**PALEOENVIRONMENTS AND AGE OF THE TALAMPAYA FORMATION:
THE PERMO-TRIASSIC BOUNDARY IN NORTHWESTERN ARGENTINA**

E.L. Gulbranson¹, P.L. Ciccioli², I.P. Montañez³, S.A. Marensi², C.O.

Limarino², M.D. Schmitz⁴ and V. Davydov^{4, 5}

1: Department of Geosciences, University of Wisconsin-Milwaukee, Wisconsin, USA

gulbrans@uwm.edu

2: IGEBA-Departamento de Geología, Facultad de Ciencias Exactas y Naturales,
Universidad de Buenos Aires. Pabellón 2, Ciudad Universitaria, Buenos Aires,
Argentina, C1428EHA. ciccioli@gl.fcen.uba.ar, smarensi@hotmail.com,

limar@gl.fcen.uba.ar

3: Department of Earth and Planetary Sciences, University of California-Davis, Davis,
California, USA ipmontanez@ucdavis.edu

4: Department of Geosciences, Boise State University, Idaho, USA.
markschmitz@boisestate.edu

5: Kazan Federal University, 18 Kremlyovskaya St., Kazan, Republic of Tatarstan 420008.
vdavydov@boisestate.edu

Corresponding author: Patricia L. Ciccioli ciccioli@gl.fcen.uba.ar

Departamento de Ciencias Geológicas –Instituto de Geociencias Básicas, Aplicadas y
Ambientales de Buenos Aires (IGeBA), Facultad de Ciencias Exactas y Naturales,
Universidad de Buenos Aires. Pabellón 2, 1° piso, Ciudad Universitaria, C1428EHA
Buenos Aires, Argentina Tel: (54-11) 4576-3300/09 int. 317; Fax: (54-11) 4576-3329.

ABSTRACT

The Talampaya Formation is the basal unit of the Ischigualasto-Villa Unión rift system and has been traditionally assigned to the Triassic based on stratigraphic relationships. A median U-Pb age of 252.38 (+0.09/-0.22) Ma was obtained from volcanic zircons collected from a tuff bed close to the top of this unit at the Bordo Atravesado locality in the Cuesta de Miranda area (La Rioja, Argentina). This radiometric age is very close to the accepted Permian-Triassic boundary indicating that, at least in this locality, sedimentation occurred during the Late Permian but may have extended into the earliest Triassic. This new evidence indicates that the onset of the extensional event that gave rise to the rift basins in western Argentina started during the Permian. Detailed sedimentological studies of the 260 meter thick Talampaya Formation allowed subdividing the succession into seven facies associations grouped into three evolutionary stages indicating that sedimentary environments initially evolved from alluvial fans to a braided river system. Subsequent intrabasinal volcanism associated with sediment deposition by low- to moderate-sinuosity rivers is recorded in the lower third of the column. The middle and upper part of the unit captures the evolution from ephemeral fluvial systems with an eolian interval to an ephemeral clastic lake with intermittent volcanic ash deposits. These changes indicate a progressive lowering of the landscape and a transition towards arid or semiarid conditions.

KEYWORDS: Talampaya Formation; Late Permian paleoclimates; Permian-Triassic boundary.

1. Introduction

Over the last two decades, there has been a great deal of interest focused on understanding the patterns and timing of extinction and recovery and plausible trigger(s) and kill mechanisms of the end-Permian biotic crisis, the largest extinction of the Phanerozoic (Burguess et al., 2014). In order to address this scientific problem, precise age models must be developed to constrain the timing and duration of the extinction in different parts of the world and to relate the event to its possible causes.

Thick sequences corresponding to the late Paleozoic Paganzo Basin and the Triassic Ischigualasto-Villa Unión Basin crop out extensively in the southwest of the La Rioja Province, northwestern Argentina. These basins developed in quite different geotectonic settings. The Paganzo Basin has been described either as a foreland, intracratonic or intermontane basin related to the collapse of the Protoprecordillera Orogen while the Ischigualasto-Villa Unión Basin is a rift with a well defined NW-SE trend. The upper part of the Late Paleozoic Paganzo Basin and the lowermost strata of the Triassic Ischigualasto- Villa Unión Basin mainly consist of red beds deposited in similar environments making them difficult to differentiate in the field. Red beds of the Paganzo Basin include the latest Carboniferous to early Permian succession (Limarino and Césari, 1987; Gulbranson et al., 2010) De la Cuesta (Turner, 1960) and the Patquía formations (Frenguelli, 1944; de Alba, 1954, 1979) while redbeds of the latter basin include the early Triassic Talampaya (Romer and Jensen, 1966) and Amaná formations (Azcuy et al., 1979). It is important to note that this former age for the Talampaya Formation is based on stratigraphic relationships given the lack of existing biostratigraphic ages or radiometric analysis for a precise age determination. As an example Stipanovic and Bonaparte (1979) used ichnofossils related to tetrapods (*Chirotherium*-type) to suggest a

Triassic age while Zhang et al. (1998) attributed the moderately diverse arthropod ichnofauna of the Talampaya Formation to the Permian.

Distinguishing Permian beds from Triassic ones is critical to differentiate strata of the Paganzo Group deposited in a back-arc basin related to the collapse of the Protoprecordillera from those beds deposited in the extensional setting related to the early breakup of Gondwana. In addition, up to now there is no mention of the Permian-Triassic boundary (PTB) occurring within the sedimentary succession in Argentina. In particular, the age of the thick redbed section in the Cuesta de Miranda area (Fig.1) has been a matter of discussion from many years. Stipanovic and Bonaparte (1979) have already pointed out to the need of separating Permian from Triassic deposits. In that sense Caselli (1998) proposed a modification of the existing stratigraphy (e.g. de Alba, 1954) recognizing the presence of Triassic strata in the Bordo Atravesado area, the summit of the Cuesta de Miranda.

Herein we report the first radiometric age obtained from the upper part of the Talampaya Formation at the Bordo Atravesado locality, Cuesta de Miranda, La Rioja Province (Argentina). At the same time, we present a geological map of the area and a paleoenvironmental interpretation for the Talampaya Formation at that locality.

2. Stratigraphy of the area

We focused our research on the Cuesta de Miranda area in La Rioja Province, northwestern Argentina (Fig. 1). Three major stratigraphic packages are recognized in the studied area: 1. Early Paleozoic metamorphic and granitic rocks, 2. A late Paleozoic continental succession included in the Paganzo Group (Bodenbender, 1912, Azcuy and Morelli, 1970), and 3. Redbed sandstones and mudstones of the Talampaya Formation

(Romer and Jensen, 1966). The Ordovician Ñuñorco granite (Turner, 1962) and the low-grade metamorphic rocks of the Negro Peinado Formation (Turner, 1962) form the basement of the late Paleozoic and Early Triassic basins in the Nevados del Famatina area.

The upper Paleozoic is represented by small outcrops of the Carboniferous Agua Colorada Formation (Turner, 1960) and the Late Carboniferous-Early Permian De La Cuesta (Turner, 1960) or Patquía formations (De Alba, 1954; 1979). The former include sandstones, mudstones, conglomerates as well as some coal beds and glacial diamictites that form the basal filling of the late Paleozoic Paganzo Basin (Limarino et al., 2006). The latter corresponds to a thick redbed succession comprising sandstones, mudstones, conglomerates and intraformational breccias, together with tuffs and some gypsum-rich intervals (Caselli and Limarino, 2002). The upper Paleozoic units onlap the Ordovician basement.

The Talampaya Formation unconformably rests on top of the De la Cuesta Formation or onlaps the basement rocks (Fig. 1). At the measured section, the Talampaya Formation is 260 m thick and it is mainly composed of red sandstones and mudstones with intercalated coarse-grained conglomerates and thin tuff levels in the lower and upper third of the succession, respectively (Figs. 2; 3a,b). This unit represents the basal infilling of the Ischigualasto-Villa Unión rift basin. According to Spalletti (1999) the Talampaya and the overlying Tarjados formations record an early stage in the development of a passive rift controlled by a previous (Famatina-Tarjados-Paganzo) fault system.

3. Sedimentology of the Talampaya Formation

According to lithology, sedimentary structures, form and type of bounding surfaces and vertical-lateral arrangement of lithofacies, eight facies associations (FA)

were recognized in the Talampaya Formation (Table 1; Fig. 2).

3.1. Facies Association 1

Description: This association, 20 m thick, rests on the crystalline basement and is mainly composed of agglomerates, boulder and pebble conglomerates, and coarse-grained sandstones (Fig. 3a). Agglomerates and boulder conglomerates are composed of clasts up to 6 m in diameter (Fig. 3b) made up of granites (80%), red sandstones (10%), low-grade metamorphic rocks (8%) and volcanic rocks (2%, Fig. 3c). The matrix is coarse-grained sand mainly composed of quartz, feldspar and granitic rock fragments.

Three different lithofacies are recognized: 1) clast-supported massive boulder and pebble conglomerates, 2) clast-supported stratified pebble conglomerates, 3) matrix-supported agglomerates and boulder conglomerates.

Clast-supported massive boulder and pebble conglomerates contain clasts up to 40 cm in diameter and are stratified in coarse beds up to 1 m thick. Occasionally they exhibit diffuse tabular cross-bedding.

Clast-supported and stratified conglomerates are fine- to medium-grained and grade to coarse-grained sandstones. They are stratified in tabular beds up to 30 cm thick with plane base and planar and trough cross-bedding. Coarse-grained and granule-sandstones are stratified in tabular beds up to 30 cm in thickness and are draped by centimeter-thick laminae of very fine-sandstones and siltstones.

Matrix-supported agglomerates and boulder conglomerates with a sandy matrix (clast/matrix ratio 40:60) are massive or show diffuse inverse grading. They contain rounded to subrounded clasts of granites with peripheral weathering up to 6 m in length and frequently form amalgamated beds.

Interpretation: The dominance of coarse-grained deposits, the large diameter of many clasts, the crude stratification observed in the major part of the conglomerates and the local provenance of the fragments (dominated by granitic and metamorphic clasts derived from the local basement) suggest that this facies association was deposited in small alluvial fans (Nemec and Postma, 1993). In this context, clast-supported stratified conglomerates represent deposition from diluted flows while matrix-supported agglomerates and boulder conglomerates likely correspond to debris flow deposits.

3.2. *Facies Association 2*

Description: This facies association is 15 m thick and transitionally overlies Facies Association 1 but it also onlaps the basement locally. It consists of coarse- to fine-grained conglomerates and coarse to fine-grained sandstones (Fig. 3d).

Conglomerates are mainly clast-supported but matrix- (sand) supported conglomerates are also present. Clasts up to 15 cm in diameter are well-rounded and composed of granite, low- grade metamorphic rocks, red sandstones and volcanic rocks. Beds are lenticular (up to 1 m thick) with erosive bases (Fig. 3e). They frequently amalgamate in meter-scale units exhibiting tabular and trough cross-bedding and occasionally parallel stratification; they can be massive.

Coarse- to fine-grained sandstones show abundant dispersed gravel clasts. Beds are up to 10 cm in thickness and are internally massive or cross-bedded. They show frequent mud drapes.

Interpretation: This facies association is interpreted as the deposits of braided rivers characterized by channels that suffered rapid avulsion (Miall, 1996; 2014). The geometry of the cross-bedded sandstones and conglomerates suggests that the channels were filled

by high to moderate relief bars dominated by downstream migration. The presence of mud drapes at the top of the cross-bedded sandstones indicates final deposition by low energy currents prior to the definitive abandonment of the channels (avulsion).

3.3. *Facies Association 3*

Description: This facies association sharply rests on Facies Association 2. It has a typical purple color (Fig. 3f) and it is mainly composed of basaltic breccias (Fig. 4a). At Cuesta de Miranda it reaches up to 15 m in thickness pinching out quickly to the south. Three main lithofacies are recognized: 1) massive basaltic breccias, 2) stratified basaltic breccias and, 3) thinly-stratified mudstones. The massive basaltic breccias are near completely composed of angular and subangular aphanitic basalt fragments (Fig. 4a,b). They are either clast- or matrix-supported. These rocks form amalgamated beds up to 2 m in thickness with individual strata between 30 and 50 cm thick.

The stratified basaltic breccias are mainly matrix-supported with basaltic clasts with a maximum size of 8 cm. They form amalgamated beds up to 2 m in thickness with individual strata up to 30 cm in thickness. Internally they show parallel stratification and a planar fabric of clasts.

The thinly-stratified mudstones intercalate with the previously described lithofacies forming intervals of 0.5 to 1 m thick with individual beds 2 to 4 cm thick.

Interpretation: This interval indicates the onset of a brief episode of effusive volcanic (basaltic) activity in the basin, which produced a significant change in the composition of the sandstones below and above this facies association. The lithic (volcanic) composition of the sandstones is very different from the arkosic nature of the major part of the sandstones belonging to the Talampaya Formation. Massive basaltic breccias were

probably deposited by debris flow from a close volcanic source while stratified breccias, and the associated thinly stratified mudstones, indicate some fluvial transportation.

3.4. *Facies Association 4*

Description: This unit, 70 m thick, transitionally covers FA3 and it is composed of fining-upward cycles of conglomerates, sandstones and mudstones. At the base and the top of the unit the cycles are 2 to 4 meter thick whereas in the middle of the interval the cycles reach up to 6 m thick (Fig. 4c).

Each cycle begins with lensoid deposits showing a planar to moderately erosive base covered by clast-supported coarse- to medium-grained conglomerates with sandy matrix. They are massive at the base or show tabular and trough-cross bedding and occasional normal grading. Basement clasts up to 30 cm of diameter are rounded while basaltic clasts are subangular to angular and up to 8 cm in diameter. Massive or occasionally cross-bedded, granule to coarse-grained sandstones grading to rippled fine-grained sandstones, appear at the top of the lensoid deposits.

Fine-grained deposits are tabular and consist of sandstones and mudstones (Fig. 4c). Sandstones form three different deposit types: 1) Thin tabular beds up to 10 cm thick of fine-grained sandstones with current-ripple cross-lamination, massive or parallel lamination, 2) Plane-convex-upward lenticular beds of medium- to fine-grained sandstones with massive, tabular cross-bedding or ripple-cross lamination and, 3) thin lenticular ~~channels~~ bodies with slightly erosive bases composed of massive coarse-grained sandstones. Massive, parallel laminated or ripple-cross laminated mudstones form tabular intervals up to 3 m thick.

Interpretation: The sediments in this interval were most likely deposited by low- to medium-sinuosity rivers (Miall, 1996; 2014). The lensoid form conglomerate beds comprising the lower part of the fining-upward cycles record limited lateral migration of channels in response to periodic avulsion without substantially changing its position on the alluvial plain. This promoted the vertical growth of the floodplain deposits including low-energy fine-grained sediments of the floodbasin and medium- and coarse-grained sandstones forming crevasse-splay deposits characterized by the convex-upward beds.

3.5. *Facies Association 5*

Description: This unit, 60 m thick, is composed of fine- to medium-grained sandstones (Fig. 4d) in which massive and laminated mudstones are sometimes intercalated. These deposits are divided in three different types based on the architecture of the sandstone beds. 1) Tabular beds, up to 30 cm thick, of medium- to fine-grained sandstone with sharp planar bases. Internally, the lower parts are massive or horizontal-laminated with parting lineation. The upper parts are ripple-cross laminated, which in some cases preserve current ripples at their tops. 2) The second type of deposits is very similar to the aforementioned but with common thin veneers of mud, and in some cases centimeter-scale intercalation of mudstones between sandstone beds. 3) The third deposit type consists of channelized beds of medium- and coarse-grained sandstones, which occur sporadically along this facies association forming lenticular beds with erosive lower bounding surfaces. While the lower and middle part of these channels are massive, or show small-scale grouped sets of both tabular and through cross-lamination, the upper part is composed of fine-grained ripple-cross laminated sandstones. The

architecture of the major part of the channels is simple consisting of single or two-story channels while multistory channels are rarely observed.

Interpretation: This facies association has a fluvial origin and probably corresponds to ephemeral sandy rivers with transitional characteristics between distal sheetflood and flashy sheetflood sandy-bed rivers (Miall, 1985; 1996). However, as pointed out by North and Davidson (2012) and Miall (2014) the term sheetflood has a vague definition with the term sandflat used interchangeably. In our case, we refer to a poorly channelized system of ephemeral nature in which sedimentation took place mostly in interchannel areas due to unconfined flows during flooding events. In this model the channelized deposits correspond to lenticular beds of medium- and coarse-grained sandstones with erosive lower bounding surfaces (third type of architecture described previously). The presence of medium- to small-scale cross-bedded sets suggests that the channels were dominated by the migration of sandy bedforms (from dunes to ripples) and only sporadically small low-relief sand bars were developed. The first type of previously described architecture formed as overflow deposits on the floodplains, where in some cases, flows were fast enough to form plane-bed lamination in upper flow regime. Rapidly decreasing high flow conditions favored the migration of current ripples and the deposition of terminal mud veneers. Architecture type 2 corresponds to floodplain deposits located in more distal positions with respect to the channel belt and characterized by lower velocity currents and longer periods of quieter flow settling of suspended mud.

3.6. *Facies Association 6*

Description: This facies association (35 m thick) is almost entirely composed of fine- grained sandstones (Fig. 4e) in some cases showing thin intercalated mudstones.

Sandstones are fine- to very fine-grained, well- to very well-sorted and near free of muddy matrix. These rocks exhibit three major types of sedimentary structures: 1) cosets up to 1.5 m thick of tabular cross-bedding, 2) trough cross-bedded sets up to 50 cm thick and 3) horizontal lamination. In this third case, deposits exhibit a delicate lamination composed of fine-grained sandstones interlaminated with medium- to coarse-grained sandstones, some of which exhibiting inverse-grading.

Towards the upper part of this interval, tabular beds of mudstones are sometimes intercalated with current ripple cross-laminated fine-grained sandstones. Mudstones are massive or laminated and commonly exhibit desiccation-cracks at the top of the beds (Fig. 4e).

Interpretation: An eolian origin is proposed for this interval based on the predominance of well-sorted, fine- to medium-grained sandstones, the common presence of cross-bedded sets, the lack of erosive surfaces and the existence of inverse-graded lamination. The common occurrence of laminated sandstones exhibiting inverse-grading in eolian sandsheet is interpreted to record the migration of ripples (Hunter, 1977, Tripaldi and Limarino, 2008). The lack of large-scale cross-bedded sets seems to suggest the existence of an eolian-fluvial interaction environment as described by Langford (1989), Veiga and Spalletti (1999), Sweet (1999) and Mountney and Jagger (2004). The intercalation of mudstone beds within sandy fluvial-eolian deposits, as observed in this study, was described as muddy-sheets by Tripaldi and Limarino (2008) and interpreted as unconfined fluvial currents that flooded the eolian area during pluvial periods.

3.7. *Facies Association 7*

Description: This facies association (45 m thick) comprises a fining-upward interval

composed of interbedded fine-grained sandstones and mudstones and a monotonous sequence of mudstones with scarce intercalations of tuffs and marls at the top (Fig. 4f). Sandstones are very fine- to fine-grained, well-sorted, and in some cases micaceous. In the lower portion, deposits are stratified in tabular beds (up to 10 cm thick), which are massive or horizontal laminated, rarely showing parting lineation. Some exhibit isolated centimeter-scale sets of current cross-lamination to cosets of climbing and wave-rippled cross-lamination. Towards the middle part of this facies association the number and thickness of the sandy intervals decrease with predominant mudstones. The muddy interval includes laminated mudstones, thin levels of tuffs and some marls. The mudstones contain an interesting ichnofauna described by Zhang et al. (1998) which includes *Cruziana problematica*, *Diplocraterion* isp., cf. *Diplopodichnus biformis*, *Kouphichnium?* isp., *Merostomichnites aicuñai*, *Miramlaichnium famatinense*, *Monomorphichnus lineatus*, *Palaeophycus tubularis*, *Umfolozia sinuosa* and *Umfolozia* cf. *U. longula* isp. Fish scales can be observed on the underside of some tuff beds.

Interpretation: Detailed studies by Zhang et al. (1998) interpreted this interval as an ephemeral hydrologically closed lake that developed under arid or semiarid climates and that it records a hierarchy of transgressive-regressive cycles. However, the fining-upward stacking of facies clearly suggests an expansion of the water body from bottom to top. Thus, the horizontal laminated and current cross-laminated sandstones that prevail in the lower part of the section may be interpreted as deposits of marginal sand flat areas dominated by poorly-channelized or non-channelized (sheet) floods during pluvial periods. The increase in muddy layers in the middle part would suggest the expansion of the water body, which reached its maximum in the upper muddy interval where the ichnofauna described by Zhang et al. (1998) was found. The tuff levels are the product of

recurrent ash fall episodes although the fine grain-size and the thin bed thickness seem to indicate a distant volcanic source.

4. Radimetric age: Methodology and results

A tuff sample was collected from upper part of the Talampaya Formation at Bordo Atravesado, Cuesta de Miranda (Fig. 1). Sample collection focused on the basal portion of the ash bed to account for the settling of zircons during deposition. Zircons were separated by standard methods of crushing, magnetic separation, and heavy liquid separation. Handpicked zircons were subjected to a modified version of the chemical abrasion method of Mattinson (2005), reflecting a preference to prepare and analyze carefully selected single crystals or crystal fragments. Zircon separates were placed in a muffle furnace at 900°C for 60 h for annealing. Single crystals were transferred to 3 mL Teflon perfluoroalkoxy (PFA) beakers, rinsed twice with 3.5 *M* HNO₃, and loaded into 300 µL Teflon PFA microcapsules. Microcapsules were placed in a large-capacity Parr vessel, and the crystals were partially dissolved in 120 µL of 29 *M* HF with a trace of 3.5 *M* HNO₃ for 10–12 hs at 180 °C. The contents of each micro capsule were returned to 3 mL Teflon PFA beakers, the HF was removed, and the residual grains were rinsed in ultrapure H₂O, immersed in 3.5 *M* HNO₃, ultrasonically cleaned for an hour, and fluxed on a hotplate at 80°C for 1 hour. The HNO₃ was removed, and the grains were again rinsed in ultrapure H₂O or 3.5 *M* HNO₃ before being reloaded into the same 300 µL Teflon PFA micro capsules (rinsed and fluxed in 6 *M* HCl during crystal sonication and washing) and spiked with the EARTHTIME (Condon, 2005; Parrish et al., 2006) mixed 205Pb-233U-235U tracer solution (ET535). These chemically abraded grains were dissolved in Parr vessels in 120µL of 29 *M* HF with a trace of 3.5 *M* HNO₃ at 220°C for

48 hs, dried to fluorides, and then re-dissolved in 6 M HCl at 180 °C overnight. U and Pb were separated from the zircon matrix using an HCl-based anion-exchange chromatographic procedure (Krogh, 1973), eluted together, and dried with 2 μ L of 0.05 N H₃PO₄. Pb and U were loaded on a single outgassed Re filament in 2 μ L of a silica-gel/phosphoric acid mixture (Gerstenberger and Haase, 1997). U and Pb isotopic measurements were made on an Isoprobe-T multicollector thermal ionization mass spectrometer (TIMS) equipped with an ion-counting Daly detector at the Boise State University Isotope Geology Laboratory. Pb isotopes were measured by peak-jumping all isotopes on the Daly detector for 100–150 cycles, and corrected for $0.22 \pm 0.04\%$ /a.m.u. mass fractionation. Transitory isobaric interferences due to high-molecular-weight organics, particularly on ²⁰⁴Pb and ²⁰⁷Pb, disappeared within ~30 cycles, while ionization efficiency averaged 104 cps/pg. Linearity (to $\geq 1.4 \times 10^6$ cps) and the associated dead time correction of the Daly detector were monitored by repeated analyses of NBS982, and have been constant since installation (2006). Uranium was analyzed as UO₂⁺ ions in static Faraday mode on 10¹¹ ohm resistors for 150–200 cycles, and corrected for isobaric interference of ²³³U¹⁸O¹⁶O on ²³⁵U¹⁶O¹⁶O with an ¹⁸O/¹⁶O of 0.00205. Ionization efficiency averaged 20 mV/ng U. U mass fractionation was corrected using the known ²³³U/²³⁵U ratio of the ET535 tracer solution. U-Pb dates and uncertainties for each analysis were calculated using the algorithms of Schmitz and Schoene (2007) and a ²³⁵U/²⁰⁵Pb ratio for ET535 of 100.18 ± 0.05 . The ²⁰⁶Pb/²³⁸U ratios and dates were corrected for initial ²³⁰Th disequilibrium using a Th/U[magma] of 3 (Crowley et al., 2007), resulting in a systematic increase in the ²⁰⁶Pb/²³⁸U dates of ~90 k.y. Common Pb in analyses was attributed to laboratory blank and subtracted based on the measured laboratory Pb isotopic composition and associated uncertainty. U blanks

were less than 0.1 pg, and correction was insignificant. Over the course of the experiment, isotopic analyses of the TEMORA zircon standard yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 417.43 ± 0.06 ($n=11$, mean square of weighted deviates [MSWD] = 0.8). The quoted age error includes analytical uncertainties based on counting statistics, spike subtraction, and common Pb correction, and is appropriate in comparisons with other $^{206}\text{Pb}/^{238}\text{U}$ ages obtained with the EARTHTIME spike, or those spikes cross-calibrated with the EARTHTIME gravimetric standards. If used in comparison with ages derived from other U-Pb methods or decay schemes (e.g., Ar/Ar, ^{187}Re - ^{187}Os), then the uncertainty in the spike U/Pb ratio and the ^{238}U decay constant can be added in quadrature, respectively.

Quoted errors for individual analyses are of the form $\pm X [Y/Z]$ (*sensu* Bowring et al., 2007) where X is analytical uncertainty, Y is the combined analytical and tracer uncertainty, and Z is the combined analytical, tracer, and ^{238}U decay constant uncertainty.

In total, 6 single zircon grains from one sample were analyzed. The data set yield majority clusters of 4 concordant zircons (considering decay constant errors) and equivalent dates that we interpret as the igneous crystallization ages of the zircons, and that approximate the eruption and deposition ages of the volcanic horizons (Reid and Coath, 2000; Crowley et al., 2007). We discard from age calculations the dates resolvable from the majority cluster at the 95% confidence interval (CI), interpreted as antecrysts (Miller et al., 2007) inherited from earlier episode(s) of magmatism or from juvenile basement to the magmatic system, or younger zircons that we interpret to have maintained open-system domains, subject to Pb-loss, after the chemical abrasion technique was applied.

The mean square of the weighted deviates (MSWD, York, 1967, 1969) was

calculated for the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of the majority clusters. Utilizing the statistical distribution of MSWD (Wendt and Carl, 1991), for $n - 1$ degrees of freedom, we calculated the acceptable degree of data scatter attributable to analytical errors; the median age passes this confidence test at the 95% CI.

The 6 prismatic zircons collected from a tuff in the upper part of playa-lake strata (Facies Association 8) at Bordo Atravesado locality in Cuesta de Miranda (Fig. 1), yield concordant U-Pb ages that provide a median $^{206}\text{Pb}/^{238}\text{U}$ age of 252.38 (+0.09/-0.22) Ma for this sample (Fig. 5, Table 1). The reported age for the upper part of the Talampaya Formation at Bordo Atravesado is very close to the accepted age of 252.17 ± 0.06 Ma for the Permian-Triassic boundary (Shen et al., 2013) and the newly proposed age of 251.880 ± 0.031 Ma (Burguess et al., 2014). It therefore indicates that most of the Talampaya Formation was deposited during the Permian. However, as the top of this unit does not crop out in the study area and at least several meters to few tens of meters of mud-flat deposits overlie the dated horizon it is very likely that the Permian-Triassic boundary is recorded in the uppermost part of the Talampaya Formation.

5. Discussion

From the regional point of view, this study of the Talampaya Formation offers at least three important findings: 1. The discovery of a previously unrecognized Late Permian basin, 2. Delineation of the paleoenvironmental and paleoclimatic evolution of the Talampaya Formation and 3. The paleogeographic significance of Talampaya Formation in a regional paleogeographic model. Despite a lack of radiometric or biostratigraphic ages, the Talampaya Formation has been traditionally considered Early Triassic in age (e.g. Stipanovic and Bonaparte, 1979; Aceñolaza and Buatois, 1991;

Milana and Alcober, 1994; Zerfass et al., 2004). This assumption suggested a considerable time gap in the stratigraphic record since the youngest beds of the underlying Patquía Formation are late Early Permian or early Middle Permian in age (Caselli and Limarino, 2002; Gulbranson et al., 2010). Therefore the region was considered as a non-subsiding area during most of the Middle Permian and entire Late Permian since the initial stage of rifting in the Ischigualasto-Villa Unión Basin was taken to be Early Triassic (Milana and Alcober, 1994; Spalletti, 1999; Zerfass et al., 2004). Stratigraphic relationships and the high-precision radiometric age reported herein indicate that the major part of the Talampaya Formation is Late Permian in age but its uppermost part extends into the earliest Triassic. Sedimentation through the critical Permian-Triassic boundary took place in a clastic playa-lake environment under arid to semiarid conditions.

The vertical stacking of facies associations of the Talampaya Formation suggests a progressive lowering of the landscape and a transition to semiarid or arid conditions. The record can be divided into three stages (Fig. 6). During stage 1 an irregular erosion surface, which developed in the basement crystalline rocks, probably during the middle Permian, favored the formation of the small alluvial fans of facies association 1 dominated by both diluted and debris flows (Fig. 6). The transition to facies association 2, deposited by braided rivers, indicates a smoothing out of the irregular landscape and very probably the expansion of the basin.

Stage 2 begins with the basaltic breccias of facies association 3, which attest to the onset of intrabasinal volcanic activity, limited to thin basaltic flows, intercalated in different stratigraphic levels depending on the paleogeographic position into the basin. In the case of the Cuesta de Miranda area, the eruptive episode was followed by

deposition of the thick fluvial sequence (not less than 70 m) of conglomerates, sandstones and mudstones of facies association 4. These rocks were deposited in wide and very probably low gradient muddy alluvial plains in which low- to medium-sinuosity channels, which showed limited lateral migration, traversed.

Stage 3 is characterized by a pronounced decrease in the energy of the fluvial systems, the appearance of eolian sandstones intercalated with ephemeral-fluvial deposits, the intercalations of thin tuff levels and the presence of muddy playa-lake facies in the uppermost parts of the succession. All of these features suggest that semiarid or arid climatic conditions prevailed during the deposition of the upper part of the Talampaya Formation. In this context, facies association 5, dominated by fine- to medium-grained sandstones, suggests a remarkable change in the nature of the fluvial systems. Stable fluvial channels composed of conglomerates almost entirely disappeared and sedimentation seems to have occurred in braided plains of ephemeral sandy rivers. Arid conditions may have intensified as indicated by the common occurrence of eolian-fluvial interaction deposits of facies association 6. Finally, in the uppermost part of the succession the dominance of fine-grained playa-lake deposits and some levels of small eolian sandstones indicate the culmination of development of fully arid conditions.

In summary, the vertical succession of facies association clearly shows a progressive change to more arid conditions towards the upper part of the Talampaya Formation. This climatic pattern is similar to that observed in other regions of South America where a transition from the icehouse conditions in the latest Carboniferous-earliest Permian to extreme greenhouse arid climate in the latest Permian has been reported (Guerra-Sommer and Cazzulo-Klepzig, 2000; Holz et al., 2010; Limarino et al., 2014; Gulbranson et al., 2015). For example, the Paraná Basin shows a progressive trend

to non-marine and more arid deposits from the Guadalupian to the Permian-Triassic boundary (Rhon et al., 2005; Holz et al., 2010; Limarino et al., 2014). In this basin the Morro Pelado Member of the Rio do Rasto Formation (early Lopingian, Fig. 7) is mainly composed of sandstones and mudstones deposited in low-energy fluvial, ephemeral lacustrine and eolian environments (Holz et al., 2010). In the upper Lopingian–earliest Triassic succession, eolian deposits are also described in the Pirambóia and Sanga do Cabral Formation (Lavina et al., 1993; Delorenzo Nardi Dias and Scherer, 2008; Fig. 7). In the southernmost part of the Paraná Basin in Uruguay, estuarine and lagoonal successions (Upper Member of the Yaguari Formation) consist of variegated sandstones and mudstones with thin intercalations of gypsum, marls and bentonite (probably altered tuffs) that record episodic desiccation and probably semiarid conditions (Goso et al., 2001; de Santa Ana et al., 2006; Limarino et al., 2014). The Cerro Conventos Member of the overlying Buena Vista Formation contains sandstones deposited in dune and extradune environments (de Santa Ana et al., 2006).

The entire present day Cordillera de los Andes was subjected to extensive volcanism throughout the Late Permian. In particular Lopingian or late Guadalupian ages were obtained from the upper section of the Choiyoi Group by Llambías et al. (2003), Kleiman and Japas (2009), Rocha-Campos et al. (2011), Barrionuevo et al. (2013), and Hervé et al. (2014) (Fig. 7). This widespread volcanism, coupled with other megavolcanic events (Siberian traps and Emeishan Igneous Province), are frequently invoked as one of the causes for the extreme greenhouse conditions during the Permo-Triassic boundary (Metcalf and Isozaki, 2009; Sun et al., 2010; Limarino et al., 2014). In relation to the paleogeographic significance of the reported new age, the reassignment of the Talampaya Formation into the Late Permian improves previous paleogeographic and tectonic

models. According to Spalletti (1999), Late Permian and Early Triassic lithospheric extension, associated with late Choiyoi magmatism, gave rise to a series of passive rifts like the Ischigualasto-Villa Unión, Marayes, Cuyana Basins and San Rafael depocenters. The Ischigualasto-Villa Unión Basin presents two main rifting episodes. The initial one corresponds to the deposition of the Talampaya and Tarjados formations (*sensu* Zerfass et al., 2004) and has been related to a fault system located along the Sierra de Famatina-Tarjados-Paganzo (Spalletti, 1999). The second and more generalized episode is related to the reactivation of the Valle Fértil fault system to the west (Spalletti, 1999) and is represented by the Middle to Late Triassic units of the Agua de la Peña Group (Milana and Alcober, 1994). As previously mentioned, the Talampaya Formation was traditionally related to the Early Triassic rifting based mainly on stratigraphic relationships (e.g. Zerfass et al., 2004). However, our studies indicate that the rifting began before the Early Triassic, probably as early as the Middle Permian or at the beginning of the Late Permian.

6. Concluding remarks

1. The new U-Pb age obtained from the Talampaya Formation indicates that it was deposited during the latest Middle and Late Permian and very probably sedimentation continued up to the Permian-Triassic boundary. Therefore, the traditionally Early Triassic age assumed for these red beds must be reconsidered.

2. The Talampaya Formation forms a fining-upward clastic sequence dominated by breccias and coarse-grained conglomerates at the base and siltstones and claystones at the top. The three stages recognized in the vertical evolution of the Talampaya Formation suggest a progressive widening of the basin that first formed by isolated depocenters (stage 1) and subsequently evolved into a more integrated basin, which

was dominated by fluvial sedimentation (stage 2) with eolian, fluvial and lacustrine deposits at the top (stage 3).

3. The shifting of the Talampaya Formation into the Late Permian indicates that lithospheric extension, associated to the late Choiyoi magmatism, began much earlier than previously supposed (Early Triassic). Thus the Talampaya Formation should correspond to the oldest rifting event in the region. A later rifting episode during the Triassic gave rise to larger rift basins such as the Ischigualasto-Villa Unión, Marayes, Cuyana and San Rafael basins.

4. The vertical stacking of facies association suggests a progressive lowering of the landscape and a transition from humid to semiarid or arid climatic conditions. This paleoclimatic evolution is recorded in several Late Permian-Early Triassic successions in South America, as for example Morro Pelado Member of the Rio do Rasto Formation, Pirambóia and Sanga do Cabral formations, the Upper Member of the Yaguarí Formation and the Buena Vista Formation.

5. The new U-Pb age indicates that progressive aridification recorded in the Talampaya Formation was a regional trend when compared to adjacent depositional basins that display a similar paleoclimatic evolution. The development of mountains associated with the extensive volcanism along the Andean Cordillera is one possible explanation for this regional aridification as is a rise in atmospheric CO₂ that has been invoked for the end-Permian (Ekart et al., 1999; Berner, 2006).

Acknowledgments

This study was funded by UBACyT GC385BA, CONICET PIP 252, ANPCyT PICT 0727/2012 research grants and by NSF grants EAR0545654 and OISE0826105 to I.P.

Montanez. Research for VID was funded in part by the subsidy of the Russian Government to support the Program of Competitive Growth of Kazan Federal University among the world leading academic centers.

References

- Aceñolaza, F.G. and Buatois, L.A., 1991. Trazas fósiles del Paleozoico Superior continental argentino. *Ameghiniana*, 28(1-2), 89-108.
- Azcuy C.L. and Morelli J.R., 1970. Geología de la Comarca de Paganzo-Amaná. El Grupo Paganzo, formaciones que lo componen y sus relaciones. *Revista Asociación Geológica Argentina*, 25(4), 405-429.
- Azcuy C.L., Morelli, JR, Valencia, DA, and Vilas, D.F., 1979. Estratigrafía de la comarca Amaná-Talampaya. 7th Congreso Geológico Argentino, Neuquén, Argentina. *Actas* 1, pp. 243-256.
- Barrionuevo, M., Arnoso, M. and Llambias E.J., 2013. Nuevos datos geocronológicos en subsuelo y afloramientos del Grupo Choiyoi en el oeste de La Pampa: implicancias estratigráficas. *Revista de la Asociación Geológica Argentina*, 70, 31-39.
- Berner, R.A., 2006. GEOCARBSULF: A combined model for Phanerozoic atmospheric O₂ and CO₂. *Geochimica et Cosmochimica Acta* 70(23), 5653–5664.
- Bodenbender, G., 1912. Constitución geológica de la parte meridional de La Rioja y Regiones Limítrofes, República Argentina. *Boletín de la Academia de Ciencias en Córdoba*, Tomo 19, 5- 220.
- Bowring, S.A., Grotzinger, J.P., Condon, D.J., Ramezani, J., Newall, M.J., and Allen, P.A., 2007, Geochronologic constraints on the chronostratigraphic framework of the Neoproterozoic Huqf Supergroup, Sultanate of Oman: *American Journal of Science*,

v. 307, p. 1097–1145.

Burguess, S.D., Bowring, S. and Shenbet, S., 2014. High-precision timeline for Earth's most severe extinction. PNAS, 111(9), 3316-3321.

Caselli, A.T., 1998. Estratigrafía y Sedimentología de las Formaciones Patquía (Pérmico) y Talampaya (Triásico Inferior), en las Sierras Pampeanas Noroccidentales y Precordillera Central (Provincias de La Rioja y San Juan). Ph. D thesis, Universidad de Buenos Aires.

Caselli, A.T. and Limarino, C.O., 2002. Sedimentología y evolución paleoambiental de la Formación Patquía (Pérmico) en el extremo sur de la sierra de Maz y cerro Bola, provincia de La Rioja, Argentina. Revista de la Asociación Geológica Argentina, 57 (4): 415-436.

Condon, D.J., 2005. Progress report on the U-Pb interlaboratory experiment. Geochimica et Cosmochimica Acta, 69, 319.

Crowley, J.L., Schoene, B., and Bowring, S.A., 2007. U-Pb dating of zircon in the Bishop Tuff at the millennial scale: Geology, 35 (12), 1123–1126.

De Alba, E., 1954. Descripción geológica de la hoja 16c Villa Unión (provincia de La Rioja). Dirección Nacional de Minería. Boletín 82, 81pp.

De Alba, E. 1979. Descripción geológica de la Hoja 16d, Chilecito, provincia de La Rioja. Servicio Geológico Nacional. Boletín 163, 87 p.

de Santa Ana, H., Veroslavsky, G., Fulfaro, V. and Rossello, E., 2006. Cuenca Norte: evolución tectónica y sedimentaria del Carbonífero–Pérmico. In: Veroslavsky, G., Ubilla, M., Martínez, S. (Eds.), Cuencas Sedimentarias de Uruguay. División Relaciones y Actividades Culturales Facultad de Ciencias, Montevideo, pp. 147–208.

- Delorenzo Nardi Dias, K., Scherer, C.M., 2008. Cross-bedding set thickness and stratigraphic architecture of aeolian systems: an example from the Upper Permian Pirambóia Formation (Paraná Basin), southern Brazil. *Journal of South American Earth Sciences* 25, 405–415.
- Ekart, D.D, Cerling, T.E., Montañez, I. and Tabor, N.J., 1999. A 400 million year carbon isotope record of pedogenic carbonate: implications for paleoatmospheric carbon dioxide. *American Journal of Science*, 299, 805-827.
- Frenguelli, J., 1944. Apuntes acerca del Paleozoico superior del noroeste argentino. *Revista del Museo de La Plata, secc. Geología*, 2, 213-265.
- Gerstenberger, H., and Haase, G., 1997. A highly effective emitter substance for mass spectrometric Pb isotope ratio determinations: *Chemical Geology*, 136, 309–312.
- Goso, C., Piñeiro, G., de Santa Ana, H., Rojas, A., Verde, M. and Alves, C., 2001. Caracterización estratigráfica de los depósitos continentales cuspidales neopérmicos (Formaciones Yaguarí y Buena Vista) en el borde oriental de la Cuenca Norte Uruguay. 11th Congreso Latinoamericano de Geología, Actas, p. 18 (CDROM). Montevideo.
- Guerra-Sommer, M. and Cazzulo-Klepzig, M., 2000. Early Permian palaeofloras from southern Brazilian Gondwana: a palaeoclimatic approach. *Revista Brasileira de Geociencias*, 30, 486–490.
- Gulbranson, E.L., Montañez, I.P., Schmitz, M.D., Limarino, C.O., Isbell, J.L., Marensi, S.A. and Crowley, J.L., 2010. High-precision U-Pb calibration of Carboniferous glaciation and climate history, Paganzo Group, NW Argentina. *GSA Bulletin*, 122 (9/10), 1480–1498.
- Gulbranson, E.L., Montañez, I.P., Tabor, N.J. and Limarino, C.O., 2015. Late

- Pennsylvanian aridification on the southwestern margin of Gondwana (Paganzo Basin, NW Argentina): A regional expression of a global climate perturbation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 417, 220–235
- Hervé, F., Fanning, C. M., Calderón, M. and Mpodozis, C., 2014. Early Permian to Late Triassic batholiths of the Chilean Frontal Cordillera (28°–31°S): SHRIMP U–Pb zircon ages and Lu–Hf and O isotope systematic. *Lithos*, 184, 436–446.
- Holz, M., França, A.B., Souza, P.A., Iannuzzi, R. and Rohn, R., 2010. A stratigraphic chart of the Late Carboniferous/Permian succession of the eastern border of the Paraná Basin, Brazil, South America. *Journal of South American Earth Sciences*, 29, 381–399.
- Hunter, R.E., 1977. Basic types of stratification in small eolian dunes. *Sedimentology*, 24, 361–387.
- Kleiman, L.E. and Japas, M.S., 2009. The Choiyoi volcanic province at 34°S–36°S (San Rafael, Mendoza, Argentina): implications for the Late Palaeozoic evolution of the southwestern margin of Gondwana. *Tectonophysics* 473, 283–299.
- Krogh, T.E., 1973. A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. *Geochimica et Cosmochimica Acta*, 37, 485–494.
- Langford, R.P., 1989. Fluvial-aeolian interactions: Part I, modern systems. *Sedimentology*, 36, 1023–1035.
- Lavina, E.L.C., Faccini, U.F., Ribeiro, H.J.S., 1993. A Formacao Pirambóia (Permo-Triássico) no estado do Rio Grande do Sul. *Acta Geológica Leopoldensia* 38, 179–197.
- Limarino, C.O. and Césari, S.N., 1987. Consideraciones sobre la edad de la sección

- superior del Grupo Paganzo (Paleozoico superior), República Argentina. 4th Congreso Latinoamericano de Paleontología, 1, pp. 315-30, Bolivia.
- Limarino, C., Tripaldi, A., Marensi, S., and Fauqué, L., 2006. Tectonic, sea-level, and climatic controls on Late Paleozoic sedimentation in the western basins of Argentina. *Journal of South American Earth Sciences*, 22, 205-226.
- Limarino, C.O., Césari, S.N., Spalletti, L.A.; Taboada, A.C., Isbell, J.L., Geuna, S., Gulbranson, E.L., 2014. A paleoclimatic review of southern South America during the late Paleozoic: A record from icehouse to extreme greenhouse conditions. *Gondwana Research*, 25, 1396–1421.
- Llambías, E., Quenardelle S. and Montenegro, T., 2003. The Choiyoi Group from Central Argentina: a subalkaline transitional to alkaline association in the carton adjacent to the active margin of the Gondwana continent. *Journal of South American Earth Sciences*, 16, 243-267.
- Mattinson, J.M., 2005. Zircon U-Pb chemical abrasion (CA-TIMS) method: combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. *Chemical Geology* 220, 47-66.
- Metcalf, I. and Isozaki, Y., 2009. Current perspectives on the Permian–Triassic boundary and end-Permian mass extinction: Preface *Journal of Asian Earth Sciences* 36, 407–412.
- Miall, A. D., 1985. Architectural-element analysis: A new method of facies analysis applied to fluvial deposits. *Earth-Science Reviews*, 22, 261- 308.
- Miall, A.D., 1996. *The geology of fluvial deposits*. Springer.
- Miall, A.D., 2014. *Fluvial Depositional Systems*. Springer International Publishing Switzerland.

- Milana, J.P. and Alcober, O., 1994. Modelo tectosedimentario de la cuenca triásica de Ischigualasto (San Juan, Argentina). *Revista de la Asociación Geológica Argentina*, 49(3-4), 217-235.
- Miller, J.S., Matzel, J.E.P., Miller, C.F., Burgess, S.D., and Miller, R.B., 2007, Zircon growth and recycling during the assembly of large, composite arc plutons. *Journal of Volcanology and Geothermal Research*, 167, 282–299.
- Mountney, N.P. and Jagger, A., 2004. Stratigraphic evolution of an aeolian erg margin system: the Permian Cedar Mesa Sandstone, SE Utah, USA. *Sedimentology*, 51, 713-743.
- Nemec, W. and Postma, G. 1993. Quaternary alluvial fans in southwestern Crete: sedimentation processes and geomorphic evolution. In: Marzo M. and Puigdefábregas C. (Eds.), *Alluvial sedimentation*, International Association of Sedimentologists, Special Publication 17, 235-276.
- North, C.P. and Davidson, S.K., 2012. Unconfined alluvial flow processes: Recognition and interpretation of their deposits, and the significance for palaeogeographic reconstruction. *Earth-Science Reviews*, 111, 199–223.
- Parrish, R.R., Bowring, S.A., Condon, D.J., Schoene, B., Crowley, J.L., and Ramezani, J., 2006, EARTHTIME U-Pb tracer for community use: Goldschmidt Conference Abstracts, v. 76, p. A473, doi: 10.1016/j.gca.2006.06.1409.
- Reid, M.R., and Coath, C.D., 2000. In situ U-Pb ages of zircons from the Bishop Tuff: No evidence for long crystal residence times: *Geology*, v. 28, p. 443–446.
- Rocha-Campos, A.C., Basei, M.A., Nutman, A.P., Kleiman, L.E., Varela, R., Llambías, E., Canile, F.M., da Rosa, O. de C.R., 2011. 30 million years of Permian volcanism recorded in the Choiyoi igneous province (W Argentina) and their source for

- younger ash fall deposits in the Paraná Basin: SHRIMP U-Pb zircon geochronology evidence. *Gondwana Research*, 19, 509-523.
- Rohn, R., Assine, M.L., Meghioratti, T., 2005. A New Insight on the Late Permian Environmental Changes in the Paraná Basin, South Brazil. *Gondwana 12 Conference, Abstracts*. Academia Nacional de Ciencias, Córdoba, p. 316.
- Romer, A.S. and Jensen, J.A., 1966. The Chañares (Argentina). Triassic reptiles fauna II. Sketch of the geology of the Río Chañares-Río Gualo región. *Breviora*, 252. Cambridge.
- Schmitz, M.D. and Schoene, B., 2007. Derivation of isotope ratios, errors, and error correlations for U-Pb geochronology using ^{205}Pb - ^{235}U -(^{233}U)-spiked isotope dilution thermal ionization mass spectrometric data. *Geochemistry, Geophysics, Geosystems*, 8 (8), doi: 10.1029/2006GC001492.
- Shen, S., Schneider, J.W., Angiolini, L. and Henderson, C.M., 2013. The international Permian timescale: march 2013 update. In: Lucas, S.G., et al. (Eds.), *The Carboniferous-Permian Transition*. New Mexico Museum of Natural History and Science, Bulletin 60, 411-416.
- Spalletti, L.A., 1999. Cuencas triásicas del Oeste argentino: origen y evolución. *Acta Geológica Hispánica*, 32 (1997), 1-2, 29-50.
- Stipanovic, P.N. and Bonaparte, J.F., 1979. Cuenca triásica de Ischigualasto-Villa Unión (Provincias de San Juan y La Rioja). In “*Geología Regional Argentina*”, Academia Nacional Ciencias Córdoba, pp. 523-575.
- Sun, Y.D., Lai, X.L., Wignall, P.B., Widdowson, M., Ali, J.R., Jiang, H.S., Wang, W., Yan, C., Bond, D.P.G. and Védérine, S., 2010. Dating the onset and nature of the Middle Permian Emeishan large igneous province eruptions in SW China using conodont

- biostratigraphy and its bearing on mantle plume uplift models. *Lithos* 119, 20–33.
- Sweet, M.L., 1999. Interaction between aeolian, fluvial and playa environments in the Permian Upper Rotliegend Group, UK southern North Sea. *Sedimentology*, 46, 171–187.
- Tripaldi, A. and Limarino, C.O., 2008. Ambientes de interacción eólica-fluvial en vales intermontanos: ejemplos actuales y antiguos. *Latin American Journal of Sedimentology and Basin Analysis*, 15(1), 43–66.
- Turner, J.C.M., 1960. Estratigrafía del tramo medio de la sierra del Famatina y adyacencias (La Rioja). *Boletín de la Academia Nacional de Ciencias* 42, pp. 109–112.
- Turner, J.C.M., 1962. Las Sierras Pampeanas como unidad estructural. *Anales de las Primeras Jornadas Geológicas Argentinas*, Tomo 2, 387–402.
- Veiga, G.D. and Spalletti, L.A., 2007. The Upper Jurassic (Kimmeridgian) fluvial/aeolian systems of southern Neuquén Basin, Argentina. *Gondwana Research*, 11, 286–302.
- Wendt, I., and Carl, C., 1991. The statistical distribution of the mean squared weighted deviation: *Chemical Geology*, 86, 275–285.
- York, D., 1967. The best isochron. *Earth and Planetary Science Letters*, 2, 479–482.
- York, D., 1969. Least squares fitting of a straight line with correlated errors. *Earth and Planetary Science Letters*, 5, 320–324.
- Zerfass, H., Chemale, Jr.F., Schultz, C.L. and Lavina, E., 2004. Tectonics and sedimentation in Southern South America during Triassic. *Sedimentary Geology*, 166(3–4), 265–292.
- Zhang, G., Buatois, L.A., Mángano, M. G. and Aceñolaza, F.G., 1998. Sedimentary facies and environmental ichnology of a Permian playa-lake complex in western

FIGURE CAPTIONS

Figure 1: Geological map of Cuesta de Miranda area showing the location of the studied section at Bordo Atravesado.

Figure 2: Schematic stratigraphic section of the Talampaya Formation at the Bordo Atravesado area showing the seven facies associations and the location of the dated sample.

Figure 3: a. Aspect of the agglomerates, boulder and pebble conglomerates of the Facies association 1; b. Clasts up to 6 m in diameter of this unit; c. volcanic and granite clasts very common in the FA1; d. Amalgamated beds of coarse- to fine-grained conglomerates and coarse to fine-grained sandstones of the Facies association 2; e. Detail of erosive base of the channel beds of FA2; f. Typical purple color of the facies association 3.

Figure 4: a. Aspect of the basaltic breccias of facies association 3; b. detail of the angular and subangular afanitic basalt fragments of FA 3; c. cycles up to 6 m thick of the FA 4; d. Lobate to tabular beds of fine to medium grained sandstones of the FA 5 (sandflat); e. Horizontal lamination of fine- to medium-grained sandstone of FA 6 showing desiccation cracks and f. Laminated mudstones with several intercalations of tuffs of the FA 7. Detail of one of the tuff.

Figure 5: A. U-Pb ages of zircons for the sample of the Talampaya Formation collected at the Bordo Atravesado locality. Black boxes were used in determination age. B. Concordia diagram. Zircons are represented as error ellipses; shaded ellipses were used in the age calculation; and dashed and unfilled ellipses were excluded from age calculation (see

text).

Figure 6: Schematic diagram of the three stages recognized in the evolution of the Talampaya Formation in the Cuesta de Miranda area.

Figure 7: Schematic paleogeographic map during the Permian-Triassic boundary.

Figure 1 revised

Figure 2 revised

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7 revised

Table 1

Table 1: U-Th-Pb isotopic data

Compositional parameters										Radiogenic Isotope Ratios										Isotopic Ages			
Wt.	Th	Pb	²⁰⁶ Pb* x10 ⁻¹³ ·mol	mol %	Pb _c *	Pb _c	²⁰⁶ Pb/ Pb _c	²⁰⁸ Pb/ ²⁰⁶ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb	% err	²⁰⁷ Pb/ ²³⁵ U	²⁰⁶ Pb/ ²³⁸ U	% err	corr.	²⁰⁷ Pb/ ²⁰⁶ Pb	% err	coef.	²⁰⁶ Pb/ ²³⁸ U	²³⁵ U	±	²⁰⁶ Pb/ ²³⁸ U	±	
Sample	mg	ppm	U	(c)	(d)	(e)	(e)	(f)	(g)	(h)	(g)	(h)	(g)	(h)		(i)	(h)		(h)	(i)	(h)	(i)	(h)
z1	0.010	190	0.925	8.9	3.1722	99.80%	171	0.51	9449	0.293	0.051265	0.069	0.282326	0.104	0.039942	0.047	0.851	252.77	1.59	252.50	0.23	252.47	0.12
z2	0.010	134	0.708	6.0	2.2376	99.61%	82	0.72	4796	0.225	0.051325	0.121	0.282625	0.150	0.039937	0.049	0.709	255.47	2.77	252.74	0.34	252.44	0.12
z3	0.010	201	1.191	10.0	3.3585	99.58%	86	1.16	4451	0.378	0.051281	0.121	0.282699	0.150	0.039982	0.050	0.697	253.49	2.78	252.80	0.34	252.72	0.12
z4	0.010	95	0.976	4.5	1.5792	99.44%	61	0.72	3351	0.309	0.051200	0.260	0.281827	0.276	0.039922	0.073	0.345	249.83	5.99	252.11	0.62	252.35	0.18
z5	0.010	47	0.960	2.2	0.7794	99.23%	44	0.50	2421	0.305	0.051332	0.297	0.282587	0.317	0.039927	0.076	0.374	255.77	6.83	252.71	0.71	252.38	0.19
z6	0.010	48	1.058	2.4	0.8057	99.10%	38	0.60	2057	0.336	0.051330	0.241	0.282323	0.283	0.039891	0.073	0.655	255.68	5.55	252.50	0.63	252.16	0.18

Bold text indicates zircons used for radiometric age determination of the sample.

(a) z1, z2 etc. are labels for fractions composed of single zircon grains or fragments, all fractions chemically abraded after Mattinson (2005).

(b) Nominal fraction weights estimated from photomicrographic grain dimensions, adjusted for partial dissolution during chemical abrasion.

(c) Nominal U and total Pb concentrations subject to uncertainty in photomicrographic estimation of weight and partial dissolution during chemical abrasion.

(d) Model Th/U ratio calculated from radiogenic 208Pb/206Pb ratio and 207Pb/235U age.

(e) Pb* and Pb_c represent radiogenic and common Pb, respectively; mol% ²⁰⁶Pb* with respect to radiogenic, blank, and initial common Pb.

(f) Measured ratio corrected for spike and fractionation only. Mass fractionation correction of 0.22 ± 0.02 (1-sigma) %/amu (atomic mass unit) was applied to all single-collector Daly analyses, based on analysis of NBS-981 and NBS-982

(g) Corrected for fractionation, spike, and common Pb; all common Pb was assumed to be procedural blank: 206Pb/204Pb=18.60±0.80‰; 207Pb/204Pb=15.69 ±0.32‰; 208Pb/204Pb=38.51±0.74‰ (all uncertainties 1-sigma).

(h) Errors are 2-sigma, propagated using algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).

(i) Calculations are based on the decay constants of Jaffey et al. (1971). 206Pb/238U and 207Pb/206Pb ages corrected for initial disequilibrium in ²³⁰Th/²³⁸U using Th/U (magma) = 4.