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 +7000 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 1000 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 Hesperides 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 Claromécó 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.

INTRODUCTION

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 1980s 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 was to make use of all the available information on the fragmental 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 prebreakup reconstructions.

**Methodology and database**

To interpret the late Paleozoic 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 wire-line logs, cuttings, core descriptions and biostratigraphic data (Archangelsky, 1996; Balarino, 2009, 2012) from two wells that drilled circa 3000 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; López Gambuí et al., 1995; Andreis & Archangelsky, 1996), the Carapacha and San Rafael basins in western central Argentina (López Gambuí et al., 1994; Azcuy et al., 1999; Melchor, 1999; Kleiman & Japas, 2009; Pazos et al., 2013), the Cuenca Norte of Uruguay (De Santa Ana et al., 2006), the Chacoparaná and Paraná basins of north-eastern Argentina and southern Brazil (Zalán et al., 1990; Winn & Steinmetz, 1998; Milani & Zalán, 1999; Azcuy et al., 2007; Milani & De Wit, 2008) and the Karoo and Kalahari basins of South Africa (Smith et al., 1993; Vevers et al., 1994; Catuneanu et al., 1998; Johnson et al., 2006; Flint et al., 2011; Lindeque et al., 2011).

**REGIONAL SETTING**

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; Pângaro & Ramos, 2012; Ramos & Naipauer, 2014) and its possible extension into the South African Agulhas plateau (Lindeque et al. 2011) 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 (2014) as a microplate detached from Antarctica and accreted to southern Gondwana between Carboniferous (Ramos, 2008) and late Lower Triassic times (Pângaro & 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 underlining the Cenozoic sedimentary cover to the north (Furque, 1965; Lesta & Sylvan, 2005). Offshore, these terms include upper Palaeozoic rocks documented by exploratory wells (Archangelsky, 1996 and references therein). This basinial 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 glaciogenic 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; Visser, 1987, 1997; Andreis & Torres Ribeiro, 2003) (Fig. 2). Above these lie low energy subaquesous 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 Malanopsis nana (Moret & Gutiérrez, 2000) and on recent palynological determinations within the Sauce Grande Formation (Di Pasquio 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 Irati 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 onshore Argentina, where the Eurydesma transgression is present on top of the glaciogenic 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. (2007) and Fildani et al. (2009) suggest a Lower Triassic age for the basal Beaufort Group at 20° E. Although newly published results by Rubidge et al. (2013) state an uppermost Guadalupian to Lopingian age for the basal Beaufort Group at 25° E, allowing to re-situate it in the upper Permian, the analysis presented by Fildani et al. (2009) 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.
Lopingian
Veevers et al.
and Cruz del Sur x-1 wells based on Pala Ventana stratigraphy after Andreis & Archangelsky (1996) and Andreis & Torres Ribeiro (2003). Stratigraphy of the Puelche x-1 well of 1993; Catuneanu South-western Gondwana upper Palaeozoic to Lower Triassic correlation chart. Time scale after International Commission on Stratigraphy (2013). San Rafael basin stratigraphy after Aczyzu et al. (1999), Pazos et al. (2013) and Henry et al. (2014). Sierras de la Ventana stratigraphy after Andreis & Archangelsky (1996) and Andreis & Torres Ribeiro (2003). Stratigraphy of the Puelche x-1 and Cruz del Sur x-1 wells based on Pángaro (2013), see text for discussion. Stratigraphy of the Dwyka, Ecca and Beaufort groups after Vevers et al. (2004), Fildani et al. (2007), Aarnes et al. (2011). (1) Age of the El Imperial Formation after Rocha-Campos et al. (2008). (2) Ages of the Chooyoi Group after Rocha Campos et al. (2006) and Kleiman & Japa (2009). (3) Age of the Sauce Grande Formation after Dipasquo et al. (2008). (4) Age of the upper portion of the Tunas Formation after López Gamundi et al. (2013). (5) Age of the upper portion of the Tunas Formation after Alessandretti et al. (2010). (6) Age of the Puelche x-1 well sedimentary rocks after Archangelsky (1996). (7) Age of the Cruz del Sur x-1 well sedimentary rocks after Balanino (2012). (8) Ages of the Dwyka Group and the Prince Albert Formation after Bangert et al. (1999). (9) Ages of the upper Ecca Group formations in the western Cape region after Fildani et al. (2007, 2009). (10) Ages of the Prince Albert, Whitehill and Collingham formations after Werner (2006). (11) Ages of the Beaufort Group after Rudge et al. (2013). (12) The upper El Imperial Formation was considered continental environment by several authors and was recently re-interpreted as marine environment by Pazos et al. (2013); see text for discussion. AB, Agua de Burros Formation; QB, Quebrada el Pimiento Formation; Co.C., Cerro Carrailalito Formation; B+T fms., Bonete and Tunas formations; PAZ Fm., Piedra Azul Formation; WH, Whitehill Formation; CoL, Collingham Formation; FB+W, Fort Brown and Weatherford Formations; Beauf. Gr., Beaufort Group.

1993; 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). The classic interpretations relied heavily on early dating of metamorphic minerals by Hambach (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 Pyskylywec & 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 Prêt 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 with its South African counterpart. Westwards, in the La Pampa and Mendoza provinces, isolated outcrops provide insights into the evolution during upper Palaeozoic (López Gamundi et al., 1994; Azcuy et al., 1999) (Fig. 3). The consequence of the nature of the Argentinean outcrops when compared with 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 Gamundi et al., 2013; Ramos et al., 2013). Despite all this, several authors recognised in Sierras de la Ventana the existence of a circa 2400 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 southwestern 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 Gamundi et al., 1995; López Gamundi, 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 Gamundi et al., 1995; Tomezzoli & Vilas, 1999). Subsurface data allow 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 Gamundi et al., 1995; Azcuy et al., 1999; Kleiman & Japas, 2009) (Figs 2 and 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 Gamundi 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 with the Glacial Episode II of Bashkirian age (López Gamundi & 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 (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 Gamundi 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 4000 m thick Carapacha Formation is characterized 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 characterized 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 Gamundi 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 (Andres & Cladera, 1992; Andres & 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 (Tomezzoli & Vilas, 1999) and the interpretation of growth strata (López Gamundi 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, S. S. Flint (pers. comm.) on the basis of the presence of quartzite material in the Upper Beaufort Group, and the thickness of this unit compared with 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.

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 and 4), which drilled more than 3000 m of upper Palaeozoic sedimentary rocks. The former drilled through 1400 m of stratigraphic strata dated as Pennsylvanian to Guadalupian (232.2–239.8 Ma) based upon recognition of Potoniesporites Lundbladispora, Striatites and Cristatisporites biozones (Archangelsky, 1996); while the
Fig. 4. Composite log of the drilled upper Palaeozoic sedimentary rocks in offshore Argentina. Biozones of the Puelche x-1 well after Archangelsky (1996); palynological associations of the Cruz del Sur x.1 well after Balarino (2009; 2012). The synthetic seismogram on the right shows the most prominent seismic reflections associated to the major stratigraphic discontinuities identified in the wells; these are the Sakmarian flooding surface and the top of the Guadalupian submarine fan system. See Fig. 3 for location.
Cruz del Sur x-1 drilled 1600 m of sedimentary rocks of Cisuralian-Guadalupian to Lopingian age (approximately 280–252 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 Gamundi et al., 2013). Other exploratory wells drilled only a few tens of metres into the pre-Mesozoic strata; these include the Gaviotin 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 with the Silurian–Devonian passive margin sedimentary rocks of southwestern 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.

### 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 diamicites and minor silty shales and sandstones. Two well cores within this interval totalling 10.5 m, along with cuttings descriptions, enabled a straightforward lithological discrimination as well as valuable facies observations. The second unit bears a thickness of 290 m, its base marked by an abrupt increase in the gamma-ray log values; these 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.

Biosтратigraphic 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 diamicites. 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 1600 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 for this unit (approximately, 283–252 Ma). This data allow 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 diamicite prone unit correlates with the Dwyka Group, while the overlying fine-grained sedi-
ments 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 with 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 Argentinian offshore data (Fig. 2).

**Detailed stratigraphic and palaeoenvironmental interpretation**

On the basis of the reconstructed +3 km thick stratigraphic column of Palaeozoic sedimentary rocks a detailed 1 : 500–1 : 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 sideway cores, cuttings descriptions and geochemical analyses.

The basal portion of the Puelche x-1 well is composed of 460 m 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 and 7); the lower one is exclusively composed of 5 m 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) where 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 allow interpreting an analogue situation to that described by Visser (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 Visser (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 lithostratigraphic 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 +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 subordin-

### Table 1. Cruz del Sur x-1 petrographic analyses results and Gamma-ray log readings obtained during wire-line logging. VF sst.: Very fine sandstone. F to VF sst.: Fine to very fine sandstone. F sst.: Fine sandstone. See Fig. 8 for location within the Cruz del Sur x-1 well

| Depth (m b.s.l.) | Classification | Grain size | Gamma-ray log value (° API) | Clasts (%) | Matrix (%) |
|----------------|----------------|------------|----------------------------|------------|------------|
| 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         |
nate 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 analyzed following the premises applied by Prélàt et al. (2009, 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 Prélàt 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 3980 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 with 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 (Prélàt et al., 2010). Considering the individual lobes which are in the range of a few to <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

**Fig. 5.** Puelche x-1 log-based 1 : 500 interpretation. The sharp Artinskian post-glacial transgression is clearly interpreted in the gamma-ray log at 3600 m. Between 3400 and 3600 m, a series of high gamma-ray values are interpreted as levels rich in organic matter. See text for discussion.
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.

**Seismic interpretation**

A regional seismic stratigraphic interpretation was carried out 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 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 8500 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 characterisation 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

Fig. 7. Puelche x-1 well core #2, see Fig. 5 for location. The core corresponds to one of the three fine grained intercalations within the glacially influenced interval. The prevailing facies are finely laminated shales and siltstones with abundant micro-dropstones, and massive diamictites; convolute bedding and soft sediment deformation are frequent. (1) Lower portion of box 7, thinly laminated shales and siltstones. Arrows indicate micro-dropstone bearing levels and isolated dropstones in the fine grained matrix. (2) Lower portion of box 7, detail of a shaly lamina-set containing micro-dropstones. (3) Upper half of box 1; the upper portion is composed by massive para-breccia with a shaly to silty matrix and characterised by poorly selected clasts that range from rounded to sharp-edged. The lower portion is composed by shales and siltstones displaying soft sediment deformation. Dropstones up to 4 mm in diameter are visible.
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-grained sand and characterised by lateral and downstream accretion on several scales, with local variability controlled both by autogenic and allocyclic factors. Correlation of the nondrilled units of the upper Paleozoic 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 Paleozoic 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. In addition, 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.

Fig. 9. Seismic line Digicom 129, northern flank of the Colorado basin. The high-amplitude parallel reflections seismic image of the Pennsylvanian to Lower Triassic sedimentary rocks stands-out from the reflection-free pre-upper Pennsylvanian units. White arrows indicate the base of the Pennsylvanian to Cisuralian diamictite-bearing interval. Modified from Pángaro (2013).

Fig. 10. Detail of seismic line Digicom 129, Locality A. (a) Interpreted seismic line highlighting the upper Palaeozoic to Lower Triassic succession. Colours of the Palaeozoic–Mesozoic unconformity denote its seismic amplitude. Red: high amplitude. Orange: moderate amplitude. Yellow: low amplitude. No vertical exaggeration. (1) Pre-Pennsylvanian basement. (2) Mesozoic syn-rift sedimentary rocks. (3) Drift-stage sedimentary rocks. (b) Detail of the uppermost portion of the late Palaeozoic to Triassic succession. Note the prominent relief of the diamictite-bearing section to the south, the sharp upper and lower boundaries of the submarine lobes unit, and the strong lateral amplitude variations of the Mesozoic–Palaeozoic unconformity. The white arrows point the sections where the unconformity’s amplitude reaches the minimum values in coincidence with the ‘Eurydesma transgression’ and with the low energy sedimentary rocks above the Guadalupian–Lopingian submarine lobes unit. Note in (a) and (b), the distinctive seismic facies of the uppermost Palaeozoic to Triassic section interpreted as continental deposits. (c) Interpretation of the seismic detail in (b).
Among the interpreted localities, of special interest are sites B and C (Figs 11 and 12) which lie only 20–30 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°; however, when considering the Guadalupian regressive surface as a datum, this figure drops to 0.2° 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 Pángaro & Ramos (2012) that indicated compressive deformation resulting in the Venta fold belt was post-depositional and hence post-Lower Triassic.
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 boundary is deeply controlled by the Atlantic break-up-related uplift of the coastal range of southern eastern boundary is deeply controlled by the Atlantic neighbour basins forming a continuous entity during Grande-Colorado basins and extends further into the Hesperides is proposed herein to refer to a basin that the Kalahari and Karoo basins to the east. The name of also affected by Mesozoic and Cenozoic kilometre-scale ran

thickness variations and with connections to the Chacoparaná basin to the west, the Paraná 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 Claramécó and Sauce Grande-Colorado basins and extends further into the neighbouring basins forming a continuous entity during the upper Palaeozoic and Lower Triassic.

Subsidence curves

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 Entendeka LIP (Stica et al., 2014; 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. Although 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 Gisuralian), 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 nonexistent. However, new data alongside the reinterpretation of old data provide 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 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 tectonic 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.

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 10–13. 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.

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One key onshore point to calibrate our denudation model is the Paragüí 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 rifting-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.

**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 (Harrington, 1972). 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 16–18. These were integrated with data gathered on the temporal and spatial evolution of the
Fig. 15. Onshore subsidence curves. The stratigraphy of the Paragüil x-1 well allowed stating that the Palaeozoic sediments were not affected by the Gondwanides orogeny, and that circa 2 km of rock were eroded according to vitrinite reflectance data. A similar denudation process is interpreted to have taken place at Sierras de la Ventana locality, hence allowing the interpretation of scenario b, in which the Palaeozoic to Lower Triassic stratigraphic record is eroded both as a consequence of the Gondwanides-related uplift and of the Mesozoic denudation events.

Fig. 16. Late Cisuralian palaeogeography of the Hesperides and surrounding basins. See Fig. 18 for references. Note the extension of the marine low-energy environment that encompasses the Kalahari, Karoo, Paraná and most of the Hesperides basin; to the west sedimentary influx is interpreted to have been higher as suggested by the time equivalent marginal marine to continental rocks cropping out in the Sierras de la Ventana. Further west, the Carapacha and San Rafael basins are interpreted to have been in close relationship with an advancing orogen. Control points: (1) Puelche x-1 well. (2) Seismic line presented in Fig. 10. (3) Age determinations by Alessandretti et al. (2010) and López Gamundi et al. (2013). (4) San Rafael basin palaeocurrents, see text for details. (5) Northern volcanic arc of Ramos (2008). (6) Tectonic transport direction in Cerro de los Viejos from Von Gosen 2003 and Chernicoff et al. 2013. (7 and 8) Extension of the Mesosaurus Inland Sea based on Werner (2006).
Gondwanides to provide a first approach into the evolution of south-eastern Gondwana.

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 Gamundi et al., 2013); these observations are in accordance with low sediment supply conditions for over 10 Ma, 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.

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). Although 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 Gamundi 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 (Pangaro & Ramos, 2012; Pangaro et al., 2013). Further east, in the Karoo basin, the correlative submarine fans of the Laingsburg and Tanqua depocentres are interpreted as well to predate 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 1500 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 Pangaro & 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 400–300 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 1500 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).

**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

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**Fig. 18. Lower Triassic palaeogeography of the Hesperides and surrounding basins.** The whole area encompassed by the Hesperides, Kalahari and Karoo basins was dominated by continental environments. The orogenic front is interpreted to have remained south of the Colorado basin until late Lower Triassic. Note that while the Gondwanides orogen was still evolving, the San Rafael basin to the northwest was subjected to extension and syn-rift volcanism (Kleiman & Japas 2009). The continuous purple line marks the maximum northwards extension to be reached by the Gondwanides orogen by latest Lower Triassic–Middle Triassic. Palaeocurrents directions in the Karoo basin after Veevers et al. (1994).
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 Aguilhas 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.

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 1995; 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 Permin 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.

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 noninterpreted Argentinean continental shelf.
- The Hesperides basin, a previously overlooked circa 1000 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 (Tankard et al., 2009; Flint et al., 2011; Lindeque 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 stratigra-
The Hesperides basin

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