refer to a basin that

encompasses the Palaeozoic Claromecó and Sauce Grande-Colorado basins and extends further into the neighbouring basins forming a continuous entity during the upper Palaeozoic and Lower Triassic.

### 4.1 Subsidence curves

In order to further constrain the proposed regional denudation event in central Argentina, several localities were analysed for subsidence history on the basis of pre-existing and newly generated data on the stratigraphy of the upper Palaeozoic to Lower Triassic and the Mesozoic units, and on published dates for regional tectonic events. The first of such events is the main compressive deformation phase in the Ventana fold belt in the study area, which was interpreted as uppermost Lower Triassic to Middle Triassic (Pángaro & Ramos 2012). The second major tectonic event is the onset of rifting in the Colorado and Salado basins, which is interpreted as Jurassic by several authors (Mpodozis & Ramos 2008; Pángaro & Ramos 2012). Regional correlation of this rifting event led to considering it coeval to the Karoo Large Igneous Province (LIP) which was dated at 184 Ma (Jourdan *et al.* 2005). No dating is available for the syn-rift stage rocks in offshore Argentina, but the interpretation of a different regional stress scenario to that of the Atlantic break-up rift event as proposed by Pángaro & Ramos (2012), and the evidences for a Jurassic Karoo-LIP-related rifting event in Namibia (Stollhofen *et al.* 2000) led to considering a similar age for the Colorado and Salado basins. The third major tectonic event is the Atlantic break-up which at the latitude of the study area is interpreted as related to the Etendeka LIP (Stica *et al.* 2013 and references therein) dated at 127 Ma (Peate 1997). Both rifting events are considered as the key processes in the denudation of the stratigraphic record in the area. Since break-up, the Argentinean continental shelf has been subjected to continuous thermal subsidence that was strongest at the plate boundary. Extra thermal subsidence related to uncompensated mass excess beneath the Colorado and Salado basins has been also active during the Cretaceous and Cenozoic (Introcaso & Ramos 1984). The bulk of the of the Buenos Aires Province area and the shallow offshore away from the Colorado and Salado depocentres, can be considered as tectonically stable or slowly subsiding since the late Cretaceous.

The first of the analysed subsidence curves is from Locality B (Fig. 11), a half-graben in the northern flank of the Colorado basin (Fig. 14). In this area structural modelling led to interpreting a minimum erosion estimated at more than 7 km of rocks in the up-thrown block (Pángaro 2013) resulting in the complete removal of the Hesperides basin stratigraphic record, which was on the other hand fully preserved in the downthrown block. The main period of denudation is interpreted to have been between 184 Ma and uppermost Cretaceous, which is the interpreted age for the oldest rocks of the drift-stage covering the up-thrown block of the half-graben. While offshore subsidence curves construction was straightforward with stratigraphy controlled by seismic and biostratigraphic analyses of the drift-stage Cretaceous units, the onshore curves faced serious uncertainties due to limited age constraints (Fig. 15). The main reason for this is the almost complete lack of stratigraphic record since the Permian, more precisely since 274.3±4.8 Ma (late Cisuralian), age of the youngest Palaeozoic rocks

outcropping in the Sierras de la Ventana (Alessandretti *et al.* 2010), and to the data from the Paragüil x-1 well in the plains north of the Sierras de la Ventana (Lesta & Sylwan 2005). To the north, in the Tandilia system control points are practically non-existent. However, new data alongside the reinterpretation of old data, provides insight into the regional evolution since the uppermost Palaeozoic. The first is the vitrinite reflectance measurements in the Paragüil x-1 well where Arzadún *et al.* (2013) established a maturity between 1.6 and 1.3 %Ro for samples at 396 m and 412 m below ground level at the uppermost levels of the Permian Tunas Formation. The interpretation of these data, given an arbitrary constant geothermal gradient through time of 30°C/km, is that at least 2 km of rocks were eroded in the locality. This interpretation agrees with that of Pángaro (2013) who postulated a minimum eroded thickness of 1.5 km. Another piece of data of high impact on subsidence curves is the analysis of telodiagenetic minerals in the Tandil ranges, where Zalba *et al.* (2007) established that a minimum of 2 km of overburden rock was removed. The third piece of data relies in a more indirect way on the determination of the existence of metamorphic illite in the Pennsylvanian to Permian sedimentary rocks of the Sierra de Pillahuincó, north of the Sierra de la Ventana (Buggisch 1987). Considering published data on the stability field of metamorphic illite (Lanson *et al.* 2002 and references therein), and given a constant geothermal gradient through time of 30°C/km, the removal of overburden rock by denudation was estimated in a minimum of 2.2 km.

Figure 14 about here.

The evidence for substantial denudation both offshore and onshore is strong, but the timing of these erosion events is still challenging. In our interpretation, supported by offshore seismic and borehole data, the main denudation process occurred during the rifting-related doming, as evidenced in the seismic lines of Figs. 10 through 13. In the Ventana fold belt uplift related to the Gondwanides orogeny is interpreted to have taken place during late Lower Triassic to Middle Triassic. This uplift cannot be accurately quantified due to the overall poor quality of seismic data in the folded area, but by analogy with a seismic line presented by Pángaro & Ramos (2012) in which a +5 km high anticline structure is evident, and considering the minimum tectonic uplift during the Gondwanides that can be interpreted in the Sierras de la Ventana, kilometre-scale uplift and erosion is to be expected. For example in the southern Sierra de Pillahuincó in the Sierras de la Ventana the whole of the upper Palaeozoic is eroded, so considering a palaeo-erosion surface in coincidence with the ranges' summits, the rock thickness eroded during the Gondwanides orogeny could exceed 4 km, which is the original thickness estimated for the Hesperides basin infill at the locality (Pángaro *et al.* 2011; Pángaro *et al.* 2013).

One key onshore point to calibrate our denudation model is the Paragüil x-1 well where a 2 km thick sedimentary column was eroded according to the aforementioned vitrinite reflectance data, and where no compressive deformation related to the Gondwanides orogeny was documented (Lesta & Sylwan 2005). Thus it can be postulated that at least 2 km of missing rock was eroded during the Mesozoic/Cenozoic. Given the proximity to the Sierras de la Ventana, and the regional scope of the rift-

related uplift and erosion process, this amount of denudation can be extended to neighbouring areas, so subsidence curves at the Sierras de la Ventana should take into account the Mesozoic/Cenozoic regional denudation event. The result of these observations is summarised in the subsidence curves of Fig. 15.

### 4.2 Palaeogeographic evolution of the Hesperides basin and its integration into the south-western Gondwana

All aforementioned interpretations allowed the reconstruction of the potential original extent of the Hesperides basin in the south-western Gondwana context (Fig. 13); this led to the realisation of the remarkable continuity of the upper Palaeozoic depocentre which evolved in front of the Gondwanides. The original extent of the basin over South Africa and South America is interpreted to have been in excess of 1,950,000 sq. km, encompassing the Karoo and Hesperides basins; if continuity is considered between the Karoo and Kalahari basins and between the Hesperides and the eastern part of the Chacoparaná basin, this figure rises to more than 3,100,000 sq. km. Regional palaeogeographic maps were constructed for the integrated Hesperides, Paraná, San Rafael and Karoo + Kalahari basins; the results are displayed in Figs. 16 through 18. These were integrated with data gathered on the temporal and spatial evolution of the Gondwanides to provide a first approach into the evolution of south-eastern Gondwana.

### 4.2.1 Late Cisuralian (280 – 277 Ma)

During late Cisuralian the Mesosaurus Inland Sea (Werner 2006 and references therein) was fully developed and encompassed South Africa, part of Namibia, the Paraná basin of southern Brazil and Uruguay, and extended into the Argentinean continental shelf as interpreted in the Puelche x-1 well (Fig. 16). Relevant pieces of data at this timeframe are the 274.3±4.8 and 280±1.9 age determinations near the top of the shallow marine to fluvial Tunas Formation in the Sierras de la Ventana (Alessandretti *et al.* 2010; López Gamundí *et al.* 2013); these observations are in accordance with low sediment supply conditions for over 10 My, although the southern Buenos Aires province area registered a higher rate. Further west in the San Rafael block the Pennsylvanian to Cisuralian El Imperial Formation is separated from the overlying Cisuralian to Guadalupian Cochicó Group volcanic and volcanoclastic rocks by an angular unconformity. Age determinations of 281±2.5 Ma in the lower units of the Cochicó Group (Rocha-Campos *et al.* 2006) allow interpreting that while the eastern part of the Gondwanides foreland basin was under a regime of highstand and low energy sedimentation, the western portion was already being cannibalised and acting as a sediment source.

### 4.2.2 Late Guadalupian – Lopingian (approximately 260 – 254 Ma)

During the late Guadalupian to Lopingian a drastic increase in sedimentary input into most of the basin is interpreted, resulting in the evolution of the submarine lobes system documented through our interpretations in the Argentinean offshore and widely described in the Karoo basin of South Africa (Fig.

17). While no age constraints are available within the Argentinean continental shelf to constraint the age of the Gondwanides deformation south of the study area, intense uplift is interpreted in the North Patagonian Massif where metamorphic rocks were exposed by a compressive event dated 261.3±2.7 Ma (late Guadalupian) (Chernicoff *et al.* 2013). Further west, in the San Rafael area an orogenic phase is interpreted to have occurred between 280 and 265-260 Ma (Kleiman & Japas 2009; López Gamundí *et al.* 2013).

From west to east the situation of an advancing deformation front remains as for late Cisuralian, in the San Rafael block arc-related volcanic and volcanoclastic rocks were deposited coeval with the San Rafael orogenic phase, while eastwards in the Argentinean offshore at the latitude of Buenos Aires province the upper Permian sedimentary record is interpreted to have been deformed after Lower Triassic (Pángaro & Ramos 2012; Pángaro *et al.* 2013). Further east, in the Karoo basin, the correlative submarine fans of the Laingsburg and Tanqua depocentres are interpreted as well to pre-date the Cape fold belt (Van Lente 2004; Prélat *et al.* 2009; Flint *et al.* 2011; Lindeque *et al.* 2011). Another relevant piece of data at this timeframe is the absence of Cape Granite suite and Cape Supergroup clasts in the composition of the upper Ecca Group units in the Laingsburg and Tanqua depocentres as established by Van Lente (2004), who interprets that the sediment source for these formations shows affinity to the North Patagonian Massif rocks of Argentina, hence implying a 1,500 km transport into the Karoo Basin. The fact that Permian deformation in northern Patagonia has been recorded in the Cerro de los Viejos and Yaminué areas (Von Gosen 2003; Chernicoff *et al.* 2013) provides further constraints for the reconstruction of the geodynamic scenario. East of these localities, any possible constraint to the time and spatial evolution of the upper Palaeozoic orogen lies offshore beneath the Mesozoic and Cenozoic sediments of the Argentinean continental shelf and in the Agulhas plateau in South Africa. The presence of the Palaeozoic orogenic core south of the Colorado basin is seen in an N-S trending seismic line that shows lower crust basement overriding the Palaeozoic sedimentary rocks, confirming the proposal of Mosquera & Ramos (2006) as interpreted by Pángaro & Ramos (2012).

Considering the aforementioned, we envisage an orogenic front placed during the Guadalupian to Lopingian in a line formed by the San Rafael area, continuing slightly south of the Carapacha basin area, then 400 to 300 km south of the Colorado basin, and somewhere south of the present day South African coast, as proposed by Lindeque *et al.* (2011). From the stratigraphic point of view, the consequence of this scenario was the evolution of a gigantic submarine fan system that might have encompassed the area between the Carapacha and the eastern Karoo basins, some 1,500 km in ESE direction. Modern analogues for this system in terms of scale and processes are the Indus and Bengal fans (Curray *et al.* 2002).

### 4.2.2 Uppermost Permian to Lower Triassic (260 – 247 Ma)

During Lopingian times the San Rafael area experienced a transition from a compressive deformation to an extensional system (Kleiman & Japas 2009) leading to the extrusion of the Choiyoi rhyolitic plateau (Llambías *et al.* 1993). At this time most of the Karoo basin reached the maximum of the continuous overall regression trend that followed the *Eurydesma* Transgression; all throughout the basin the Beaufort Group and time equivalent units are composed mostly of fluvial environment sedimentary rocks that reflect the culmination of marine sedimentation (Fig. 18). One pioneer interpretation for this change was provided by Pysklywec & Mitrovica (1999) who postulated a dynamic subsidence model for the Karoo basin and interpreted that the transition to the Beaufort Group sedimentation was a consequence of the cessation of the mechanism driving the regional dynamic subsidence and the consequent rebound of the basin. Considering the direct correlation of the Argentinean continental shelf stratigraphy with that of the Karoo basin, a similar scenario can be proposed for the former.

Between the San Rafael area and the Argentinean continental shelf, 258±2 Ma (Lopingian) late-tectonic to post-tectonic igneous rocks crop out in the López Lecube area some 80 km west of Sierras de la Ventana (Pankhurst *et al.* 2006). This implies that the Gondwanides-related compressive deformation was very active in the area during Guadalupian to Lopingian times, probably sourcing sediments to basin. Further east, in the Sierras de la Ventana, no rocks of this age crop out so constraints to the tectonic evolution are still elusive.

It is important to point out that according to our seismic-based interpretations and models, and to the recent interpretations on the Cape fold belt, the orogenic front had not reached yet the latitude of the Buenos Aires province offshore (Pángaro & Ramos 2012) nor the Cape region (Van Lente 2004; Lindeque *et al.* 2011). The Beaufort Group time equivalent units within the study area in offshore Argentina were deposited in an environment still dominated by the dynamic subsidence and rebound processes, and in relationship with an orogen situated to the south; but not in a foreland basin directly controlled by flexural load. If a classical syn-orogenic flexural depocentre existed at the time, it was situated farther south and was later cannibalised by the advance of the deformation front. Evidences of this feature should be looked for in the Agulhas plateau or in the Argentinean continental shelf south of the Colorado basin. However, as seen in one 2D seismic line linking the Colorado and Rawson basins, these rocks must have been eroded during the last stage of Gondwanides deformation.

### 4.2.3 Late Lower Triassic to Middle Triassic (approximately 247 – 237 Ma)

During this time the orogenic front reached its maximum northwards propagation into the Hesperides basin, as documented by Pángaro & Ramos (2012) and Pángaro (2013) (Fig. 18). Offshore Argentina and in the western Cape region the orogenic front penetrated further north as a result of the differential

rheological response of the Dom Feliciano and Gariep belts with respect to that of the cratonic areas resulting in the Colorado and Cape syntaxes (de Beer 1989; Pángaro & Ramos 2012). Offshore Argentina the Colorado Syntaxis accommodates a differential northwards propagation of the orogenic front of more than 200 km. Due to the interpreted cannibalisation of the potential flexural fore-deep basin, no stratigraphic evidences of syntectonic sedimentation were detected through our seismic interpretation. Especially remarkable is the fact that the upper portion of the Permian to Lower Triassic succession north and south of the fold belt maintains a layer cake configuration similar to that of the rest of the basin as shown in the regional cross section of Fig. 13.

## 5. REGIONAL IMPLICATIONS AND CONCLUDING REMARKS

- The interpretations presented in this paper lead to the inter-continental integration of the upper Palaeozoic to Lower Triassic basins of south-western Gondwana through the filling of the 250,000 sq. km gap of the previously non-interpreted Argentinean continental shelf.
- The Hesperides basin, a previously overlooked circa 1,000 km long basin with a thickness ranging from +7 km south of the Colorado basin to near 1 km in the Punta del Este basin area in offshore Uruguay was delineated.
- The continuity of this basin into the Buenos Aires province is herein proposed and documented through indirect data; its continuity into the Chacoparaná and Paraná basins, previously proposed by several authors (Harrington 1962; Azcuy et al. 2007; Milani & De Wit 2008) is supported with further interpretations. Northwards, the connection with the Paraná basin through the offshore of Uruguay and southern Brazil is proposed.
- Through the stratigraphic interpretation of the Argentinean offshore and the realisation of a sedimentary infill that correlates remarkably well with that of the Karoo basin, a series of linked basins of far wider scope than previously envisaged is interpreted. The original areal extent of the Hesperides and Karoo basins was of some 1,950,000 sq. km; if continuity with the Kalahari and Chacoparaná basins is considered this figure rises to 3,100,000 sq. km.
- Stratigraphic relationships, basin geometry and the observation of a one-stage compressive deformation in the orogenic front in the Argentinean offshore, led to the interpretation of dynamic subsidence as the primary control on long term accommodation in the upper Palaeozoic to Lower Triassic stratigraphy. This interpretation is consistent with recent proposals by several authors who envisage a post Lower Triassic evolution for the Cape Fold Belt (Lindeque et al. 2011; Tankard et al. 2009; Flint et al. 2011).
- The eastwards and northwards evolution of the Gondwanides orogen is presented through the integration of published data onshore Argentina with our stratigraphic and structural interpretations offshore. The impact of this evolution on the stratigraphy of the Hesperides and Karoo basins is evident in several time frames throughout its history. Especially remarkable are the absence of the Mesosaurus Inland Sea in Argentinean onshore during uppermost Cisuralian times, and the evolution of a gigantic submarine fan system in coincidence with accelerated deformation in the San Rafael area and the North Patagonian Massif during late Guadalupian to Lopingian.

- The Triassic regional-scale uplift due to the cessation of dynamic subsidence-driving processes proposed by Pysklywec & Mitrovica (1999) is further extrapolated into Argentina and supported with the interpretation of Beaufort Group equivalent facies in the Argentinean offshore.
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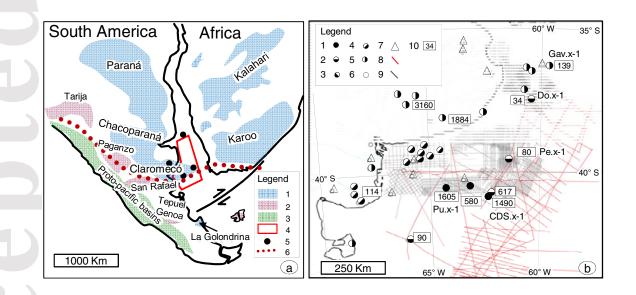
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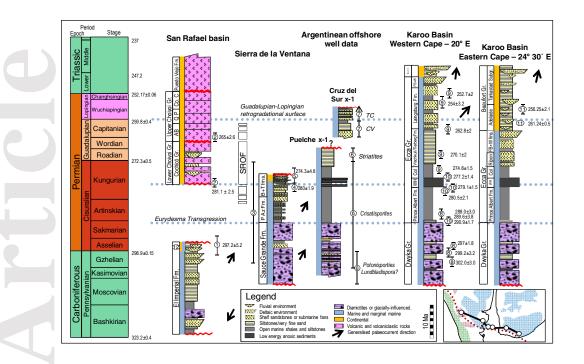
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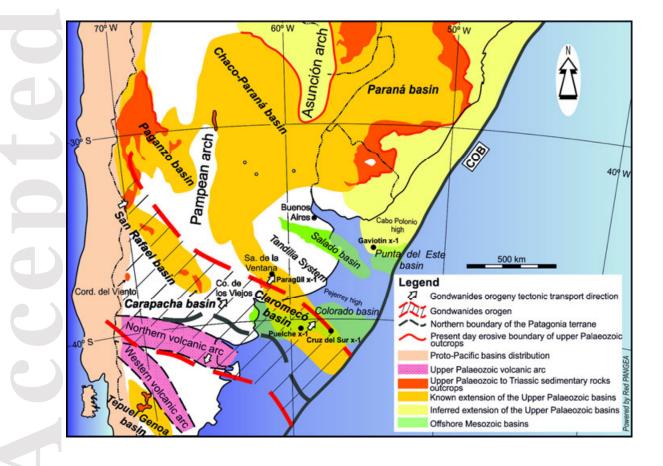
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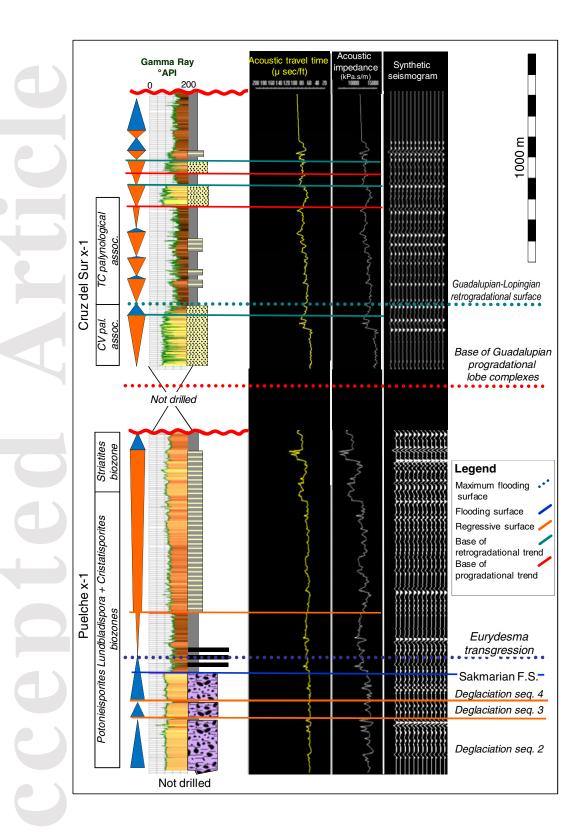
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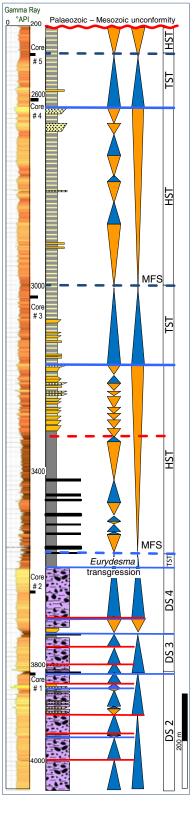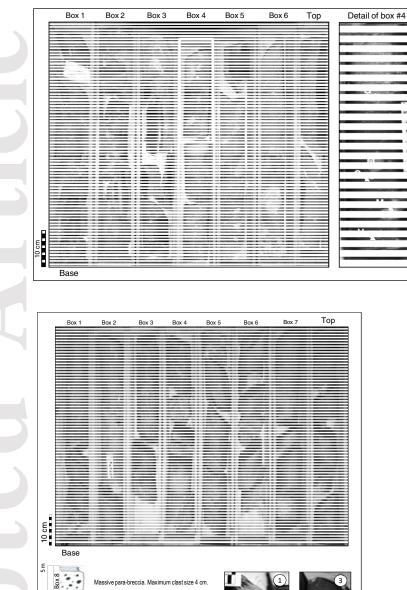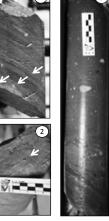| Depth | Classification | Grain size | Gamma ray log value | Clasts | Matrix |
|---|---|---|---|---|---|
| (m b.s.l.) | | | (° API) | (%) | (%) |
| 3242 | Feldspathic wacke | VF sst. | 100 | 64 | 12 |
| 3265 | Feldspathic wacke | F to VF sst. | 90 | 51 | 22 |
| 3308 | Feldspathic wacke | F sst. | 85 | 51 | 15 |
| 3421 | Feldspathic wacke | VF sst. | 95 | 58 | 16 |
| 3480 | Quartz-rich sandstone | F sst. | 65 | 61 | 9 |
| 3490 | Quartz-rich sandstone | F sst. | 80 | 58 | 7 |
| 3502 | Quartz-rich sandstone | F sst. | 65 | 61 | 8 |
| 3686 | Siltstone | VF sst. to silt | 130 | 65 | 19 |
| 3776 | Feldspathic wacke | Vf sst. | 150 | 55 | 20 |
| 3995 | Siltstone | Silt | 150 | 540 | 25 |

Box 1  Box 2  Box 3  Box 4  Box 5  Box 6  Top    Detail of box #4

10 cm

Base

Box 1  Box 2  Box 3  Box 4  Box 5  Box 6  Box 7  Top

10 cm

Base

5 m

Box 8 — Massive para-breccia. Maximum clast size 4 cm.

Box 7 — Massive para-breccia. Maximum clast size 8 cm.

Thinly laminated shales and siltstones (laminae thinner than 1 mm). Frequent micro-dropstone levels and laminated siltstone intercalations.

Box 6 — Thinly laminated shales (laminae thinner than 1 mm). Frequent micro-dropstone levels and laminated siltstone intercalations. Maximum clast size is 5 mm.

Box 5 — Thinly intercalated shales, siltstones and breccias. Soft sediment deformation.

Box 4 — Thin intercalation of shales, siltstones and carbonaceous shales.

Massive para-breccia. Clasts up to 20 cm.

Box 3 — Massive para-breccia with soft sediment deformation. Maximum clast size is 3 cm.

Box 2 — Massive para-breccia. Maximum clast size is 1 cm.

Box 1 — Massive para-breccia. Igneous and metamorphic clasts. Fluidized mudstone clasts. Shaly to limolitic matrix.

Para-breccia and interbedded convolute bedding siltstone layers. Occasional mud clasts with soft sediment deformation.
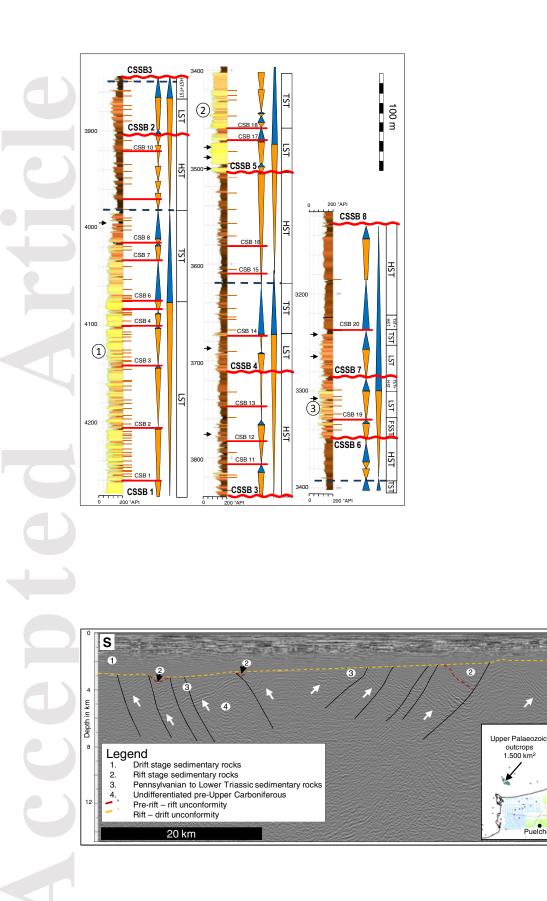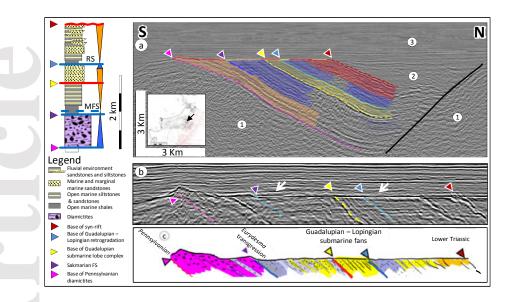
4

2

0

Legend

Fluvial environment
sandstones and siltstones
Marine and marginal
marine sandstones
Open marine siltstones
& sandstones
Open marine shales
Diamictites

Base of syn-rift
Base of Guadalupian –
Lopingian retrogradation
Base of Guadalupian
submarine lobe complex
Sakmarian FS
Base of Pennsylvanian
diamictites

**Legend**

| | | | |
|---|---|---|---|
| 1 | | 7 | |
| 2 | | 8 | |
| 3 | | 9 | |
| 4 | | 10 | |
| 5 | | 11 | |
| 6 | | 12 | △  ○ |

**A** — **B**

0 km
7020 m

Ventana fold belt

Locality B
260 km
4500 m

550 km
2300 m

645 km
2000 m

4 km

200 km



Time Ma

350  300  250  200  150  100  50  0

Marine transgression

Sea bottom
Top K
Top Jur. rift
Lwr. Tr
Lop FS
Base Penn.

**Locality B
Downthrown**

Depth in metres

*Hesperides basin*    *Rift I*    *Drift*

Karoo LIP   Etendeka LIP

Sea bottom
Top K
Pre-Penn.

**Locality B
Upthrown**

*Hesperides basin*    *Rift I*    *Drift*