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Title: A PROVENANCE STUDY OF THE PALEOZOIC VENTANIA SYSTEM (ARGENTINA): TRANSIENT COMPLEX SOURCES FROM WESTERN AND EASTERN GONDWANA

Article Type: Research Paper

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Abstract: The U-Pb and Lu-Hf isotopic analyses of the different sedimentary sequences of the Ventania System, an old Paleozoic orogenic belt exposed in the southern region of the Río de la Plata Craton in the province of Buenos Aires, Argentina, provide new evidence for the understanding of the tectonic evolution of the western sector of the Gondwanides mountain belt. These ranges formed as result of the late Paleozoic collision of the Patagonia terrane against the continental margin of Gondwana. The provenance analysis together with the sedimentary paleocurrents confirm a dominant source from the Tandilia System, a Paleoproterozoic mountain belt formed during the amalgamation of the Río de la Plata Craton at about 1,800-2,200 Ma, and incorporated to Western Gondwana during the Brasiliano Orogeny at 550-530 Ma. The local dominant source at the base of the early Paleozoic changed to more distant supplies toward the top of the sequences, when is recorded an increasing participation of detritus from first, Cambrian (560-520 Ma) zircons from the Pampean Orogen, and later on Ordovician (480-460 Ma) zircons from the Famatinian Orogen. The detrital zircon patterns and the maximum age of the units shed light on some previous discrepancies in the early Paleozoic stratigraphy. The Balcarce Formation, an early Paleozoic sedimentary cover of the Tandilia metamorphic and igneous basement, shows striking differences when compared with the new data from the Ventania System. The two data-sets reveal different sources for the two regions. The late Paleozoic foreland basin deposits mark an abrupt change of 180º in the paleocurrent directions, in the petrographic composition of the sediments, and in the provenance of detrital zircons. These data indicate a southern provenance with the first evidence of Carboniferous and Permian magmatic zircons. The oldest Archean zircons together with the finding of clasts with archeocyathids support the provenance from Patagonia, which was derived from Eastern Gondwana. The U-Pb ages of the ash-fall tuffs in the Tunas Formation confirm the Early Permian age of the Eurydesma Fauna in the Ventania System. The U-Pb data together with the Lu-Hf isotopic data enhance the comprehension of the tectonic evolution of the Ventania System as part of the larger Gondwanides Belt that amalgamated to Western Gondwana during Late Permian times with some independent pieces derived from Eastern Gondwana.

Response to Reviewers: In the attach "answer to the reviewers" we give a detail report of the changes made. We have no major differences with the recommended corrections.

July 6th, 2013.-

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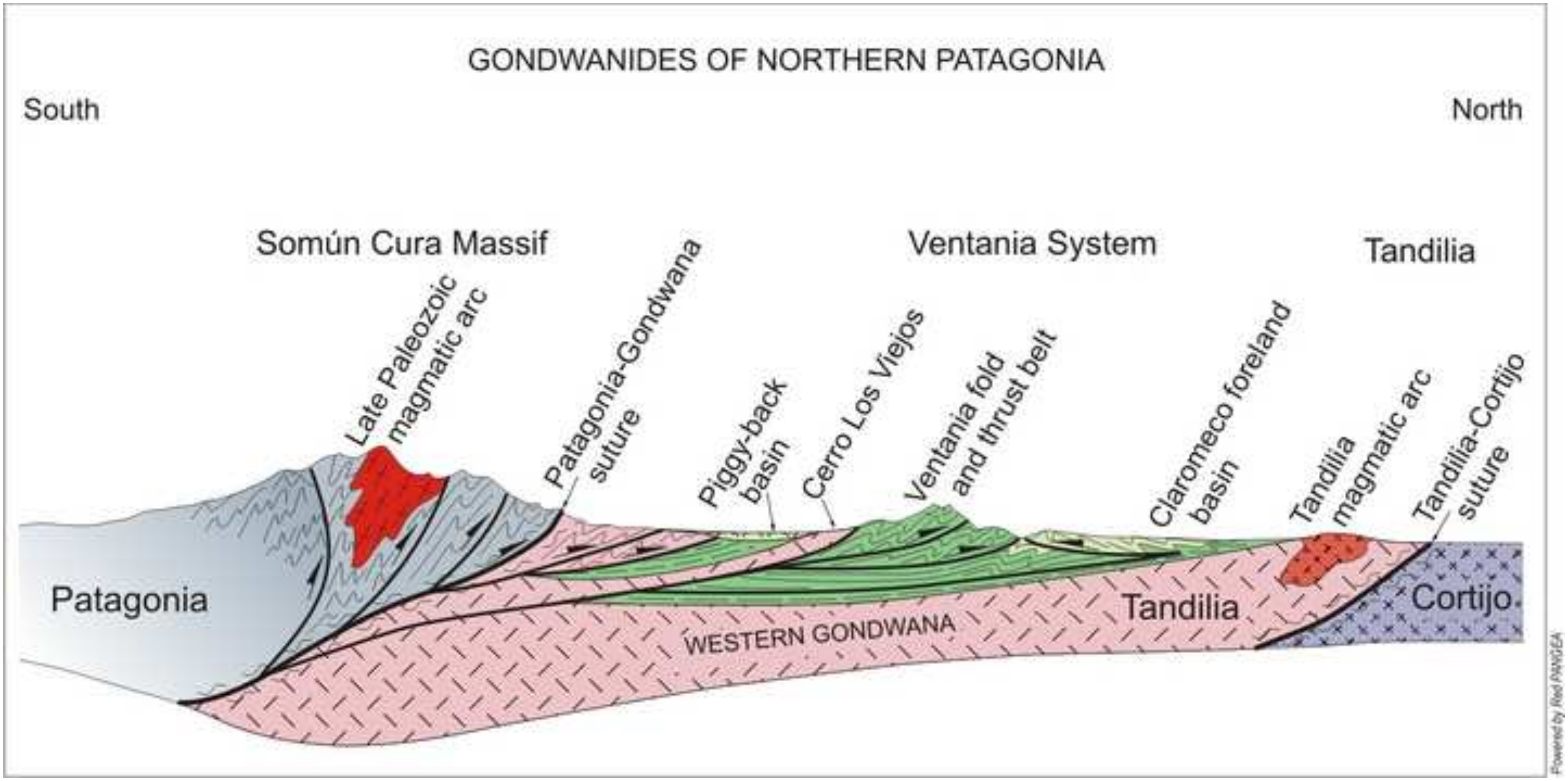
Dear Dr Collins,

We are submitting the comments to the reviewers, new figures and the revised version of the manuscript. We have had very constructive and positive reviews and we acknowledge the reviewers for their excellent reviews. It is a pity that one of the reviewers is anonymous, because he has done positive comments that improved the manuscript.

Best regards,

Victor A. Ramos

*Graphical Abstract (for review)



HIGHLIGHTS

• Comprehensive detrital zircon U-Pb age database of the Paleozoic Ventania Fold Belt.

• Changing sources through time shed light in the paleogeography of this sector of Gondwana.

• An abrupt change in provenance associated with the collision of Patagonia.

• Different Precambrian sources and Paleozoic similarities when compared with the Cape Fold Belt.

***Detailed Response to Reviewers**

Ms. Ref. No.: GR-D-13-00117
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Answers to the reviewers' comments

Reviewer #1:

The article in question presents a complete set of U-Pb detrital zircon ages from rocks of the Ventania System located at the southern portion of the Buenos Aires Province. At the same time makes comparisons with Table Mountain Belt of South Africa. This is an article where the data, predominantly LAICPMS zircon ages, are interpreted based on local and regional geological contexts, providing robustness to the paleogeographic reconstructions presented.
1) The cited articles are relevant and updated with minor problems reported in the text. Most of these problems concerns articles of the U-Pb and Lu-Hf methodologies not mentioned in the text but presented in the list of references.

The following cites that were missing are now included:

Deleted cites:

Blichert-Toft and Albarede, 1997.

Bodet and Scharer, 2000

Eggins et al., 1998

Patchett and Ruiz, 1987

Scherer et al., 2001

Woodhead et al., 2004

Woodhead and Hergt, 2005

Add cites:

Goodge, J.W., Vervoort, J.D., 2006. Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence. Earth and Planetary Science Letters 243, 711–731.

Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters 26, 207–221.

Harrington, H.J., 1955. The Permian Eurydesma fauna of Eastern Argentina. Journal of Paleontology 29, 112-128.

Ramos, V. A., 1988. Tectonic of the Late Proterozoic-Early Paleozoic: a collisional history of the southern South American. Episodes, 12: 168-174.

2) Comments and discussions of the internal structures of the zircon crystals that can help to interpret the ages obtained are missing. Ideally the tables showing the analytical data have an additional column next to the spot number with the indications concerning the place of the grain effectively analyzed. For example, a detailed examination of the images of back-scatter, could clarify some of the authors doubts concerning the Pan de Azucar sample. If the analyzed domains correspond to igneous portions (oscillatory zoning) would most likely consider this rock a quartzite belonging to low-grade metamorphic units of La Lola Fm, and probably derived from a source other than the underlying metamorphic basement. On the other hand if the analyzed portion corresponds to metamorphic rims (overgrowths), the age of 545Ma likely indicate the time of the main metamorphic event of the underlying paragneiss basement.

The suggestion of the reviewer was correct. We are showing the BSE images of zircon crystals from sample VE-02 (Pan de Azúcar sample) to support interpretation. The internal textures and Th/U ratio in each dated zircon indicate an igneous origin; apparently deformational and metamorphic process has not reached the detrital zircons. The images have been incorporated in the new Figure 6, where is indicated the spot places in each grain.

3) The plots presented in Figures 6b, 8, 9, 10, 11, 13, 14, 15, and 18 represent the frequency diagrams constructed with U-Pb detrital zircon ages for the different samples. This manner of representation is interesting but, the absence of the histograms in the same figure, prevents the reader easily see how many points were used in each sample.

The recommendation was followed and now we have drawn all the histograms in the frequency diagrams in all these figures.

4) Furthermore, it is important to inform which age (206Pb/238U or 207Pb/206Pb) was used in the preparation of the diagram. A question arises - to build the plot was used only the value presented in the column "best age" of Table 2?

For zircons older than Early Paleozoic we use $^{207}Pb/^{206}Pb$ *ages and for Late Paleozoic zircons we use* $^{206}Pb/^{238}U$ *ages. We build the plot diagrams with the value presented in the column "best age" of Table 2.*

5) As consequences of this, two cases stand out: 1) the sample SLV VE 07 has only 4 points and the curve corresponding to this sample in Figure 12 does not allow the reader to recognize the discrepancy in data quality of this sample compared with the other samples presented in this figure, 2) the plot of Piedra Azul Formation (sample VE 17) in Figure 13 was also made with only 3 points. We suggest suppressing the curve of sample VE 07 of Figure 12 and the plot of the sample VE-17 of Figure 13.

The plot of the sample SLV-VE-07 was deleted of Figure 12 as the reviewer recommended but we did not suppress the plot of the sample SLV-17 of Figure 13 *because is the only sample of this formation. We put the number of dated grained into the plot diagram and preserve the sample.*

6) The reviewer was unable to locate the plot of the sandstone of Tunas Fm. (sample SLV-VE-24) whose data are in Table 2 (guess it is the Gonzalez Chaves sample). If I´m right, please write SLV-VE-24 in the figure 15.

The reviewer is right. We wrote SLV-VE 24 in the legend of figure 15 to indicate that it is the González Chaves sandstone as indicated in the Figure 2.

7) On the other hand the data of the formations Sierra Grande and El Jaguelito (Figure 14) are not listed in table 2. Also absent from table 2 are the data of Punta Mogotes Fm. If these data have been presented in other articles, make that very clear in the text and in the figure. If they are new results, the analytical data need to be included in Table 2 otherwise the plots must be deleted.

These data are from previous works such as Pankhurst et al., 2006; Uriz et al., 2011; Rapela et al., 2007, 2011; Naipauer et al., 2010, 2011. Therefore we indicated the source not only in the text, but into the plot diagrams to facilitate the comprehension (see Figures 11, 14, and 18).

7) In the comparison of Curamalal and Ventana groups performed in section 5.4 the authors indicate the large difference observed in the detrital zircon pattern of these units. However, when compared in detail, the Mascota and Bravard Fms. are quite similar, with both showing the same peaks of Cambrian age (predominant), and Paleoproterozoic-Grenviliano.

We do not entirely agree with the reviewer. Although Bravard Formation has a frequency that is transitional to the top of the Curamalal Group, the detail examination indicates conspicuous differences. Those differences are even higher when the top of both groups are compared.

8) In Chapter 5.6 the authors consider the rhyolites of the Somún Cura Massif as the only source area for the volcanic ash levels interlayered in the Tunas Fm. It is plausible to consider that Massif has been important source area of these rocks, but another possible source is the Choiyoi Group (NW Argentina) since it represents a Permian explosive volcanism with large volume of pyroclastic rocks, which was responsible for numerous ash-falls levels intercalated in the Upper Paleozoic units of Paraná Basin.

This is the classic interpretation to explain the pyroclastic levels in the Paraná Basin in southern Brazil. Based on the U-Pb dates of Rocha Campos et al. (2011) with ages around 281.4±2.5 Ma Los Reyunos Fm, and the northeast paleocurrent directions measured in the aeolian sandstones of the Reyunos Fm by Pazos (2011), it looks quite probable that Choiyoi is the source of the tuffs in the Paraná Basin. However, if we want to use the same Choiyoi source to the pyroclstic deposits of Las Tunas the dominant winds should be southeast (different from what it was measured in the Choiyoi intercalated aeolian sandstones). The distance is much shorter from Somún

Cura, ages are similar to the one measured, and the required paleowind direction is also northeast). Therefore we prefer as a potential source the Early Permian calderas and volcanic rocks of the same age found in the Somún Cura Massif. This interpretation also explains the source of the igneous Carboniferous detrital zircons found in Las Tunas Formation.

Nevertheless, we modified the text to briefly explain the potential source for the Permian zircons.

Added:
Rocha Campos, A.C., Basei, M.A., Nutman, A.P., Kleiman, L.E., Varela, R., Llambias, 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.
Pazos, P.J., Rey, F., Marsicano C., Ottone G., de la Fuente M. 2011. Permian unroofing, palaeoenvironmental and palaoeclimate evolution in the San Rafael foreland basin, Mendoza, Argentina. In: da Silva, R., Schmitt, R.Trow, R.A, de Souza Carvalho I., and Collins A.,(eds.), Gonwana 14, Reuniting Gondwana: East meets West, Abstracts , p. 149. Buzios.

9) The Chapter 7 is very well grounded in the data available, having been built in order to lead the reader, even those unfamiliar with the local geology, follow the paleogeographic evolution proposed by the authors. In this context, in the opinion of the reviewer, the interpretation of the meaning of the angular unconformity between the Balcarce Fm. and lower units as a result of the Pampia Block collision against the Rio de la Plata Craton deserves a more detailed explanation. What is the regional expression of this unconformity? Is there other evidence to support this interpretation?

The reviewer is right. The unconformity could be either Pampean (early Cambrian) or Famatinian (middle Ordovician). The sedimentary record of Balcarce Fm indicate a post Hirnantian glaciation age. The Pampean unconformity is seen in different places and dated in 530 Ma by Escayola et al. (2007) and Ianizzotto et al. (2013), but as the main source is coming from eastern Sierras Pampeanas which is closer to Tandilia is more probable that deformation is related to the Pampean orogen (see for further details Pazos and Rapalini,2011).

10) In Figure 20, the orogenic front of the Permian belt truncates the Pampian belt but appears to be truncated by Pampia Block. This termination deserves a refinement in the design presented.

The reviewer is absolutely right! With Dr Pangaro (coauthor of that figure) we have discussed the western extreme of this orogenic front, and we learnt that we may have another syntaxis. But unfortunately the excellent geophysical data base we have used to build the map ends at this boundary and we do not have enough information to define the trace of the syntaxis.

11) The structural profile that summarizes the Gondwanides northern portion of Patagonia (Figure 5) is very interesting and is based on a large number of information obtained by several previous works. However, the discussion of this figure is contained in a few lines discussing the relationship between Patagonia and Gondwana tectonics. This discussion is far from the importance of this figure. In addition, to facilitate the reader, it is necessary to clarify some of the details contained in it, such as:

The reviewer is right and the following paragraph has been added to the text:

Based on the new offshore seismic data presented by Pángaro and Ramos (2012) a series of interesting observations can be summarized (Fig. 5). One of the main objections that have been put forwards to interpret the Ventania System as a collisional orogen was the lack of some lower to middle crustal metamorphic rocks related to the main Permian deformation (Trow and De Witt, 2008). However, the seismic line shows the inner part of the orogen where lower to middle crust is overriding the Paleozoic sedimentary sequences. The correlation with Cerro Los Viejos exposures supports the age of these units, as well as the magmatic arc developed in the Somún Cura Massif as result of the closure of the Colorado Ocean (Ramos, 2008, Rapalini, 2005). The low-grade dynamic metamorphism exposed in the southern part of Sierra de la Ventana is just a second order upper crust middle-to-high pressure deformation, which is related to the intense folding of the Paleozoic quartzites (Von Gosen et al., 1991; Ramos, 2008). The structural triangle zone with opposite vergence is known since the early work of Keidel (1916), and is supported by the detail structural study of Tomezzoli and Cristallini (2004). The seismic lines through the Claromecó foreland basin depict and confirm these structures (Ramos and Kostadinoff, 2005). Regarding the Tandilia System, the pioneer work of Teruggi et al. (1988) interpreted the granitoids of Tandilia as a Paleoproterozoic magmatic arc, which collided with the island arc terrane of Cortijo (Cingolani, 2011). Recently, the geophysical work of Chernicoff (2012b) has identified the precise location of the suture between the Tandilia and Cortijo blocks, as well as other complexities in the basement. The structural cross-section depicts the deformation at the end of the Late Paleozoic. The opening of the South Atlantic Ocean during Late Jurassic – Early Cretaceous had an aborted branch that developed an aulacogenic basin between the Somún Cura Massif and the Ventania System, which is the present Colorado Basin (Ramos, 1996).

11.1) The expression in the area of Somún Cura Massif is compatible with a magmatic arc resulting from the closure of Ocean Colorado?

The reviewer is right. The Somún Cura is the magmatic arc developed by subduction of the Colorado Ocean and the following phrase and the corresponding cites were added to the revised text:

The correlation with Cerro Los Viejos exposures supports the age of these units, as well as the magmatic arc developed in the Somún Cura Massif as result of the closure of the Colorado Ocean (Rapalini, 2005, Ramos, 2008).

11.2) The reason as the Claromeco foreland basin is represented as an allochthonous fragment with transport contrary to the thrusts of Ventania System?

The sedimentary rocks of the Claromecó Basin developed a structural triangle zone. The following text was added:

The structural triangle zone with opposite vergence is known since the early work of Keidel (1916), and is supported by the detail structural study of Tomezzoli and Cristallini (2004). The seismic lines through the Claromecó foreland basin depict and confirm these structures (Ramos and Kostadinoff, 2005).

11.3) What is the difference between the basements of Tandilla and Cortijo? 4) The Suture between Tandilla and Cortijo is Paleoproterozoic?

The Tandilia is a continental block that collided with the Cortijo Island arc in the Paleoproterozoic. The following text and the corresponding new cite was added:

Regarding the Tandilia System, the pioneer work of Teruggi et al. (1988) interpreted the granitoids of Tandilia as a Paleoproterozoic magmatic arc, which collided with the island arc terrane of Cortijo (Cingolani, 2011). Recently, the geophysical work of Chernicoff (2012b) has identified the precise location of the suture between the Tandilia and Cortijo blocks, as well as other complexities in the basement.

12) In summary, it is an article with a large number of new data and presenting a tectonic interpretation quite suitable for most of the available information. The specific comments are indicated in the revised text, the figures and tables attached.

We have modified the tables following the comments of the reviewer and the specific comments in the text. We are sorry that we cannot acknowledge the excellent review of this anonymous reviewer.

Reviewer #2:
Eric Tohver
University of Western Australia

I have completed my review of the manuscript "A provenance study of the Paleozoic Ventania system (Argentina): transient complex sources from western and eastern Gondwana" by V. Ramos et al., submitted for publication in Gondwana Research. The manuscript is well-written, and reports a large body of data that will prove of great interest to the GR reader. Most of the assertions made by the authors are borne out by data, and I will concentrate the majority of my more critical comments to those more tangential conclusions of the authors. These comments can be accommodated by minor revisions.

1) There are two major issues that the authors are trying to address; first, the provenance of the different Paleozoic supergroups of the Ventania region, and second, less credibly, the East Antarctica origin of the Patagonian massif.

We agree with this statement. The second, less credibly East Antarctica origin of Patagonia is developed in a parallel paper specifically devoted to this subject that is in press. Therefore we added this text and cited that paper for those seeking more data in the origin of Patagonia.

This match indicates that Patagonia should have originated in Eastern Gondwana, and that it was transferred to Western Gondwana during the Gondwanan orogeny (for further details see Ramos and Naipauer, 2013).

Ramos, V.A. and Naipauer, M. 2013. Patagonia: Where does it come from? Iberian Geology (in press).

2) A third theme pertains to the non-rotation of the Falklands/Malvinas block. The first issue, the detrital provenance of the Ventania stratigraphy, is expertly treated. There are some minor questions about some awkwardly inconsistent ages for the tuffs in the Tunas Formation between the LA-ICP-MS ages and the previously determined SHRIMP ages.

See answers to previous reviewer.

3) The second issue regarding the putative allochthonous origin of Patagonia is really immaterial to the article (especially lines 684-690). None of the data presented, with the exception of the occurrence of Archeocyathids in clasts of the Sauce Grande Fm., really say much about the original whereabouts of Patagonia in Paleozoic times. I confess to some self-aggrandizing interest here in drawing Dr. Ramos' attention to a recent paper by Augusto Rapalini in press at Terra Nova that suggests Patagonia was always part of South America (Augusto Rapalini, Monica Lopez de Luchi, Eric Tohver, Peter Cawood, 2013. The South American ancestry of the North Patagonian Massif: geochronological evidence for an autochthonous origin? Terra Nova, Feb. 8, 2013. doi: 10.1111/ter.12043).

This paragraph was added:

Although some recent paper proposed a continuation of the magmatic activity for the early Paleozoic from the Sierras Pampeanas to the Somún Cura area (Rapalini et al., 2013), classic proposal advanced by Bracaccini (1960), is not able to elucidate the presence of archeocyathids (see discussion in Ramos and Naipauer, 2013). Rapalini et al. (2013) follows the arguments of Dalziel et al. (2013) who propose a continuous archeocyathid reef along the margin of Antarctica. However, this argument needs a magmatic arc located in the Somún Cura arc more than thousand kilometers away from the Pacific margin (see discussion in Ramos, 2008).

4) With regards to the position of the Falklands/Malvinas block (Lines 428-434 and elsewhere), I think that this issue is so far removed from the subject matter of the text that it does not bear mention. I regard this is as an important, highly interesting subject matter, but it distracts the reader from the topic at hand, that is, the data from stratigraphic units in the Ventania region. This should be removed entirely.

All the statement of Lines 428-434 has been modified and the mention to the rotation of the Malvinas Island has been deleted.

5) Line 13 - replace "show" with "provide"
Done.

6) Lines 14-16 - See 2nd point from above discussion.
The two alternatives have been discussed in the text.

7) Lines 18-23 - The record of reversals in paleocurrent should be mentioned more prominently here.
Done.

8) Line 27 - The two datasets reveal different sources for the two regions.
Done.

9) Line 31 - Replace "confirm" with "support"
Done.

10) Lines 35-37 - Again, see 2nd point from above.
The two alternatives have been discussed in the text.

11) Line 60 - Replace "has consensus" with "agree"
Done.

12) Line 114 - "4500 m thick, with the two lowermost sequence measuring 2400 m thick"
Done.

13) Line 126 - "monomict" and "situated at"
Done.

14) Line 131 - "crossbeds up to 4 m in amplitude are common…"
Done.

15) Line 137 - Replace "bipolar crossbedding" with "herringbone crossbeds"
Done.

16) Line 138 - Remove "which", insert "and" after "Ventana Group"
Done.

17) Line 149 - Replace "irregularly" with "unconformably"
Done.

18) Lines 161 - Paleomagnetism, not paleomag. The explanation of the 180 degree rotation misleads the reader into supposing that there is some mismatch between the SE

position of the Falklands and the paleomagnetic data. A clearer explanation would be helpful.

The paragraph has been simplified.

19) Line 166 and elsewhere - Replace "overlaid" with "overlain"
Done.

19') Materials and Methods section and throughout text - Isotope masses are in superscript.
Done.

20) Line 312 - 317 - The precision of the LA-ICP-MS data does not really preclude the intrusive relation for the Cerro Colorado Granite reported by Tohver et al. (2012). As written, there is no mention given of this interpretation (One that I am not particularly confident about, I must say, not having seen the contact myself) and its implications for a possible pre-Mascota Fm. Quartzite unit.

Text has been modified.

21) Lines 430-434 - Remove, separate subject.
Paragraph has been modified and rotation eliminated.

22) Line 453-454 - Awkward phrasing.
Done.

23) Line 464 - Awkward phrasing. What are "lepidofites"
Done.

24) Line 472 - There is some controversy over the APWP for South America, so some of R. Tomezzoli's age assignments could be incorrect. See M. Domeier, R. Van der Voo, E. Tohver, R.N. Tomezzoli, H. Vizan, T.H. Torsvik, Jordan Kirshner,, 2011, New Late Permian Constraints on the Apparent Polar Wander Path and Paleo-Marginal Deformation of Gondwana, Geochem. Geophys. Geosyst., 12, Q07002.
Done and new cite included.

25) Lines 485 - 492 - The imprecision of the LA-ICP-MS data is highlighted here, since the difference between 304 Ma (laser) and 282 Ma (SHRIMP) is outside of the probable analytical error. The "mixed" age explanation provided does not seem correct, since the laser analyses were probably individual grains. Since these are magmatic, the likelihood of metamorphic rims is low. Something is wrong with the explanation, the data, or both.

The reviewer is right, since only the juvenile Laser ablation ages are closed to the SHRIMP ages.

26) Line 508 - 510 - See recent papers by Rocha-Campos (Gondwana Research, 2011) and Domeier et al. 2011 (above) and M. Domeier, R. Van der Voo, R.N. Tomezzoli, E. Tohver, B.W.H. Hendriks, T. Torsvik, H. Vizan, A. Dominguez, 2011, Support for an "A-type" Pangea reconstruction from high-fidelity paleomagnetic records. Journal of Geophysical Research, 116, B12, art. no. B12114.
Paragraph has been modified as requested by reviewer 1 and the Rocha Campos et al 2011 paper cited.

27) Line 595 - Here, and elsewhere in the text, replace "inexistent" with "non-existent".
Done.

28) Line 629 - What is "immature" relief? High? "High relief of the Somún Cura Massif in Permian times…"
Juvenile poorly dissected relief in geomorphic grounds, which produce immature sandstones.

28) Lines 684-690 - Remove?

The text was modified and for further details the paper of Ramos and Naipauer (2013) was recommended. That paper analyzes and discusses the origin of Patagonia in the Transantarctic Mountains.

Both reviewers are strongly acknowledged, and we are sorry that first reviewer was anonymous because his excellent revision should be recognized.

A provenance study of the Paleozoic Ventania System (Argentina): transient complex sources from Western and Eastern Gondwana

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ABSTRACT

The U-Pb and Lu-Hf isotopic analyses of the different sedimentary sequences of the Ventania System, an old Paleozoic orogenic belt exposed in the southern region of the Río de la Plata Craton in the province of Buenos Aires, Argentina, provide new evidence for the understanding of the tectonic evolution of the western sector of the Gondwanides mountain belt. These ranges formed as result of the late Paleozoic collision of the Patagonia terrane against the continental margin of Gondwana. The provenance analysis together with the sedimentary paleocurrents confirm a dominant source from the Tandilia System, a Paleoproterozoic mountain belt formed during the amalgamation of the Río de la Plata Craton at about 1,800-2,200 Ma, and incorporated to Western Gondwana during the Brasiliano Orogeny at 550-530 Ma. The local dominant source at the base of the early Paleozoic changed to more distant supplies toward the top of the sequences, when is recorded an increasing participation of detritus from first, Cambrian (560-520 Ma) zircons from the Pampean Orogen, and later on Ordovician (480-460 Ma) zircons from the Famatinian Orogen. The detrital zircon patterns and the maximum age of the units shed light on some previous discrepancies in the early Paleozoic stratigraphy. The Balcarce Formation, an early Paleozoic sedimentary cover of the Tandilia metamorphic and igneous basement, shows striking differences when compared with the new data from the Ventania System. The two data-sets reveal different sources for the two regions. The late Paleozoic foreland basin deposits mark an abrupt change of 180º in the paleocurrent directions, in the petrographic composition of the sediments, and in the provenance of detrital zircons. These data indicate a southern provenance with the first evidence of Carboniferous and Permian magmatic zircons. The oldest Archean zircons together with the finding of clasts with archeocyathids support the provenance from Patagonia, which was derived from Eastern Gondwana. The U-Pb ages of the ash-fall tuffs in the Tunas Formation confirm the Early Permian age of the *Eurydesma*

Fauna in the Ventania System. The U-Pb data together with the Lu-Hf isotopic data enhance the comprehension of the tectonic evolution of the Ventania System as part of the larger Gondwanides Belt that amalgamated to Western Gondwana during Late Permian times with some independent pieces derived from Eastern Gondwana.

Keywords: Gondwanides, *Eurydesma* Fauna, Patagonia, collision, Famatinian and Pampean belts, zircon geochronology, tectonics.

1. Introduction

The Ventania System is a complex fold and thrust belt developed in the southwestern margin of Gondwana during late Paleozoic times (Keidel, 1916; Harrington, 1942,1947; Suero, 1972; Killmurray, 1975; Ramos 1986; Von Gosen et al., 1990). Since the early work of Du Toit (1927) it is assumed that Ventania was part of a larger system, which encompasses the Cape Fold Belt of South Africa. Du Toit (1937) named this orogen as the Gondwanides following pioneer work of Keidel (1921), and confirmed later by several works (see Veevers 2003, 2004; Milani and De Witt, 2008). In recent years many studies have analyzed the evolution of the Ventania System (Fig. 1) and the adjacent Claromecó foreland basin (Varela et al., 1987; Tomezzoli and Vilas, 1999; Tomezzoli and Cristallini, 1998; Dimieri et al., 2005; Cingolani 2005; Ramos and Kostadinoff, 2005). Current studies were able to track the extent of the Ventania Fold Belt in the offshore based on new seismic and geophysical data, depicting the Colorado Syntaxis (Pángaro and Ramos, 2012). This feature is the mirror image of the Cape Syntaxis and has similar characteristics (De Beer, 1995; Johnston, 2000).

FIGURE 1 NEAR HERE

There are two main problems in the tectonic interpretation of Ventania. The first problem is the stratigraphy of the early Paleozoic units as for some authors the Curamalal and Ventana Groups are the same unit tectonically repeated (Kilmurray, 1975; Tomezzoli and Cristallini, 2004), although most of the stratigraphers agree about the original sequences proposed by Harrington (1947) where Ventana is younger than Curamalal. The second problem, and perhaps the most important, is if the Ventania fold and thrust belt was originated by collision with an allochthonous Patagonia terrane in the late Paleozoic (Ramos, 1984, 2008; Kay et al., 1989; Sellés Martínez, 1989; Von Gosen, 2003; Chernicoff and Zappettini, 2004; among others), or was an intracratonic basin inverted by contraction and strike-slip tectonics related to oblique subduction further to the south along the present continental margin (Cobbold et al., 1991; López Gamundí et al., 1994, 1995; Rossello et al., 1997;

Dalziel et al., 2000; Gregori et al., 2008, among others). Some authors refute the allochthony of Patagonia based on paleogeographic and paleoclimatic reconstructions (López Gamundí and Rossello, 1998). The provenance analyses here presented shed light to both problems and provide a robust answer to previous uncertainties.

1.1 Location

The Ventania System is a 30 km wide mountain chain located in the southern part of the province of Buenos Aires in central eastern Argentina. It is surrounded by plains locally known as pampas, and has a length of 180 km with a W-NW trend (Fig. 2).

FIGURE 2 NEAR HERE

These mountains have a maximum height in the Cerro Tres Picos of 1,250 meters. There are several ranges as the Sierras de Curamalal, Ventana and Pillahuincó (Fig. 2), which expose the early and late Paleozoic sequences, tightly folded, with a constant northeast vergence (Harrington, 1947; Suero, 1972).

2. Stratigraphy

2.1 Metamorphic and igneous basement

There are very scarce exposures of the basement in the southwestern slope of the Sierra de Curamalal. Most of the authors recognized the igneous origin of these rocks, which are highly deformed, with typical cataclastic and mylonitic textures (Kilmurray, 1968; Gregori et al., 2005). There are also rhyolites exposed in different sectors further north (Figs. 2 and 3) and some isolated outcrops of granites exposed in Cerro Colorado and López Lecube quarries further to the west.

FIGURE 3 NEAR HERE

The available geochronological data indicate an age of 607 ± 5.2 Ma for the deformed granites of Cerro Corral (U-Pb SHRIMP ages in zircons, Rapela et al., 2003), that confirm old Rb-Sr ages of ~ 603-612 Ma of Varela and Cingolani (1976). New data of the Pan de Azúcar Granite yielded an age of 581 ± 8 Ma (U-Pb SHRIMP ages in zircons, Tohver et al., 2012). The postectonic granites in Cerro Colorado (531.1 ± 4.1 Ma and 523.8 ± 4 Ma), San Mario (524.3 ± 5.3 Ma), and Los Chilenos (533 ± 12 Ma), as well as the La Ermita Rhyolite (509 ± 5.3 Ma and 505 ± 18 Ma), were assigned to the Cambrian (Rapela et al., 2003; Tohver et al., 2012). The Agua Blanca Granite has an inheritance age of 2182 ± 18 Ma that indicates a Paleoproterozoic basement in the area as part of the Río de la Plata Craton (Tohver et al., 2012). The westernmost outcrops of López Lecube quarry yielded an age of 258.5 ± 1.9 Ma by U-Pb SHRIMP in zircons that corresponds to postectonic granites of the Gondwanide Orogeny and it is not part of the Ventania basement (Rapela and Kostadinoff, 2005).

The igneous rocks have been divided in two suites based on their composition and tectonic setting: a calcalkaline orogenic and collisional Neoproterozoic suite and a postorogenic extensional Cambrian suite (Gregori et al., 2005). The last episode was associated with a Cambrian rift by Rapela et al. (2003).

2.2 The Paleozoic sedimentary successions

The early Paleozoic sedimentary succession includes two sequences, the Curamalal and Ventania Groups (Fig. 4) deposited during Ordovician and Devonian times (Harrington, 1947; Sellés Martínez, 2001). The late Paleozoic is represented by the Pillahuincó Group (Fig. 4), which is mainly Cisuralian (Early Permian). The whole Paleozoic succession is around 4,500 m thick, with the two lowermost sequences measuring 2,400 m thick. The upper part of the succession documents a higher subsidence rate compared with the underlying part, but also a contrasting paleocurrent pattern, which varies from SW to SE, with strong NE prograding deltaic lobes in the uppermost part of the sedimentary section. The succession contains mainly sandstones, claystones and conglomerates in the lower part. However, glacial diamictites and glaciomarine deposits constitute a special type of coarse-grained deposits that document the late Paleozoic glaciation (Andreis et al., 1989).

The Curamalal Group, which represents the beginning of the sedimentary record in the basin, contains conglomerates with coarse-grained clasts in clast-supported to patchy sandy matrix-supported types, with beds up to 1.5 m in thickness and erosive to sharp bases in the lower part of La Lola Formation. Internally they contain well rounded quartzite clasts showing normal or rarely reverse gradation. The outcrops of the source area remain unknown but the almost monomict composition suggests a quartzite unit situated at a certain distance that allowed the well roundness of clasts by hyperconcentrated flows or diluted debris flows. Sandy deposits include different types of cross-bedding; some of them were interpreted as hummocky cross stratification by Zavala et al. (2000). However, they exhibit a unidirectional pattern and in all cases resemble more bidimensional subaqueous dunes. Giant cross-beds up to 4 m in amplitude are common in medium grained sandstones containing clay chips, and mud drapes. Thin beds show the same sedimentary structures and in cases depict clear bidirectional paleocurrents that document tidal control during the sedimentation. In the Ventana Group, the lower unit (Bravard Formation) has some fine conglomerates with a quartzitic composition of the clasts. The overlying Napostá Formation is well known for its ichnological content that includes *Skolithos*, *Arenicolites* and *Daedalus*. Abundant tidal features have been observed, including herringbone crossbeds and mud drapes. The Lolén Formation is the uppermost unit of the Ventana Group and exhibits more variability in clast composition and contains brachiopods and lycophytid plant remains as *Haplostigma* that have been used to date the top part in the Middle Devonian (Cingolani et al., 2002).

A paraconformity separates the Ventana from the overlying Pillahuincó Group, deposited between the latest Carboniferous and the Cisuralian (Early Permian) indicating a prolonged hiatus spanning the Upper Devonian to the middle Pennsylvanian. This group is crucial to understand the evolution of the Ventana System because a thick succession was deposited in a relatively short time. This fact documents a high subsidence rate related to a foreland basin which contrasts with the stable depositional settings for the underlying groups (Fig. 4).

FIGURE 4 NEAR HERE

The Sauce Grande Formation rests unconformably over the Ventana Group and is a glaciomarine succession that documents the late Paleozoic glaciation in the Atlantic basins of Argentina. The Sauce Grande Formation represents Late Carboniferous-earliest Permian (Cisuralian) glacial deposits 400 m thick that are also recognized in the Claromecó Basin, which correlates with the Dwyka Formation in the Karoo Basin. This correlation of glacial deposits is known since the pioneer studies of Keidel (1916) and Du Toit (1927). The Malvinas /Falkland Islands also record equivalent glacial deposits in the Lafonia Formation (Frakes and Crowell, 1969; Bellosi and Jalfín, 1984, 1989). The pre-breakup position of the Malvinas (Falkland) Islands based on the early reconstruction of Martin et al. (1981) is south of the Karoo Basin and off the coast of South Africa. Recent studies of the Sauce Grande tillites have found reworked limestone clasts with archeocyathids that indicate a Patagonian derivation from an Antarctic source (González et al., 2011, 2013). Some paleomagnetic studies support a position further to the east, but need a 180º rotation to match the data (Mitchell et al., 1986). Based on these data, López Gamundí and Rossello (1998) conclude that the paleoice flow directions of the Dwyka and the Lafonia glacial sequences were similar, but different from the south-north direction of the Sauce Grande tillites.

The Piedra Azul Formation represents early postglacial transgressive deposits, which are overlain by the marine Bonete Formation. These deposits represent the maximum flooding of the basin in the Early Permian and bear the typical Gondwana fauna of *Eurydesma* (Harrington, 1955). This thick-shelled bivalve *Eurydesma* was a cold-resistant and immobile, epifaunal suspension feeder that dominated marine environment of Gondwana in the Early

Permian (Jones et al., 2006). Above these levels, intertidal plains deposits bear an abundant *Glossopteris* flora, a widespread typical Gondwana flora also known in the Early Permian of Africa, India, Antarctica and Australia (Benedetto, 2010). The upper unit of the group is the Tunas Formation, represented by prodeltaic to subaerial delta plain deposits with paleocurrents that indicate a source area situated to the south-southwest. Very well preserved ichnofossils as *Cochlichnus* and *Gordia* have been observed in the Las Mostazas quarry and cross-bedding exposures that confirm the paleocurrent pattern suggested by Andreis and Cladera (1992) for the unit.

Recent studies on the microflora of several wells of the offshore Claromecó Basin have identified on palynological bases almost the entire Permian sequence, including for the first time Lopingian assemblages (Balarino, 2012).

3. Structure

The structure of the Ventania fold and thrust belt was a matter of discussion since the early work of Harrington (1947). Based on the extraordinary ductile folding of the early Paleozoic quartzites described by Keidel (1916) and Du Toit (1927), most of the authors interpreted the structure as a dominant fold-type (Harrington, 1970). Detailed surveys done by Varela et al. (1987), Von Gosen et al. (1990, 1991) and Tomezzoli and Cristallini (1998) recognized the main thrusts and confirmed the old thrust hypothesis of Schiller (1930). Seismic studies performed in the offshore depict those thrusts and their relationship with lower to middle crustal deformed rocks exposed further south in the Somún Curá Massif in the hinterland region (Pángaro and Ramos, 2012). These authors have shown that the Ventania foreland fold and thrust belt is separated from the hinterland by an area of minimum deformation interpreted as a late Paleozoic piggy-back basin. This basin is now beneath the Colorado Basin, a Jurassic to Early Cretaceous aulacogenic basin developed above the suture between Patagonia and Western Gondwana. This suture previously proposed by different authors in land, has been depicted in the offshore by a magnetic anomaly interpreted as evidence of mafic and ultramafic rocks by Max et al. (1999) and Ghidella et al. (1995).

FIGURE 5 NEAR HERE

The age of deformation of the Ventania fold and thrust belt is constrained in the Early Permian based on the growth strata of Tunas Formation described by López Gamundí et al. (1995), the paleomagnetic evidence of syndeformational magnetization of Tomezzoli and Vilas (1999), and the illite recrystallization age of Buggish (1987).

4. Material and methods

A systematic field reconnaissance was made of the different Paleozoic units and the metamorphic basement, analyzing their main sedimentological and structural characteristics. A large volume of 24 samples from Curamalal, Ventana and Pillahuincó Groups with detailed sampling in the uppermost tuff layers were collected. The location of the samples is indicated in Figs. 2 and 4 and the sample list and the U-Pb and Lu-Hf analytical data are presented in the electronic supplementary material. Petrographic and geochemistry information of sedimentary and tuff samples can be found in Alessandretti et al. (2013).

Samples were crushed and milled using jaw crusher. Then, the zircons were separated by conventional procedures using heavy liquids and an isodynamic magnetic separator after concentration by hand panning. The most clear and inclusion-free zircons from the least magnetic fractions were handpicked. All zircons were mounted in epoxy in 2.5-cm-diameter circular grain mounts and polished until the zircons were just revealed. Images of zircons were obtained using the optical microscope (Leica MZ 125) and back-scatter electron microscope (Jeol JSM 5800) at the Eletron Microscope Center of the Federal University of Río Grande do Sul, but are only illustrated when necessary to support the interpretation. Zircon grains were dated with laser ablation microprobe (New Wave UP213) coupled to a MC-ICP-MS (Neptune) at the Geochronology Laboratory of the University of Brasilia.

U-Pb isotope data were acquired using static mode with spot size of 30 um in diameter. Laser-induced elemental fractional and instrumental mass discrimination were corrected by the reference zircon (GJ-1) (Jackson et al., 2004), following the measurement of two GJ-1 analyses to every four sample zircon spots. The collector configuration used for simultaneous measurements of Th, U, Pb and Hg isotopes was ^{238}U, ^{232}Th and ^{208}Pb in faraday cups (H4, H2 and L4, respectively) and ^{207}Pb, ^{206}Pb, $^{204}Pb^{+}Hg$ and ^{202}Hg in Multiplier Ion Counting (MIC) channels attached to the L4 (MICs IC5, IC4, IC3 and IC2, respectively). The external error is calculated after propagation error of the GJ-1 mean and the individual sample zircon (or spot). A detailed description of analytical conditions and data reduction can be found in Chemale et al. (2012). Isoplot 3 software (Ludwig, 2003) was used to generate the concordia diagrams and histograms. For the concordia age calculations and frequency histograms, only the analyses with 100 ± 10% of concordance were used. All of the calculated ages are reported at the 95% confidence level.

Lu, Yb and Hf isotopes in single zircon crystals were acquired using static mode with spot size of 50 um in diameter. The laser spot was driven to the same site or zircon phase dated by the U-Pb method. To minimize aerosol deposition around the ablation pit and to improve transport efficiency, He was flushed along with Ar into the ablation cell. The Faraday collectors were arranged the following way: ^{171}Yb (low 4), ^{173}Yb (low 3), ^{174}Hf (low 2), ^{175}Lu (low 1), $^{176}(Hf+Yb+Lu)$ (Center), ^{177}Hf (high 1), ^{178}Hf (high 2) and ^{179}Hf (high 3). Detail of operation analytical conditions can be found in Chemale et al. (2011a). To correct for isobaric interferences of Lu and Yb isotopes on mass 176, the isotopes ^{171}Yb, ^{173}Yb and ^{175}Lu were simultaneously monitored during the analyses. The ^{176}Lu and ^{176}Yb concentrations were calculated using a $^{176}Lu/^{175}Lu$ ratio of 0.026549 and a $^{173}Yb/^{171}Yb$ ratio of 1.123456 (Chu et al., 2002; Thirwall and Walder, 1995). Correction of Hf isotopic ratios for instrumental mass bias was based on an exponential law and used the reference $^{179}Hf/^{177}Hf$ value of 0.7325 (Patchett et al., 1981). Each analytical session included determinations of the βHf and βYb factors for each individual spot. The mass bias behavior of Lu was assumed to follow that of Yb.

Lu-Hf model ages (TDM) of zircon grains were calculated based on a depleted mantle source with $^{176}Hf/^{177}Hf = 0.28325$ and $^{176}Lu/^{177}Hf = 0.0388$ (Andersen et al., 2009). We also calculated model ages of individual zircons for felsic and mafic sources assuming the following parental magma compositions: mafic, Lu/Hf = 0.022; felsic, Lu/Hf = 0.010 (Pietranik et al., 2008). The values of εHf(t) were calculated assuming the CHUR $^{176}Hf/^{177}Hf$ ratio of 0.282785 (Bouvier et al., 2008) and the decay constant of $\lambda^{176}Lu = 1.867 \times 10{-}11/a$ (Söderlund et al., 2004).

5. Results

5.1 Pan de Azúcar mylonitic belt

This belt of highly deformed metamorphic rock was identified as the Pan de Azúcar Formation by Cuerda et al. (1975) in the eastern slope of the Cerro Pan de Azúcar beneath the contact with the La Lola Formation. Previous authors interpreted rocks similar to sample SLV-VE 02 (Fig. 6a), as derived from igneous protolith, whereas others as Von Gosen et al. (1990) described paragneisses from these exposures. We interpreted this sample based on the internal textures seen in the back-scattering image and the Th/U ratio in each dated zircon (Fig. 6) as gneiss of igneous origin; apparently deformational and metamorphic process has not affected the detrital zircons. One of the main frequency peaks (Fig. 6b) coincides with the ages of the Cambrian suite proposed by Gregori et al. (2005), although the major frequency peak clearly indicates a Paleoproterozoic component in this rock (Fig. 6 a-b), similar to the age interpreted by Tohver et al. (2012) as a basement inheritance in the granites of Agua Blanca. These ages are between the main magmatic activity (2250–2120 Ma) and the collisional overprint (2100–2080 Ma) recorded in the basement of Tandilia by Cingolani (2011). There are also some few older and younger zircons.

FIGURE 6 NEAR HERE

It is possible that the orthogneiss affected by a post-540 Ma contractional deformation may correlate with the main orogeny of the Saldania Belt recognized by Chemale et al. (2011b) in southernmost Africa. In a Gondwana plate tectonic context, a subduction zone has been proposed at the southern margin of the Kalahari plate, close to the Precambrian-Cambrian boundary, as suggested by Rozendaal et al. (1999), and its extension in the Sierra de la Ventana Orogen (Chemale et al., 2011b). Following Gregori et al. (2005) deformation in Sierra de la Ventana should be older than 533 Ma, which is the age of the postectonic granites. The age pattern of this orthogneiss shows different inherited zircons.

However, another possible alternative would be to consider that sample a highly deformed quartzite of La Lola Formation, due to the similar pattern of zircon ages in comparison with other samples of this unit (see SLV-VE 05 in Fig. 8). This interpretation would indicate that the main deformation of this sample could be Gondwanian in age, instead of Brasiliano.

5.2 Curamalal Group

The base of this group is represented by La Lola Formation, which is nicely exposed in the eastern slope of Cerro Pan de Azúcar (Andreis and López Gamundí, 1989). There is a 30 m thick orthoconglomerate dominantly formed by clasts of quartzite (SLV-VE-03). These conglomerates are covered by quartzitic sandstones (SLV-VE-05). It is interesting to remark that tectonically interposed with these quartzites, east of the Abra Mayer, there are some lenses of mylonitic granite. One of these lenses with calcalkaline composition has a unique frequency peak at 541.0 ± 8.4 Ma within the range of basement granites (Figs. 7 a,b).

FIGURE 7 NEAR HERE

The sedimentary facies and provenance of these conglomerates have been studied by Zavala et al. (2000), who recognized a proximal shelfal environment in a flood- dominated fan delta system developed from the Tandilia area. However, the good mineralogical maturity almost dominated by quartzite clasts up to 25 cm in size and good roundness suggest that the source area was closer, indicating that the present day quartzite outcrops of Tandilia extended well into the south. The pattern of detrital zircons of both samples (see samples SLV-03 and SLV-05 in Fig. 8) confirms the proposal of Zavala et al. (2000), and shows that the main peak around 2050-2170 Ma corresponds with the maximum magmatic activity of the Tandilia arc according with Cingolani (2011). The lower levels of La Lola Formation have minor Cambrian peaks at 545 and 520 Ma, which indicate exhumation of the post-tectonic rocks in the surrounding area.

The sample SLV-VE-09 is from the lower part of Mascota Formation from Sierra de Chasicó, which is unconformably overlying the Cerro Colorado Granite (Harrington, 1968).The maximum age of sedimentation is 534 Ma as indicated by the highest frequency peak (Fig. 8). This quartzite has been interpreted as being older than the Los Chilenos Granite (533 Ma, Thover et al, 2012), but the present data may favor that the Mascota Formation is younger than the granite based on field observations that coincide with criteria used in the Harrington (1947) map. The sample SLV-VE-10 was collected east of Tornquist (see Fig. 2) from the Mascota Formation, and presents similar age distribution pattern as sample SLV-VE-09. In these samples the Paleoproterozoic sources start decreasing and some minor Mesoproterozoic peaks are visible.

The analysis of the older units of the Curamalal Group shows an interesting trend in their sources (Fig. 8) with a continuous decrease in the Paleoproterozoic provenance from the La Lola Formation at the base of the Curamalal Group upwards, parallels the increase of the Cambrian zircons towards the top of the Mascota Formation. This increase of Cambrian peaks of 545 and 534 Ma may indicate a potential derivation from Eastern Sierras Pampeanas (see Fig. 1) which has been exhumed at that time. The input of Grenville-age zircons around 1200 Ma in the Mascota Formation is somewhat older to be derived from the Namaqua belt of western Kalahari craton, but similar ages recorded in the detrital zircons of the Punta Mogotes basement from a borehole core, were interpreted as derived from the western Kaapval Craton by Rapela et al. (2011). Similar age zircons were also recognized in the Cerro Largo Formation from Tandilia by Gaucher et al. (2008). However, the most potential Grenville-age source based on the rank of ages observed could be the Eastern Sierras Pampeanas where ages from 1000 to 1200 Ma are common (Escayola et al., 2007).

FIGURE 8 NEAR HERE

5.3 Ventana Group

The different units of the Ventana Group are conformably deposited on the Curamalal Group. The provenance analysis based on the detrital zircons shows as the most important frequency peak Brasiliano ages around (564-540 Ma) (Fig. 9). The Paleoproterozoic ages of Tandilia are less significant and tend to disappear. Some minor evidence of Ordovician zircons (482 Ma) is seen in the Napostá Formation, as well as in the Bravard Formation, which will be dominant in the upper part of the sequence. Uriz et al. (2012) analyzed a sample from the Napostá Formation and detected an important frequency peak of 473 Ma, partially equivalent to the Ordovician peak found by us.

FIGURE 9 NEAR HERE

The zircons of Providencia Formation follow the same trend of the lower section of the Ventana Group (compare with Fig. 10), but an important change is recorded in the Lolén Formation, already recognized by Uriz et al. (2011). There, an important peak of Early Ordovician zircons is seen for the first time (490 Ma), as well as increasingly old Brasiliano ages (641-612 Ma). The first occurrence of an Ordovician frequency peak in the Lolén Formation is very similar to the one recognized by Rapela et al. (2007) further to the northeast, in somewhat equivalent nearshore quartzitic sandstones of the Balcarce Formation. This unit is exposed nearby the town of Balcarce (see location in Fig.1), and is unconformably deposited on the metamorphic basement of the Tandilia System and pinch out over the glacial diamictites of the Volcán Formation (Pazos et al., 2008).

There are not precise biostratigraphic constraints for its age, but it was assumed to be broadly between Ordovician and Early Silurian based on its trace fossils (Borrello, 1966). According to Rapela et al. (2007) who reported detrital zircon ages as young as 475–480 Ma, the Balcarce Formation is not older than Early Ordovician, suggesting a Late Ordovician to Early Silurian sedimentation age. Moreover, the trace fossils described by Seilacher et al. (2002) from several localities, differ significantly from the familiar Arenigian suite. Rather, they resemble the Lower Silurian ichnofaunas of Libya, Chad and Benin, with trilobite tunnels (*Cruziana ancora*), palmate *Arthrophycus alleghaniensis* and *Gyrochorte zigzag* as shared elements (Seilacher et al., 2002), but also *Diplocraterion* conforming monospecific suites has been observed. These authors therefore assigned an Early Silurian age to the Balcarce Formation and they mentioned that the ichnofauna possibly signals an even further southward extension of the Malvinocaffric Province. It is interesting to remark that the matrix of the Cerro Volcán diamictites, a four meters thick level underlying typical quartzites of the Balcarce Formation, has detrital zircons 485-490 Ma old and a maximum peak of 530 Ma (Zimmermann and Spalletti, 2009; Van Staden et al., 2010). These data reinforce the assignation to the Silurian of this unit since these glacial deposits could be interpreted as representing the Hirnantian glaciation of the end of the Ordovician.

FIGURE 10 NEAR HERE

The siliciclastic deposits of the Balcarce Formation were developed in a nearshore and inner shelf environment on a tide dominated platform, affected by storm events in a marine system that was open to the south based on the pattern of progradational clinoforms (Poiré et al., 2003). Paleocurrents indicate a north dominant sediment supply for the western and central areas of the Balcarce Formation, while in the eastern part of the basin the main transport directions are east-west oriented (Teruggi, 1964).

The Lolén Formation is the only unit bearing marine invertebrate fossils in the lower Paleozoic sequences of the Ventania System and the occurrence of brachiopods is known since the early work of Harrington (1947). Benedetto (2010) analyzed these brachiopods and assigned them to *Cryptonella*, an Early Devonian genus. Based on the age of these brachiopods, Newton and Cingolani (1990) correlated the Lolén Formation with the Bokkeveld Group of the Cape Fold Belt, confirming the correlation of Du Toit (1937).

Therefore, a partial correlation between Lolén and Balcarce Formations is proposed based on the detrital zircon pattern (Fig. 11), not only the Early Ordovician sources, but also the range of Brasiliano ages (640-610 Ma), which are older than previous ages recorded in the early Paleozoic of Ventania. The Ordovician provenance of both units should come from the northwest, derived from the Western Sierras Pampeanas Orogen, the only sector that records plutonic and volcanic rocks of Famatinian age at these latitudes (Ramos et al., 2010).

FIGURE 11 NEAR HERE

5.4 Comparison between the Curamalal and the Ventana Groups

Kilmurray (1975) proposed that both groups were result of a tectonic repetition based on an apparent similarity between the quartzitic sandstones. Tomezzoli and Cristallini (2004) formalized Kilmurray' hypothesis in their study of the structure of Sierras de la Ventana and Curamalal through a viable structural section of these ranges, which shows both groups as a single sequence tectonically repeated. However, our present results indicate a striking difference between the detrital zircon patterns of both groups. When the pattern of La Lola Formation (Fig. 8) is compared with the lower part of the Ventana Group, in particular the Bravard and Napostá Formations (Fig. 9), it is clear the absence of Paleoproterozoic population in these units (Fig. 12).

FIGURE 12 NEAR HERE

The Curamalal Group begins with a high frequency peak of Paleoproterozoic ages with a minor peak in the Brasiliano ages, showing exhumation of the Tandilia rocks at that time. An irregular exposed topography extended to the south of the present ranges that explains the zircon detrital pattern and facies of the conglomerates of La Lola Formation. The absence of carbonate clasts contrasts with the abundance of carbonates in the Neoproterozoic sedimentary cover of Tandilia. This could be explained by a combination of climate and transport that favored resistant lithologies over carbonates.

The maximum frequency in the base of Ventana Group shows exhumation of the Brasiliano rocks and almost no existence of Paleoproterozoic ages, contrasting with the Curamalal Group pattern. These different patterns also characterize the upper part of the Curamalal and Ventana Groups (see Figs. 8 and 10). The major difference is the first occurrence of Ordovician zircons which is exclusive of the Ventana Group and Balcarce Formation (Fig. 12). The Cerro Largo Formation in the Tandilia System has been considered correlatable with the Balcarce Formation, but Pazos and Rapalini (2011) kept the unit in the Precambrian as traditionally suggested in agreement with the detrital pattern of this unit.

These evidences permit to discard the correlation of both groups and revaluate the early proposed stratigraphy of Harrington (1947) which, at the present level of knowledge, is the one that best explains the data.

5.5 Pillahuincó Group

The late Paleozoic deposits of this group indicate the inception of a foreland basin stage in the evolution of the Ventania System (Ramos, 1984; López Gamundí and Rossello, 1992, among others). The unconformity that separates the Ventana and Pillahuincó Group, although quite elusive in the structural evidence (López Gamundí and Rossello, 1993), coincides with an important change in the petrography of the sandstones (Andreis and Cladera, 1992). Compositionally, the initial passive margin phase of the continental platform was characterized by quartz-rich, craton-derived detritus, but was followed by a foreland phase that shows a paleocurrent reversal and dominance of arc/foldbelt-derived material (López Gamundí and Rossello, 1998).

The recent finding of subrounded clasts with archeocyathids in the glaciomarine Sauce Grande Formation in Ventania derived from Antarctica (González et al., 2013) as well as in the Lafonia (Fitzroy) tillites in the Malvinas (Falkland) Islands, and in the Dwyka tillites (South Africa) support the correlation of these glacial deposits (Veevers and Saeed, 2013).

The analysis of the detrital zircon provenance of the late Paleozoic deposits (Fig. 13) shows several differences regarding the early Paleozoic sequences. The first important difference is that in the Sauce Grande Formation there are Archean zircons with conspicuous ages of 2729, 2990 and 3200 Ma, not seen in the lower Paleozoic sequence of Ventania. As the Tandil area shows strong evidence supporting the derivation from a Neoarchean crust (less than 2.65 Ga) as inferred by Cingolani (2011) based on the positive εHf data, those zircons together with the reversal of the paleocurrents indicate a different old cratonic source south of the study area. The second striking difference is the frequency peaks of 319-322 Ma in the Piedra Azul, Bonete, and Tunas formations that are characteristic from northern Patagonia, as well as the Silurian 432-417 Ma peaks, similar to the age recorded in Los Pájaros Island in northeastern Patagonia granites (Nuñez et al., 1975). The Piedra Azul Formation represents early postglacial transgressive deposits, which are overlain by the marine deposits of the Bonete Formation bearing the typical *Eurydesma* Gondwana fauna (Harrington, 1955), which represent the maximum flooding of the basins in the Early Permian. Above this fauna, some intertidal plain deposits bear an abundant *Glossopteris* flora, a typical Gondwana flora also known in the Early Permian of Africa, India, Antarctica and Australia (Benedetto, 2010).

FIGURE 13 NEAR HERE

The other frequency peaks (Fig. 13) are common ages in the crystalline basement of northern Somún Cura Massif. Zircons ages of Grenvillian (1100-1000 Ma), Brasiliano (584-532 Ma), and Ordovician (491-450) have been widely reported by Pankhurst et al. (2001, 2006); Ramos (2008), and Naipauer et al. (2010). This spectrum of frequency peaks is duplicated by the detrital zircons of the Sierra Grande Formation (Fig. 14), a Siluro-Devonian sedimentary cover unconformably deposited over the crystalline basement (Uriz et al., 2011).

FIGURE 14 NEAR HERE

There are some minor outcrops of sandstones near González Chaves, 113 km east of the Coronel Pringles in the middle of the Claromecó Basin (Figs. 1 and 2) (Llambías and Prozzi, 1975). Monteverde (1937) correlated these sandstones with the quartzites of Las Mostazas in the southeastern part of the Sierra de Pillahuincó (Tunas Formation). Furque (1965) described similar quartzites with rest of lepidophytes in a similar setting 50 km further east of González Chaves. A representative sample of these outcrops near González Chaves was dated (SLV-VE 24, Fig. 15).

FIGURE 15 NEAR HERE

The detrital zircon ages show two important frequency peaks, one in the Late Carboniferous (316 Ma), and another in the Early Devonian (406 Ma), a pattern characteristic of other Pillahuincó Group rocks (Fig. 13). It is important to note that the youngest sedimentary deposits exposed in the Claromecó Basin belong to this group, although Tomezzoli and Vilas (1997) and Tomezzoli (2009) indicated that these exposures are consistent with an Early to Late Permian age based on paleomagnetic grounds. This has been challenged by Domeier et al. (2011), who supported younger ages based on recent dating in Sierra Chica.

5.6 The Permian ash-fall tuffs of Tunas Formation

The occurrence of pyroclastic levels in the Tunas Formation first described by Iñiguez et al. (1988) is one of the best time-lines to constrain the age of the late Paleozoic sequences. The age of this unit was based on the *Eurydesma* Fauna and the *Glossopteris* Flora in the deposits underlying the Tunas Formation, both of Early Permian age (Harrington 1947, 1955; Benedetto, 2010). The upper part of the Tunas Formation bears the *Gangamopteris* Flora of latest Early Permian age according to Archangelsky and Cúneo (1984).

Several ash-fall tuffs levels were sampled in the Abra del Despeñadero, in the southeastern sector of Sierra de Pillahuincó. There, thin beds of smectite-rich claystones have been identified in the predominantly sandy upper half of the Tunas Formation and are characterized by abundant vitroclasts and fragments of vitric tuffs (Iñiguez et al., 1988; López Gamundí, 2006). The dated zircons of three beds yielded an average $^{206}Pb/^{238}U$ age of 304 Ma, that corresponds to some sort of mixing of zircons formed between 280 and 288 Ma (interpreted as juvenile zircons based on εHf data) and zircons formed between 290 to 315 Ma. Alessandreti et al. (2013) presented for the same SLV-VE-19 sample an U-Pb in situ LA-MC-ICPMS age of 284 ± 15 Ma.

One tuff layer of the same outcrop as the samples SLV-VE-19, 20 and 21 has been dated by Tohver et al. (2008) and yielded an age of 282.4 ± 2.8 Ma (U-Pb-SHRIMP). A similar age of 280.9 ± 1.9 Ma (U-Pb SHRIMP) was recently reported by López-Gamundí et al. (2013) on volcanic zircons from a tuff layer in the uppermost section of the Tunas Formation. Both SHRIMP U-Pb ages are more reliable.

Based on these data, it is assumed that the tuff layers with the younger frequency peaks, have crystallization ages close to 280 and 288 Ma (see Fig. 13), indicating a middle Early Permian age, consistent with SHRIMP recent ages and the biochron of the fossil fauna and flora.

The intimate relationship between volcanic activity inboard of the paleo-Pacific margin, deformation in the adjacent orogenic belt, and subsidence and sedimentation in the contiguous foreland basin led López Gamundí and Rossello (1998) to interpret the magmatic belt as an Andean-type margin related to the paleo-Pacific margin. This proposal was followed by Turner (1999) and Dalziel et al. (2000), among others. The main problem of this interpretation is that the magmatic arc, as pointed out by Turner (1999) was located over 1,000 km away from the continental margin. No subduction related magmatism can exist that far from the margin, even if a flat-subduction is proposed. A magmatic arc belt cannot be developed further than 300-400 km away of the trench. Some authors proposed an intermediate location (Pankhurst et al., 2006), but still inconsistent with a magmatic arc along northern Patagonia in the Somún Cura Massif. Recent work of Chernicoff et al. (2012 a) demonstrates that a series of calc-alkaline orthogneisses are Permian in age and represent the relicts of the late Paleozoic magmatic arc developed in the northern Patagonia as proposed by different authors (Ramos, 2008, and cites therein).

Although, the classic interpretation to explain the pyroclastic levels in the Las Tunas Formation and in the Paraná Basin in southern Brazil is a source in the Choiyoi volcanic rocks (Kay et al., 1989), we favor a more proximal origin. Based on U-Pb SHRIMP ages around 281.4 ± 2.5 Ma from Los Reyunos Formation, lower section of the Choiyoi volcanic rocks, Rocha Campos et al. (2011) correlated these rocks with the older tuffs of the Paraná Basin. This correlation is supported by the northeast paleocurrent directions measured in the aeolian sandstones of Los Reyunos Formation by Pazos et al. (2011). However, if we want to use the same Choiyoi source for the pyroclastic deposits of Las Tunas Formation, even with similar ages, the dominant winds should be to the southeast, different from what was measured in the Choiyoi intercalated aeolian sandstones. The distance is closer from Somún Cura, the ages are similar, and the required paleowind direction is also to the northeast. Therefore, we prefer as a potential source the Early Permian widespread calderas and rhyolites of the same age found in the Somún Cura Massif. This interpretation also explains the source of the large amount of volcanic debris and igneous Carboniferous detrital zircons found in Las Tunas Formation.

6. Lu-Hf-Isotope analyses

Hf isotopes have been analyzed in 65 detrital zircons of samples from the Cambrian paragneiss (SLV-VE-02), and from the Lolén (SLVE-01) and Tunas (SLV-VE 20/21) Formations, in order to understand the characteristics of the source region (Fig. 16).

Several zircons from different representative sources have been analyzed in the sample of metamorphic basement (SLV-VE-02). Two Neoarchean zircons yielded negative values of εHf(t) of -7.06 and -5.11 and TDM ages 2.98 and 3.22 Ga; one Mesoarchean zircon has an εHf(t) of +1.73 with a TDM age of 3.06 Ga. The Paleoproterozoic source was analyzed in eight zircons, which yielded values of εHf(t) between + 2.19 and -1.8. These values are typical of the juvenile arc granitoids of Tandilia (Fig. 16). The younger zircon of 1,782 Ma gave a quite negative value of -5.57 far from the previous ones; the TDM ages yielded between 2.57 and 2.19 Ga. This 1.78 Ga corresponds to the age of post-collisional granites in the Tandilia area (Cingolani, 2011), which clearly shows important crustal recycling (Fig. 16).

A few Mesoproterozoic zircons analyzed have disperse εHf(t) values from -14.8 and an TDM age of 2.05 Ga, to εHf(t) positives and TDM ages 1.87 and 1.62 Ga. The other well represented fraction is the Neoproterozoic (ca. 552 Ma) with εHf(t) values between -5.4 and -3.08 with similar TDM Mesoproterozoic ages between 1.34 and 1.26 Ga within the range described for the Sierras Pampeanas by Dahlquist et al. (2013).

FIGURE 16 NEAR HERE

In the Lolén Formation 35 zircons have been analyzed from sample (SL-VE-01) representing different sources (Fig. 16). The Paleoproterozoic source yielded values of εHf(t) of +2.86 and -1.57 and TDM ages between 2.49 and 2.31 Ga; however, a few zircons yielded εHf(t) values more negatives between -4.04 and -20.68 and older TDM ages between 2.81 and 2.59 Ga. Grenville-age zircons yielded similar εHf(t) values, but highly positive, between +12.75 and +7.22, and model ages close to the crystallization ages, between 1.27 and 1.50 Ga, showing their juvenile nature (Fig. 16). The Neoproterozoic zircons have variable characteristics with a group of highly negative εHf(t) values between -35.17 and -18.22 and model ages between 2.52 and 1.80 Ga; a second group has less negative εHf(t) values between -5.64 and -0.73 and younger TDM ages between 1.16 and 1.35 Ga. The Paleozoic sources can also be grouped in two sets, a group of Cambrian, Ordovician, and Devonian zircons with very negative εHf(t) values (-43.93 and -11.09) and TDM ages between 2.61 and 1.47 Ga; the other group has more positive εHf(t) values (+28.71 and -5.01) and younger TDM ages (1.26 and 1. 03 Ga).

The last samples from the Tunas Formation (SLV-VE 20/21), which have late Paleozoic zircons (290-340 Ma) yielded εHf(t) values between +10.51 and -1.87, with TDM ages restricted between 0.98 and 0.80 Ga. These zircons probably belong to the juvenile magmatic arc of northern Patagonia (see Ramos, 2008). There is also a crystal with highly negative εHf(t) value (-30.82) and a model age of 1.82 Ga, very distinct of the rest of the group (Fig. 16). Those highly negative values were also recorded by Chernicoff et al. (2012 a).

7. Analyses of the provenance

Based on the previous detrital zircon analyses, together with conventional petrographic and paleocurrents studies performed by Reinoso (1968), Andreis and Cladera (1992) and López Gamundí and Rossello (1998), among others, a tentative paleogeography can be reconstructed along a series of stages.

7.1 Cambrian-Ordovician

The provenance at this stage looks simple and conditioned by the basement exposed at that time. The Paleoproterozoic of Tandilia is the main source, a clear indication that these mountains were conspicuous at that time. Through time, the Pampean basement of Ventania starts being exhumed and Cambrian and Neoproterozoic granitoids became the main source (Fig. 17).

FIGURE 17 NEAR HERE

The proposed paleogeography shows an old mountain system being exhumed, represented by the Tandilia mountains, surrounded to the west (present coordinates) by the Pampean orogenic belt of Eastern Sierras Pampeanas. The exhumation of this belt produced an increased participation of this source through time. At the eastern side the Punta Mogotes Belt, a Brasiliano orogen related to the final closure of Adamastor Ocean at Early Cambrian times (Gaucher et al., 2005), was one of the last events related to the amalgamation of Gondwana. However, this orogen was not source of the analyzed samples of Ventania. The comparison of the different units of the Curamalal Group (Figs. 7 and 8) with the Mogotes Formation detrital zircon patterns shows striking differences (Fig.18).

FIGURE 18 NEAR HERE

The Cambrian-Ordovician paleogeography is illustrated in Fig. 19. The drainage should have an important component from the west or northwest to explain the lack of zircons from the Punta Mogotes Belt seen in the frequency peaks of Fig. 18. Note that these peaks are partially recognized in the younger Balcarce Formation (Fig. 11).

FIGURE 19 NEAR HERE

7.2 Silurian-Devonian

At this time the main dominant provenance was from the west and northwest. The Pampean basement of Eastern Sierras Pampeanas as described by Rapela et al. (1998), Ramos et al. (2010) and Chernicoff et al. (2009, 2012 b), was the main source of the lower Ventana Group (Fig. 17). The angular unconformity between the Balcarce Formation and the Neoproterozoic and Early Cambrian sedimentary cover of Tandilia (Cingolani, 2011) may be either the result of the collision of Pampia with the Río de la Plata Craton (Early Cambrian), or the Famatinian collision (Middle Ordovician). The sedimentary record of Balcarce Formation indicates a post Hirnantian glaciation age (Late Ordovician). The Pampean unconformity is seen in different places of Eastern Sierras Pampeanas and was dated in 530 Ma by Escayola et al. (2007) and Ianizzotto et al. (2013). But, as the main source is coming from Eastern Sierras Pampeanas which is closer to Tandilia, it is more probable that deformation is related to the Pampean orogen (see further details in Pazos and Rapalini, 2011).

Through time, the Pampean Belt had the relief partially eroded, and during Silurian times the first Ordovician zircons were recorded, indicating that either the Famatinian Belt was supplying zircons to the area, or some scarce Ordovician granitoids in the Eastern Pampean Belt were exhumed. Also, Grenvillian-age zircons began to appear in the pattern of provenance, suggesting that the Mesoproterozoic basement of Cuyania and/or Pampia was also exhumed (Sato et al., 2000). The relief of Tandilia was almost non-existent as a source. At this time, an important source from Punta Mogotes Belt is recorded in the Balcarce Formation, indicating that this belt was actively exhumed. In Silurian times the paleogeography was characterized by higher mountains in the Famatinian Belt in the west, a partially eroded Pampean Belt, almost non-existent Tandilia Mountains, and an important relief in the Punta Mogotes Belt. Some sort of by-pass existed through the Pampean Belt in order to register Ordovician zircons in the Balcarce and Lolén Formations. The continental margin was opened to the present south (Fig. 19).

7.3 Late Paleozoic

A drastic change in paleogeography was produced at this time. A volcanic relief associated with a magmatic arc was located to the south, in present northern Patagonia. Volcanic debris (Andreis and Cladera, 1992) together with magmatic zircons were recorded in Ventania from 320 to 270 Ma. Classic petrographic provenance studies in Ventania and Cape Fold Belt of South Africa indicate a dissected arc source for these rocks (López Gamundí and Rossello, 1998). The older data of Late Carboniferous age observed as detrital zircons are in agreement with their derivation from the northern late Paleozoic magmatic arc proposed by Ramos (2008) in northern Patagonian along the Somún Cura Massif. Recent studies of Chernicoff et al. (2012 a) in the Yaminué region in the Somún Cura Massif show that a biotite paraschist has a maximum U/Pb SHRIMP age of 318 ± 5 Ma coherent with the frequency peaks of several units of the Pillahuincó Group of the Ventania System. On the other hand, the tonalitic orthogneiss has a crystallization age of 261.3 ± 2.7 Ma, which is broadly coeval with deformation, and Neoarchean-Paleoproterozoic inheritance, indicating the occurrence of Archean crust in this sector of Patagonia. Hf TDM ages of Permian zircons are mainly Meso-Paleoarchean (2.97–3.35 Ga) with highly negative ε(Hf) values (ca. –33) according to Chernicoff et al. (2012 a). It is interesting to remark that the first Archean zircons observed in

Ventania are the 2729, 2990 and 3200 Ma frequency peaks of Sauce Grande Formation, within the range of inherited Archean zircons of the Yaminué region described by these authors.

The obtained zircon dates of the ash-fall tuffs of the Tunas Formation indicate an Early Permian age, close to the depositional age of this unit (López Gamundí et al., 1995), which was interpreted as synorogenic deposits based on the occurrence of growth strata. The age of deformation is consistent with the deformation ages of the orthogneisses in north Patagonia in the adjacent Somún Cura Massif (Chernicoff et al., 2012a).

A Permian very juvenile poorly dissected relief dominated the Somún Cura Massif and the uplifted Ventania fold belt providing immature detritus to the Claromecó Basin. The Ventania fold and thrust belt continues in the offshore in the Colorado syntaxis (Pángaro and Ramos, 2012), a mirror image of the Cape Syntaxis (Fig. 20).

8. Correlation with the Cape Fold Belt in South Africa

It is important to note that in South Africa, the Cape Fold Belt was developed at the same time that the Ventania Belt (Fig. 20) as parts of the Gondwanides Orogen (Keidel, 1916, 1921). There is consensus in the correlation of the different units of the Neoproterozoic-Cambrian basement and the Paleozoic sedimentary sequences since the early work of Keidel (1916) and DuToit (1927) followed by Harrington (1947). This correlation was based on the rock types and age of the basement as proposed by Rapela et al. (2003), Milani and DeWitt (2008), and Chemale et al. (2011b). On fossiliferous grounds the correlation was based on the *Eurydesma* fauna and the *Glossopteris* flora, as well as in the Devonian marine fossils (Harrington, 1955; Benedetto, 2010). Another piercing point is the correlation of the glacial deposits of Sauce Grande and the Dwyka Tillite, which has been identified since the early work of Keidel (1913), and corroborated several times by more recent works (López Gamundi and Rossello, 1998).

FIGURE 20 NEAR HERE

A recent study on the detrital zircons of several pre-Carboniferous units of the Cape Supergroup shows striking differences and similarities with the Ventania System (Fourie et al., 2011). The main difference is the dominant Mesoproterozoic (1.0-1.2 Ga) provenance of the Cape Supergroup that points out to the Namaqua Belt as the source area. The Curamalal and Ventana Groups have the Paleoproterozoic ages from Tandilia Belt (2.2-2.0 Ga) as the main Precambrian source. The similarities are the Neoproterozoic-Cambrian ages derived in the present study from the Eastern Sierras Pampeanas, and from the pan-African belts and the

Cape Granites for Fourie et al. (2011). Both studies have also a striking coincidence in the Ordovician ages. The analyses performed in the pre-Carboniferous rocks of the Cape Fold Belt have a noticeable frequency peak at 469 Ma, similar to the frequency peak of 475 Ma of Lolén Formation in the Ventania Belt that in the present study is straight forward derived from the Famatinian Belt of Western Sierras Pampeanas. A similar Ordovician peak (478 Ma, see Fig. 11) was identified in the Balcarce Formation by Rapela et al. (2011). Nonetheless, Fourie et al. (2011) assumed that the source area could be either the Ross Orogen in Antarctica or the Patagonian Deseado Massif of Argentina. As we noticed, the abrupt change in provenance occurred after the collision of Patagonia, where a very different provenance is recorded for the first time.

Based on the evaluation of both detrital zircon data bases we consider the Ordovician (480-460 Ma) provenances in both Ventania and Cape belts, as derived from Western Sierras Pampeanas, while the Neoproterozoic-Cambrian (560-530 Ma) zircons have local sources. Zircons are derived in the Ventania Belt from Eastern Sierra Pampeanas, but in the Cape Fold Belt come from local pan-African belts.

9. Concluding remarks

The obtained data permit to confirm some hypotheses and discard some previous interpretations. The comparison of the provenance between the Curamalal and Ventana Groups allows once more to confirm the stratigraphy of Harrington (1947), and to reject some hypotheses that interpreted these units as tectonic repetitions of the same succession. These pre-Carboniferous sequences of the Ventania Belt have a pattern derived from the Tandilia Belt, as well as from Eastern and Western Sierras Pampeanas. These characteristics can be compared with the detrital zircon pattern of the pre-Carboniferous Cape Fold Belt sequences. Differences and similarities can be explained with common and local sources; both belts share a similar Early to Middle Ordovician age zircons, which seem to be derived from the Sierras Pampeanas Belt.

The change in provenance between the early Paleozoic deposits of the Ventana Group and the late Paleozoic foreland sequences of the Pillahuincó Group indicates a different source region from these deposits. A series of Carboniferous to Permian zircons, absent in the previous units, together with the drastic change in paleocurrents indicate their derivation from northern Patagonia as part of the Gondwanides Belt. The source area for the Pillahuincó Group matches one to one the lithological characteristics of the Somún Cura Massif (see location in Fig. 1), and the U-Pb ages of the main igneous and metamorphic rocks.

The occurrence of clasts with archeocyathids in the Somún Cura Massif sequences, together with the detrital zircon patterns, are compatible with a source in Eastern Antarctica (González et al., 2011; Naipauer et al., 2011; Ramos and Naipauer, 2012; Veevers and Saeed, 2013). The recent finding of archeocyathids in clasts of the Sauce Grande tillites (González et al., 2013), reinforces this provenance. This match indicates that Patagonia should have originated in Eastern Gondwana, and that it was transferred to Western Gondwana during the Gondwanan orogeny. For further details see the recent analysis of Ramos and Naipauer (2013 and cites there in). Although some recent papers proposed a continuation of the magmatic activity in the early Paleozoic from the Sierras Pampeanas to the Somún Cura area (Rapalini et al., 2013), a classic proposal advanced by Bracaccini (1960), it is not able to elucidate the presence of archeocyathids (see discussion in Ramos and Naipauer, 2013). Rapalini et al. (2013) follow the arguments of Dalziel et al. (2013) who propose a continuous archeocyathid reef along the margin of Antarctica. However, this argument needs a magmatic arc located in the Somún Cura arc more than thousand kilometers away from the Pacific margin (see discussion in Ramos, 2008).

The integrated evolution of the Gondwanides in this sector of the southwestern Gondwana margin with the general evolution of the Terra Australis Orogen as defined by Cawood (2005) and modified by Ramos (2009), shows some interesting features. The early Paleozoic continental margin of Ventania interrupts the almost continuous Famatinian-Ross orogens. The Famatinian Orogen characterizes an active continental margin with a voluminous magmatic arc developed along the proto-Andean margin of Western Gondwana from Venezuela and Colombia through most of Argentina down to Ventania, during latest Cambrian and Middle Ordovician times. The Ross Orogen (Stump, 1995; Myrow et al., 2001) continues to the present east from Patagonia all along the Transantarctic Mountains and Australia, and has a latest Cambrian to Early Ordovician magmatic arc. The Ventania early Paleozoic basin is devoid of any magmatic activity in these intervals, representing a passive continental margin. The tectonic causes of such differences are beyond the present research.

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Figure captions

Figure 1: Location of the Ventania and Tandilia systems in the province of Buenos Aires, localities mentioned in the text, and main basement provinces of central Argentina and Uruguay (based on Ramos, 2009 and Cingolani, 2011).

Figure 2: Main geological features of the Ventania System in the province of Buenos Aires. Numbers indicate the samples with detrital zircon U/Pb Laser ablation analyses (geology after Schiller, 1930; Harrington, 1947; Suero, 1972).

Figure 3: Main basement exposures of the Ventania System with available ages based on Varela et al. (1987), Rapela et al. (2003), Rapela and Kostadinoff (2005), and Tohver et al. (2012).

Figure 4: Stratigraphic column of the Paleozoic sedimentary rocks of the Ventania System (based on Harrington, 1947), with the stratigraphic positions of the analyzed samples. Paleocurrents after Reinoso (1968), Andreis and Cladera (1992), and López Gamundí and Rossello (1998).

Figure 5: Structural cross section of the Gondwanides of northern Patagonia restored for the end of the Paleozoic. The hinterland region developed in present Somún Cura Massif with exhumed late Paleozoic arc-granitoids is shown as well as the Ventania System with the fold and thrust belt and associated Claromecó Basin (based on Von Gosen et al., 1991; Tomezzoli and Cristallini, 1998; Ploskiewicz, 1999; Ramos, 2008; Pángaro and Ramos, 2012). The location of potential sutures among Patagonia, Tandilia and Cortijo terranes, as well as the Tandilia magmatic arc further north, are indicated after Teruggi et al. (1988), Max et al. (1999), Ramos, (2008) and Cingolani (2011).

Figure 6: a) Detail of the sample site; b) U-Pb frequency plot ages from zircons of a paragneiss (sample VE-02) of the metamorphic basement in the eastern slope of Cerro Pan de Azúcar, western Sierra de Curamalal (see location in Fig. 2).

Figure 7: a) Tectonic lense of mylonitic granite within quartzite layers of La Lola Formation; b) LA-ICP-MS from concordant zircons of this mylonitic granite (sample SLV-VE-04, see location in Fig. 2 and analytical data in the supplementary material).

Figure 8: U/Pb frequency plot ages from detrital zircons of the Curamalal Group: SLV-VE-03 from a quartzite clast of the basal conglomerate of the La Lola Formation, and SLV-VE-05, quartzitic sandstones interfingered in the upper part of the conglomerates; SLV-VE-09 from Mascota Formation from Cerro Colorado area; SLV-VE-10 from Mascota Formation east of Tornquist (location in Fig. 2).

Figure 9: U/Pb frequency plot ages from detrital zircons of lower part of the Ventana Group. Note the up-sequence decrease of the Paleoproterozoic ages (sample location in Fig. 2) and clear dominance of Late Neoproterozoic to Cambrian zircons.

Figure 10: U/Pb frequency plot ages from detrital zircons of upper part of the Ventana Group. Note that the samples from the Lolén Formation are more than 10 km distant, but have coherent patterns (see sample location in Fig. 2).

Figure 11: U/Pb frequency plot ages from detrital zircons of Balcarce Formation (samples FBA 264 and PMOG 233) based on Rapela et al. (2007, 2011). Note the important frequency peaks of Early Ordovician and Early Cambrian ages (location in Fig. 1).

Figure 12: Comparison of the detrital zircons provenance based on between Curamalal Group and lower and upper Ventana Group. Note the prominent frequency peak of Paleoproterozoic zircons in the Curamalal Group which is poorly developed in the Ventana Group, and the Famatinian peak (475 Ma) in upper Ventana Group, which does not occur in the older units. (FAM: Famatinian; BRAS: Brasiliano-Pampean; GRENV: Grenvillian, and TRANS: Transamazonian).

Figure 13: U/Pb frequency plot ages from detrital zircons of the fine sandstones and shales of Pillahuincó Group. Note the prominent frequency peaks of 322-304 Ma and the 291-282 Ma peaks may be correlated with igneous ages in the northern Somún Cura Massif (Chernicoff et al., 2012a, and cites therein).

Figure 14: U/Pb frequency plot ages from zircons from the northern Somún Cura Massif of the, a) Sedimentary cover of Sierra Grande Formation (Silurian-Devonian), and b) pre-Ordovician metasedimentary basement of the El Jagüelito, Mina Gonzalito, and Nahuel Niyeu Formations (after Pankhurst et al., 2006; Naipauer et al., 2011 and Uriz et al., 2011).

Figure 15: U/Pb frequency plot ages from detrital zircons of the fine sandstone of González Chaves locality. Note the prominent frequency peak at 316 Ma (Late Carboniferous).

Figure 16: Hf isotopic analyses of selected samples from the Ventania System. See supplementary material for sample number and figure 2 for location.

Figure 17: U/Pb frequency plot ages from zircons from the Sierra de La Ventana region obtained in the present study and the main orogenic events ((FAM: Famatinian; BRAS: Brasiliano-Pampean; GRENV: Grenvillian, and TRANS: Transamazonian).

Figure 18: U-Pb frequency plots of detrital zircons of Mogotes Formation. Note the different pattern with the Balcarce Formation of Fig. 11(after Rapela et al., 2007, 2011).

Figure 19: Paleogeography of the Ventania System through time; a) Cambrian-Ordovician; b) Silurian-Devonian; and c) late Paleozoic times. The Pampean Orogen depicted after Ramos (1988), Rapela et al. (1998), and Tohver et al. (2012); the Punta Mogotes Belt based on

Gaucher et al. (2005); the Gondwanides Orogen based on Ramos (2008) and Pángaro and Ramos (2012).

Figure 20: Location of the Ventania Fold Belt in the province of Buenos Aires, Argentina and its correlation with the Cape Fold Belt of South Africa as part of the Gondwanides. Tectonic framework of the pre-break up of Western Gondwana is based on the reconstruction of Pángaro and Ramos (2012).

A provenance study of the Paleozoic Ventania System (Argentina): transient complex sources from Western and Eastern Gondwana

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ABSTRACT

The U-Pb and Lu-Hf isotopic analyses of the different sedimentary sequences of the Ventania System, an old Paleozoic orogenic belt exposed in the southern region of the Río de la Plata Craton in the province of Buenos Aires, Argentina, provide new evidence for the understanding of the tectonic evolution of the western sector of the Gondwanides mountain belt. These ranges formed as result of the late Paleozoic collision of the Patagonia terrane against the continental margin of Gondwana. The provenance analysis together with the sedimentary paleocurrents confirm a dominant source from the Tandilia System, a Paleoproterozoic mountain belt formed during the amalgamation of the Río de la Plata Craton at about 1,800-2,200 Ma, and incorporated to Western Gondwana during the Brasiliano Orogeny at 550-530 Ma. The local dominant source at the base of the early Paleozoic changed to more distant supplies toward the top of the sequences, when is recorded an increasing participation of detritus from first, Cambrian (560-520 Ma) zircons from the Pampean Orogen, and later on Ordovician (480-460 Ma) zircons from the Famatinian Orogen. The detrital zircon patterns and the maximum age of the units shed light on some previous discrepancies in the early Paleozoic stratigraphy. The Balcarce Formation, an early Paleozoic sedimentary cover of the Tandilia metamorphic and igneous basement, shows striking differences when compared with the new data from the Ventania System. The two data-sets reveal different sources for the two regions. The late Paleozoic foreland basin deposits mark an abrupt change of 180º in the paleocurrent directions, in the petrographic composition of the sediments, and in the provenance of detrital zircons. These data indicate a southern provenance with the first evidence of Carboniferous and Permian magmatic zircons. The oldest Archean zircons together with the finding of clasts with archeocyathids support the provenance from Patagonia, which was derived from Eastern Gondwana. The U-Pb ages of the ash-fall tuffs in the Tunas Formation confirm the Early Permian age of the *Eurydesma*

Fauna in the Ventania System. The U-Pb data together with the Lu-Hf isotopic data enhance the comprehension of the tectonic evolution of the Ventania System as part of the larger Gondwanides Belt that amalgamated to Western Gondwana during Late Permian times with some independent pieces derived from Eastern Gondwana.

Keywords: Gondwanides, *Eurydesma* Fauna, Patagonia, collision, Famatinian and Pampean belts, zircon geochronology, tectonics.

1. Introduction

The Ventania System is a complex fold and thrust belt developed in the southwestern margin of Gondwana during late Paleozoic times (Keidel, 1916; Harrington, 1942,1947; Suero, 1972; Killmurray, 1975; Ramos 1986; Von Gosen et al., 1990). Since the early work of Du Toit (1927) it is assumed that Ventania was part of a larger system, which encompasses the Cape Fold Belt of South Africa. Du Toit (1937) named this orogen as the Gondwanides following pioneer work of Keidel (1921), and confirmed later by several works (see Veevers 2003, 2004; Milani and De Witt, 2008). In recent years many studies have analyzed the evolution of the Ventania System (Fig. 1) and the adjacent Claromecó foreland basin (Varela et al., 1987; Tomezzoli and Vilas, 1999; Tomezzoli and Cristallini, 1998; Dimieri et al., 2005; Cingolani 2005; Ramos and Kostadinoff, 2005). Current studies were able to track the extent of the Ventania Fold Belt in the offshore based on new seismic and geophysical data, depicting the Colorado Syntaxis (Pángaro and Ramos, 2012). This feature is the mirror image of the Cape Syntaxis and has similar characteristics (De Beer, 1995; Johnston, 2000).

FIGURE 1 NEAR HERE

There are two main problems in the tectonic interpretation of Ventania. The first problem is the stratigraphy of the early Paleozoic units as for some authors the Curamalal and Ventana Groups are the same unit tectonically repeated (Kilmurray, 1975; Tomezzoli and Cristallini, 2004), although most of the stratigraphers agree about the original sequences proposed by Harrington (1947) where Ventana is younger than Curamalal. The second problem, and perhaps the most important, is if the Ventania fold and thrust belt was originated by collision with an allochthonous Patagonia terrane in the late Paleozoic (Ramos, 1984, 2008; Kay et al., 1989; Sellés Martínez, 1989; Von Gosen, 2003; Chernicoff and Zappettini, 2004; among others), or was an intracratonic basin inverted by contraction and strike-slip tectonics related to oblique subduction further to the south along the present continental margin (Cobbold et al., 1991; López Gamundí et al., 1994, 1995; Rossello et al., 1997;

Dalziel et al., 2000; Gregori et al., 2008, among others). Some authors refute the allochthony of Patagonia based on paleogeographic and paleoclimatic reconstructions (López Gamundí and Rossello, 1998). The provenance analyses here presented shed light to both problems and provide a robust answer to previous uncertainties.

1.1 Location

The Ventania System is a 30 km wide mountain chain located in the southern part of the province of Buenos Aires in central eastern Argentina. It is surrounded by plains locally known as pampas, and has a length of 180 km with a W-NW trend (Fig. 2).

FIGURE 2 NEAR HERE

These mountains have a maximum height in the Cerro Tres Picos of 1,250 meters. There are several ranges as the Sierras de Curamalal, Ventana and Pillahuincó (Fig. 2), which expose the early and late Paleozoic sequences, tightly folded, with a constant northeast vergence (Harrington, 1947; Suero, 1972).

2. Stratigraphy

2.1 Metamorphic and igneous basement

There are very scarce exposures of the basement in the southwestern slope of the Sierra de Curamalal. Most of the authors recognized the igneous origin of these rocks, which are highly deformed, with typical cataclastic and mylonitic textures (Kilmurray, 1968; Gregori et al., 2005). There are also rhyolites exposed in different sectors further north (Figs. 2 and 3) and some isolated outcrops of granites exposed in Cerro Colorado and López Lecube quarries further to the west.

FIGURE 3 NEAR HERE

The available geochronological data indicate an age of 607 ± 5.2 Ma for the deformed granites of Cerro Corral (U-Pb SHRIMP ages in zircons, Rapela et al., 2003), that confirm old Rb-Sr ages of ~ 603-612 Ma of Varela and Cingolani (1976). New data of the Pan de Azúcar Granite yielded an age of 581 ± 8 Ma (U-Pb SHRIMP ages in zircons, Tohver et al., 2012). The postectonic granites in Cerro Colorado (531.1 ± 4.1 Ma and 523.8 ± 4 Ma), San Mario (524.3 ± 5.3 Ma), and Los Chilenos (533 ± 12 Ma), as well as the La Ermita Rhyolite (509 ± 5.3 Ma and 505 ± 18 Ma), were assigned to the Cambrian (Rapela et al., 2003; Tohver et al., 2012). The Agua Blanca Granite has an inheritance age of 2182 ± 18 Ma that indicates a Paleoproterozoic basement in the area as part of the Río de la Plata Craton (Tohver et al., 2012). The westernmost outcrops of López Lecube quarry yielded an age of 258.5 ± 1.9 Ma by U-Pb SHRIMP in zircons that corresponds to postectonic granites of the Gondwanide Orogeny and it is not part of the Ventania basement (Rapela and Kostadinoff, 2005).

The igneous rocks have been divided in two suites based on their composition and tectonic setting: a calcalkaline orogenic and collisional Neoproterozoic suite and a postorogenic extensional Cambrian suite (Gregori et al., 2005). The last episode was associated with a Cambrian rift by Rapela et al. (2003).

2.2 The Paleozoic sedimentary successions

The early Paleozoic sedimentary succession includes two sequences, the Curamalal and Ventania Groups (Fig. 4) deposited during Ordovician and Devonian times (Harrington, 1947; Sellés Martínez, 2001). The late Paleozoic is represented by the Pillahuincó Group (Fig. 4), which is mainly Cisuralian (Early Permian). The whole Paleozoic succession is around 4,500 m thick, with the two lowermost sequences measuring 2,400 m thick. The upper part of the succession documents a higher subsidence rate compared with the underlying part, but also a contrasting paleocurrent pattern, which varies from SW to SE, with strong NE prograding deltaic lobes in the uppermost part of the sedimentary section. The succession contains mainly sandstones, claystones and conglomerates in the lower part. However, glacial diamictites and glaciomarine deposits constitute a special type of coarse-grained deposits that document the late Paleozoic glaciation (Andreis et al., 1989).

The Curamalal Group, which represents the beginning of the sedimentary record in the basin, contains conglomerates with coarse-grained clasts in clast-supported to patchy sandy matrix-supported types, with beds up to 1.5 m in thickness and erosive to sharp bases in the lower part of La Lola Formation. Internally they contain well rounded quartzite clasts showing normal or rarely reverse gradation. The outcrops of the source area remain unknown but the almost monomict composition suggests a quartzite unit situated at a certain distance that allowed the well roundness of clasts by hyperconcentrated flows or diluted debris flows. Sandy deposits include different types of cross-bedding; some of them were interpreted as hummocky cross stratification by Zavala et al. (2000). However, they exhibit a unidirectional pattern and in all cases resemble more bidimensional subaqueous dunes. Giant cross-beds up to 4 m in amplitude are common in medium grained sandstones containing clay chips, and mud drapes. Thin beds show the same sedimentary structures and in cases depict clear bidirectional paleocurrents that document tidal control during the sedimentation. In the Ventana Group, the lower unit (Bravard Formation) has some fine conglomerates with a quartzitic composition of the clasts. The overlying Napostá Formation is well known for its ichnological content that includes *Skolithos*, *Arenicolites* and *Daedalus*. Abundant tidal features have been observed, including herringbone crossbeds and mud drapes. The Lolén Formation is the uppermost unit of the Ventana Group and exhibits more variability in clast composition and contains brachiopods and lycophytid plant remains as *Haplostigma* that have been used to date the top part in the Middle Devonian (Cingolani et al., 2002).

A paraconformity separates the Ventana from the overlying Pillahuincó Group, deposited between the latest Carboniferous and the Cisuralian (Early Permian) indicating a prolonged hiatus spanning the Upper Devonian to the middle Pennsylvanian. This group is crucial to understand the evolution of the Ventana System because a thick succession was deposited in a relatively short time. This fact documents a high subsidence rate related to a foreland basin which contrasts with the stable depositional settings for the underlying groups (Fig. 4).

FIGURE 4 NEAR HERE

The Sauce Grande Formation rests unconformably over the Ventana Group and is a glaciomarine succession that documents the late Paleozoic glaciation in the Atlantic basins of Argentina. The Sauce Grande Formation represents Late Carboniferous-earliest Permian (Cisuralian) glacial deposits 400 m thick that are also recognized in the Claromecó Basin, which correlates with the Dwyka Formation in the Karoo Basin. This correlation of glacial deposits is known since the pioneer studies of Keidel (1916) and Du Toit (1927). The Malvinas /Falkland Islands also record equivalent glacial deposits in the Lafonia Formation (Frakes and Crowell, 1969; Bellosi and Jalfín, 1984, 1989). The pre-breakup position of the Malvinas (Falkland) Islands based on the early reconstruction of Martin et al. (1981) is south of the Karoo Basin and off the coast of South Africa. Recent studies of the Sauce Grande tillites have found reworked limestone clasts with archeocyathids that indicate a Patagonian derivation from an Antarctic source (González et al., 2011, 2013). Some paleomagnetic studies support a position further to the east, but need a 180º rotation to match the data (Mitchell et al., 1986). Based on these data, López Gamundí and Rossello (1998) conclude that the paleoice flow directions of the Dwyka and the Lafonia glacial sequences were similar, but different from the south-north direction of the Sauce Grande tillites.

The Piedra Azul Formation represents early postglacial transgressive deposits, which are overlain by the marine Bonete Formation. These deposits represent the maximum flooding of the basin in the Early Permian and bear the typical Gondwana fauna of *Eurydesma* (Harrington, 1955). This thick-shelled bivalve *Eurydesma* was a cold-resistant and immobile, epifaunal suspension feeder that dominated marine environment of Gondwana in the Early

Permian (Jones et al., 2006). Above these levels, intertidal plains deposits bear an abundant *Glossopteris* flora, a widespread typical Gondwana flora also known in the Early Permian of Africa, India, Antarctica and Australia (Benedetto, 2010). The upper unit of the group is the Tunas Formation, represented by prodeltaic to subaerial delta plain deposits with paleocurrents that indicate a source area situated to the south-southwest. Very well preserved ichnofossils as *Cochlichnus* and *Gordia* have been observed in the Las Mostazas quarry and cross-bedding exposures that confirm the paleocurrent pattern suggested by Andreis and Cladera (1992) for the unit.

Recent studies on the microflora of several wells of the offshore Claromecó Basin have identified on palynological bases almost the entire Permian sequence, including for the first time Lopingian assemblages (Balarino, 2012).

3. Structure

The structure of the Ventania fold and thrust belt was a matter of discussion since the early work of Harrington (1947). Based on the extraordinary ductile folding of the early Paleozoic quartzites described by Keidel (1916) and Du Toit (1927), most of the authors interpreted the structure as a dominant fold-type (Harrington, 1970). Detailed surveys done by Varela et al. (1987), Von Gosen et al. (1990, 1991) and Tomezzoli and Cristallini (1998) recognized the main thrusts and confirmed the old thrust hypothesis of Schiller (1930). Seismic studies performed in the offshore depict those thrusts and their relationship with lower to middle crustal deformed rocks exposed further south in the Somún Curá Massif in the hinterland region (Pángaro and Ramos, 2012). These authors have shown that the Ventania foreland fold and thrust belt is separated from the hinterland by an area of minimum deformation interpreted as a late Paleozoic piggy-back basin. This basin is now beneath the Colorado Basin, a Jurassic to Early Cretaceous aulacogenic basin developed above the suture between Patagonia and Western Gondwana. This suture previously proposed by different authors in land, has been depicted in the offshore by a magnetic anomaly interpreted as evidence of mafic and ultramafic rocks by Max et al. (1999) and Ghidella et al. (1995).

FIGURE 5 NEAR HERE

The age of deformation of the Ventania fold and thrust belt is constrained in the Early Permian based on the growth strata of Tunas Formation described by López Gamundí et al. (1995), the paleomagnetic evidence of syndeformational magnetization of Tomezzoli and Vilas (1999), and the illite recrystallization age of Buggish (1987).

4. Material and methods

A systematic field reconnaissance was made of the different Paleozoic units and the metamorphic basement, analyzing their main sedimentological and structural characteristics. A large volume of 24 samples from Curamalal, Ventana and Pillahuincó Groups with detailed sampling in the uppermost tuff layers were collected. The location of the samples is indicated in Figs. 2 and 4 and the sample list and the U-Pb and Lu-Hf analytical data are presented in the electronic supplementary material. Petrographic and geochemistry information of sedimentary and tuff samples can be found in Alessandretti et al. (2013).

Samples were crushed and milled using jaw crusher. Then, the zircons were separated by conventional procedures using heavy liquids and an isodynamic magnetic separator after concentration by hand panning. The most clear and inclusion-free zircons from the least magnetic fractions were handpicked. All zircons were mounted in epoxy in 2.5-cm-diameter circular grain mounts and polished until the zircons were just revealed. Images of zircons were obtained using the optical microscope (Leica MZ 125) and back-scatter electron microscope (Jeol JSM 5800) at the Eletron Microscope Center of the Federal University of Río Grande do Sul, but are only illustrated when necessary to support the interpretation. Zircon grains were dated with laser ablation microprobe (New Wave UP213) coupled to a MC-ICP-MS (Neptune) at the Geochronology Laboratory of the University of Brasilia.

U-Pb isotope data were acquired using static mode with spot size of 30 um in diameter. Laser-induced elemental fractional and instrumental mass discrimination were corrected by the reference zircon (GJ-1) (Jackson et al., 2004), following the measurement of two GJ-1 analyses to every four sample zircon spots. The collector configuration used for simultaneous measurements of Th, U, Pb and Hg isotopes was ^{238}U, ^{232}Th and ^{208}Pb in faraday cups (H4, H2 and L4, respectively) and ^{207}Pb, ^{206}Pb, $^{204}Pb^{+}Hg$ and ^{202}Hg in Multiplier Ion Counting (MIC) channels attached to the L4 (MICs IC5, IC4, IC3 and IC2, respectively). The external error is calculated after propagation error of the GJ-1 mean and the individual sample zircon (or spot). A detailed description of analytical conditions and data reduction can be found in Chemale et al. (2012). Isoplot 3 software (Ludwig, 2003) was used to generate the concordia diagrams and histograms. For the concordia age calculations and frequency histograms, only the analyses with 100 ± 10% of concordance were used. All of the calculated ages are reported at the 95% confidence level.

Lu, Yb and Hf isotopes in single zircon crystals were acquired using static mode with spot size of 50 um in diameter. The laser spot was driven to the same site or zircon phase dated by the U-Pb method. To minimize aerosol deposition around the ablation pit and to improve transport efficiency, He was flushed along with Ar into the ablation cell. The Faraday collectors were arranged the following way: ^{171}Yb (low 4), ^{173}Yb (low 3), ^{174}Hf (low 2), ^{175}Lu (low 1), ^{176}(Hf+Yb+Lu) (Center), ^{177}Hf (high 1), ^{178}Hf (high 2) and ^{179}Hf (high 3). Detail of operation analytical conditions can be found in Chemale et al. (2011a). To correct for isobaric interferences of Lu and Yb isotopes on mass 176, the isotopes ^{171}Yb, ^{173}Yb and ^{175}Lu were simultaneously monitored during the analyses. The ^{176}Lu and ^{176}Yb concentrations were calculated using a $^{176}Lu/^{175}Lu$ ratio of 0.026549 and a $^{173}Yb/^{171}Yb$ ratio of 1.123456 (Chu et al., 2002; Thirwall and Walder, 1995). Correction of Hf isotopic ratios for instrumental mass bias was based on an exponential law and used the reference $^{179}Hf/^{177}Hf$ value of 0.7325 (Patchett et al., 1981). Each analytical session included determinations of the βHf and βYb factors for each individual spot. The mass bias behavior of Lu was assumed to follow that of Yb.

Lu-Hf model ages (TDM) of zircon grains were calculated based on a depleted mantle source with $^{176}Hf/^{177}Hf = 0.28325$ and $^{176}Lu/^{177}Hf = 0.0388$ (Andersen et al., 2009). We also calculated model ages of individual zircons for felsic and mafic sources assuming the following parental magma compositions: mafic, Lu/Hf = 0.022; felsic, Lu/Hf = 0.010 (Pietranik et al., 2008). The values of εHf(t) were calculated assuming the CHUR $^{176}Hf/^{177}Hf$ ratio of 0.282785 (Bouvier et al., 2008) and the decay constant of $\lambda^{176}Lu = 1.867 \times 10-11/a$ (Söderlund et al., 2004).

5. Results

5.1 Pan de Azúcar mylonitic belt

This belt of highly deformed metamorphic rock was identified as the Pan de Azúcar Formation by Cuerda et al. (1975) in the eastern slope of the Cerro Pan de Azúcar beneath the contact with the La Lola Formation. Previous authors interpreted rocks similar to sample SLV-VE 02 (Fig. 6a), as derived from igneous protolith, whereas others as Von Gosen et al. (1990) described paragneisses from these exposures. We interpreted this sample based on the internal textures seen in the back-scattering image and the Th/U ratio in each dated zircon (Fig. 6) as gneiss of igneous origin; apparently deformational and metamorphic process has not affected the detrital zircons. One of the main frequency peaks (Fig. 6b) coincides with the ages of the Cambrian suite proposed by Gregori et al. (2005), although the major frequency peak clearly indicates a Paleoproterozoic component in this rock (Fig. 6 a-b), similar to the age interpreted by Tohver et al. (2012) as a basement inheritance in the granites of Agua Blanca. These ages are between the main magmatic activity (2250–2120 Ma) and the collisional overprint (2100–2080 Ma) recorded in the basement of Tandilia by Cingolani (2011). There are also some few older and younger zircons.

FIGURE 6 NEAR HERE

It is possible that the orthogneiss affected by a post-540 Ma contractional deformation may correlate with the main orogeny of the Saldania Belt recognized by Chemale et al. (2011b) in southernmost Africa. In a Gondwana plate tectonic context, a subduction zone has been proposed at the southern margin of the Kalahari plate, close to the Precambrian-Cambrian boundary, as suggested by Rozendaal et al. (1999), and its extension in the Sierra de la Ventana Orogen (Chemale et al., 2011b). Following Gregori et al. (2005) deformation in Sierra de la Ventana should be older than 533 Ma, which is the age of the postectonic granites. The age pattern of this orthogneiss shows different inherited zircons.

However, another possible alternative would be to consider that sample a highly deformed quartzite of La Lola Formation, due to the similar pattern of zircon ages in comparison with other samples of this unit (see SLV-VE 05 in Fig. 8). This interpretation would indicate that the main deformation of this sample could be Gondwanian in age, instead of Brasiliano.

5.2 Curamalal Group

The base of this group is represented by La Lola Formation, which is nicely exposed in the eastern slope of Cerro Pan de Azúcar (Andreis and López Gamundí, 1989). There is a 30 m thick orthoconglomerate dominantly formed by clasts of quartzite (SLV-VE-03). These conglomerates are covered by quartzitic sandstones (SLV-VE-05). It is interesting to remark that tectonically interposed with these quartzites, east of the Abra Mayer, there are some lenses of mylonitic granite. One of these lenses with calcalkaline composition has a unique frequency peak at 541.0 ± 8.4 Ma within the range of basement granites (Figs. 7 a,b).

FIGURE 7 NEAR HERE

The sedimentary facies and provenance of these conglomerates have been studied by Zavala et al. (2000), who recognized a proximal shelfal environment in a flood- dominated fan delta system developed from the Tandilia area. However, the good mineralogical maturity almost dominated by quartzite clasts up to 25 cm in size and good roundness suggest that the source area was closer, indicating that the present day quartzite outcrops of Tandilia extended well into the south. The pattern of detrital zircons of both samples (see samples SLV-03 and SLV-05 in Fig. 8) confirms the proposal of Zavala et al. (2000), and shows that the main peak around 2050-2170 Ma corresponds with the maximum magmatic activity of the Tandilia arc according with Cingolani (2011). The lower levels of La Lola Formation have minor Cambrian peaks at 545 and 520 Ma, which indicate exhumation of the post-tectonic rocks in the surrounding area.

The sample SLV-VE-09 is from the lower part of Mascota Formation from Sierra de Chasicó, which is unconformably overlying the Cerro Colorado Granite (Harrington, 1968).The maximum age of sedimentation is 534 Ma as indicated by the highest frequency peak (Fig. 8). This quartzite has been interpreted as being older than the Los Chilenos Granite (533 Ma, Thover et al, 2012), but the present data may favor that the Mascota Formation is younger than the granite based on field observations that coincide with criteria used in the Harrington (1947) map. The sample SLV-VE-10 was collected east of Tornquist (see Fig. 2) from the Mascota Formation, and presents similar age distribution pattern as sample SLV-VE-09. In these samples the Paleoproterozoic sources start decreasing and some minor Mesoproterozoic peaks are visible.

The analysis of the older units of the Curamalal Group shows an interesting trend in their sources (Fig. 8) with a continuous decrease in the Paleoproterozoic provenance from the La Lola Formation at the base of the Curamalal Group upwards, parallels the increase of the Cambrian zircons towards the top of the Mascota Formation. This increase of Cambrian peaks of 545 and 534 Ma may indicate a potential derivation from Eastern Sierras Pampeanas (see Fig. 1) which has been exhumed at that time. The input of Grenville-age zircons around 1200 Ma in the Mascota Formation is somewhat older to be derived from the Namaqua belt of western Kalahari craton, but similar ages recorded in the detrital zircons of the Punta Mogotes basement from a borehole core, were interpreted as derived from the western Kaapval Craton by Rapela et al. (2011). Similar age zircons were also recognized in the Cerro Largo Formation from Tandilia by Gaucher et al. (2008). However, the most potential Grenville-age source based on the rank of ages observed could be the Eastern Sierras Pampeanas where ages from 1000 to 1200 Ma are common (Escayola et al., 2007).

FIGURE 8 NEAR HERE

5.3 Ventana Group

The different units of the Ventana Group are conformably deposited on the Curamalal Group. The provenance analysis based on the detrital zircons shows as the most important frequency peak Brasiliano ages around (564-540 Ma) (Fig. 9). The Paleoproterozoic ages of Tandilia are less significant and tend to disappear. Some minor evidence of Ordovician zircons (482 Ma) is seen in the Napostá Formation, as well as in the Bravard Formation, which will be dominant in the upper part of the sequence. Uriz et al. (2012) analyzed a sample from the Napostá Formation and detected an important frequency peak of 473 Ma, partially equivalent to the Ordovician peak found by us.

FIGURE 9 NEAR HERE

The zircons of Providencia Formation follow the same trend of the lower section of the Ventana Group (compare with Fig. 10), but an important change is recorded in the Lolén Formation, already recognized by Uriz et al. (2011). There, an important peak of Early Ordovician zircons is seen for the first time (490 Ma), as well as increasingly old Brasiliano ages (641-612 Ma). The first occurrence of an Ordovician frequency peak in the Lolén Formation is very similar to the one recognized by Rapela et al. (2007) further to the northeast, in somewhat equivalent nearshore quartzitic sandstones of the Balcarce Formation. This unit is exposed nearby the town of Balcarce (see location in Fig.1), and is unconformably deposited on the metamorphic basement of the Tandilia System and pinch out over the glacial diamictites of the Volcán Formation (Pazos et al., 2008).

There are not precise biostratigraphic constraints for its age, but it was assumed to be broadly between Ordovician and Early Silurian based on its trace fossils (Borrello, 1966). According to Rapela et al. (2007) who reported detrital zircon ages as young as 475–480 Ma, the Balcarce Formation is not older than Early Ordovician, suggesting a Late Ordovician to Early Silurian sedimentation age. Moreover, the trace fossils described by Seilacher et al. (2002) from several localities, differ significantly from the familiar Arenigian suite. Rather, they resemble the Lower Silurian ichnofaunas of Libya, Chad and Benin, with trilobite tunnels (*Cruziana ancora*), palmate *Arthrophycus alleghaniensis* and *Gyrochorte zigzag* as shared elements (Seilacher et al., 2002), but also *Diplocraterion* conforming monospecific suites has been observed. These authors therefore assigned an Early Silurian age to the Balcarce Formation and they mentioned that the ichnofauna possibly signals an even further southward extension of the Malvinocaffric Province. It is interesting to remark that the matrix of the Cerro Volcán diamictites, a four meters thick level underlying typical quartzites of the Balcarce Formation, has detrital zircons 485-490 Ma old and a maximum peak of 530 Ma (Zimmermann and Spalletti, 2009; Van Staden et al., 2010). These data reinforce the assignation to the Silurian of this unit since these glacial deposits could be interpreted as representing the Hirnantian glaciation of the end of the Ordovician.

FIGURE 10 NEAR HERE

The siliciclastic deposits of the Balcarce Formation were developed in a nearshore and inner shelf environment on a tide dominated platform, affected by storm events in a marine system that was open to the south based on the pattern of progradational clinoforms (Poiré et al., 2003). Paleocurrents indicate a north dominant sediment supply for the western and central areas of the Balcarce Formation, while in the eastern part of the basin the main transport directions are east-west oriented (Teruggi, 1964).

The Lolén Formation is the only unit bearing marine invertebrate fossils in the lower Paleozoic sequences of the Ventania System and the occurrence of brachiopods is known since the early work of Harrington (1947). Benedetto (2010) analyzed these brachiopods and assigned them to *Cryptonella*, an Early Devonian genus. Based on the age of these brachiopods, Newton and Cingolani (1990) correlated the Lolén Formation with the Bokkeveld Group of the Cape Fold Belt, confirming the correlation of Du Toit (1937).

Therefore, a partial correlation between Lolén and Balcarce Formations is proposed based on the detrital zircon pattern (Fig. 11), not only the Early Ordovician sources, but also the range of Brasiliano ages (640-610 Ma), which are older than previous ages recorded in the early Paleozoic of Ventania. The Ordovician provenance of both units should come from the northwest, derived from the Western Sierras Pampeanas Orogen, the only sector that records plutonic and volcanic rocks of Famatinian age at these latitudes (Ramos et al., 2010).

FIGURE 11 NEAR HERE

5.4 Comparison between the Curamalal and the Ventana Groups

Kilmurray (1975) proposed that both groups were result of a tectonic repetition based on an apparent similarity between the quartzitic sandstones. Tomezzoli and Cristallini (2004) formalized Kilmurray' hypothesis in their study of the structure of Sierras de la Ventana and Curamalal through a viable structural section of these ranges, which shows both groups as a single sequence tectonically repeated. However, our present results indicate a striking difference between the detrital zircon patterns of both groups. When the pattern of La Lola Formation (Fig. 8) is compared with the lower part of the Ventana Group, in particular the Bravard and Napostá Formations (Fig. 9), it is clear the absence of Paleoproterozoic population in these units (Fig. 12).

FIGURE 12 NEAR HERE

The Curamalal Group begins with a high frequency peak of Paleoproterozoic ages with a minor peak in the Brasiliano ages, showing exhumation of the Tandilia rocks at that time. An irregular exposed topography extended to the south of the present ranges that explains the zircon detrital pattern and facies of the conglomerates of La Lola Formation. The absence of carbonate clasts contrasts with the abundance of carbonates in the Neoproterozoic sedimentary cover of Tandilia. This could be explained by a combination of climate and transport that favored resistant lithologies over carbonates.

The maximum frequency in the base of Ventana Group shows exhumation of the Brasiliano rocks and almost no existence of Paleoproterozoic ages, contrasting with the Curamalal Group pattern. These different patterns also characterize the upper part of the Curamalal and Ventana Groups (see Figs. 8 and 10). The major difference is the first occurrence of Ordovician zircons which is exclusive of the Ventana Group and Balcarce Formation (Fig. 12). The Cerro Largo Formation in the Tandilia System has been considered correlatable with the Balcarce Formation, but Pazos and Rapalini (2011) kept the unit in the Precambrian as traditionally suggested in agreement with the detrital pattern of this unit.

These evidences permit to discard the correlation of both groups and revaluate the early proposed stratigraphy of Harrington (1947) which, at the present level of knowledge, is the one that best explains the data.

5.5 Pillahuincó Group

The late Paleozoic deposits of this group indicate the inception of a foreland basin stage in the evolution of the Ventania System (Ramos, 1984; López Gamundí and Rossello, 1992, among others). The unconformity that separates the Ventana and Pillahuincó Group, although quite elusive in the structural evidence (López Gamundí and Rossello, 1993), coincides with an important change in the petrography of the sandstones (Andreis and Cladera, 1992). Compositionally, the initial passive margin phase of the continental platform was characterized by quartz-rich, craton-derived detritus, but was followed by a foreland phase that shows a paleocurrent reversal and dominance of arc/foldbelt-derived material (López Gamundí and Rossello, 1998).

The recent finding of subrounded clasts with archeocyathids in the glaciomarine Sauce Grande Formation in Ventania derived from Antarctica (González et al., 2013) as well as in the Lafonia (Fitzroy) tillites in the Malvinas (Falkland) Islands, and in the Dwyka tillites (South Africa) support the correlation of these glacial deposits (Veevers and Saeed, 2013).

The analysis of the detrital zircon provenance of the late Paleozoic deposits (Fig. 13) shows several differences regarding the early Paleozoic sequences. The first important difference is that in the Sauce Grande Formation there are Archean zircons with conspicuous ages of 2729, 2990 and 3200 Ma, not seen in the lower Paleozoic sequence of Ventania. As the Tandil area shows strong evidence supporting the derivation from a Neoarchean crust (less than 2.65 Ga) as inferred by Cingolani (2011) based on the positive εHf data, those zircons together with the reversal of the paleocurrents indicate a different old cratonic source south of the study area. The second striking difference is the frequency peaks of 319-322 Ma in the Piedra Azul, Bonete, and Tunas formations that are characteristic from northern Patagonia, as well as the Silurian 432-417 Ma peaks, similar to the age recorded in Los Pájaros Island in northeastern Patagonia granites (Nuñez et al., 1975). The Piedra Azul Formation represents early postglacial transgressive deposits, which are overlain by the marine deposits of the Bonete Formation bearing the typical *Eurydesma* Gondwana fauna (Harrington, 1955), which represent the maximum flooding of the basins in the Early Permian. Above this fauna, some intertidal plain deposits bear an abundant *Glossopteris* flora, a typical Gondwana flora also known in the Early Permian of Africa, India, Antarctica and Australia (Benedetto, 2010).

FIGURE 13 NEAR HERE

The other frequency peaks (Fig. 13) are common ages in the crystalline basement of northern Somún Cura Massif. Zircons ages of Grenvillian (1100-1000 Ma), Brasiliano (584-532 Ma), and Ordovician (491-450) have been widely reported by Pankhurst et al. (2001, 2006); Ramos (2008), and Naipauer et al. (2010). This spectrum of frequency peaks is duplicated by the detrital zircons of the Sierra Grande Formation (Fig. 14), a Siluro-Devonian sedimentary cover unconformably deposited over the crystalline basement (Uriz et al., 2011).

FIGURE 14 NEAR HERE

There are some minor outcrops of sandstones near González Chaves, 113 km east of the Coronel Pringles in the middle of the Claromecó Basin (Figs. 1 and 2) (Llambías and Prozzi, 1975). Monteverde (1937) correlated these sandstones with the quartzites of Las Mostazas in the southeastern part of the Sierra de Pillahuincó (Tunas Formation). Furque (1965) described similar quartzites with rest of lepidophytes in a similar setting 50 km further east of González Chaves. A representative sample of these outcrops near González Chaves was dated (SLV-VE 24, Fig. 15).

FIGURE 15 NEAR HERE

The detrital zircon ages show two important frequency peaks, one in the Late Carboniferous (316 Ma), and another in the Early Devonian (406 Ma), a pattern characteristic of other Pillahuincó Group rocks (Fig. 13). It is important to note that the youngest sedimentary deposits exposed in the Claromecó Basin belong to this group, although Tomezzoli and Vilas (1997) and Tomezzoli (2009) indicated that these exposures are consistent with an Early to Late Permian age based on paleomagnetic grounds. This has been challenged by Domeier et al. (2011), who supported younger ages based on recent dating in Sierra Chica.

5.6 The Permian ash-fall tuffs of Tunas Formation

The occurrence of pyroclastic levels in the Tunas Formation first described by Iñiguez et al. (1988) is one of the best time-lines to constrain the age of the late Paleozoic sequences. The age of this unit was based on the *Eurydesma* Fauna and the *Glossopteris* Flora in the deposits underlying the Tunas Formation, both of Early Permian age (Harrington 1947, 1955; Benedetto, 2010). The upper part of the Tunas Formation bears the *Gangamopteris* Flora of latest Early Permian age according to Archangelsky and Cúneo (1984).

Several ash-fall tuffs levels were sampled in the Abra del Despeñadero, in the southeastern sector of Sierra de Pillahuincó. There, thin beds of smectite-rich claystones have been identified in the predominantly sandy upper half of the Tunas Formation and are characterized by abundant vitroclasts and fragments of vitric tuffs (Iñiguez et al., 1988; López Gamundí, 2006). The dated zircons of three beds yielded an average ^{206}Pb/^{238}U age of 304 Ma, that corresponds to some sort of mixing of zircons formed between 280 and 288 Ma (interpreted as juvenile zircons based on εHf data) and zircons formed between 290 to 315 Ma. Alessandreti et al. (2013) presented for the same SLV-VE-19 sample an U-Pb in situ LA-MC-ICPMS age of 284 ± 15 Ma.

One tuff layer of the same outcrop as the samples SLV-VE-19, 20 and 21 has been dated by Tohver et al. (2008) and yielded an age of 282.4 ± 2.8 Ma (U-Pb-SHRIMP). A similar age of 280.9 ± 1.9 Ma (U-Pb SHRIMP) was recently reported by López-Gamundí et al. (2013) on volcanic zircons from a tuff layer in the uppermost section of the Tunas Formation. Both SHRIMP U-Pb ages are more reliable.

Based on these data, it is assumed that the tuff layers with the younger frequency peaks, have crystallization ages close to 280 and 288 Ma (see Fig. 13), indicating a middle Early Permian age, consistent with SHRIMP recent ages and the biochron of the fossil fauna and flora.

The intimate relationship between volcanic activity inboard of the paleo-Pacific margin, deformation in the adjacent orogenic belt, and subsidence and sedimentation in the contiguous foreland basin led López Gamundí and Rossello (1998) to interpret the magmatic belt as an Andean-type margin related to the paleo-Pacific margin. This proposal was followed by Turner (1999) and Dalziel et al. (2000), among others. The main problem of this interpretation is that the magmatic arc, as pointed out by Turner (1999) was located over 1,000 km away from the continental margin. No subduction related magmatism can exist that far from the margin, even if a flat-subduction is proposed. A magmatic arc belt cannot be developed further than 300-400 km away of the trench. Some authors proposed an intermediate location (Pankhurst et al., 2006), but still inconsistent with a magmatic arc along northern Patagonia in the Somún Cura Massif. Recent work of Chernicoff et al. (2012 a) demonstrates that a series of calc-alkaline orthogneisses are Permian in age and represent the relicts of the late Paleozoic magmatic arc developed in the northern Patagonia as proposed by different authors (Ramos, 2008, and cites therein).

Although, the classic interpretation to explain the pyroclastic levels in the Las Tunas Formation and in the Paraná Basin in southern Brazil is a source in the Choiyoi volcanic rocks (Kay et al., 1989), we favor a more proximal origin. Based on U-Pb SHRIMP ages around 281.4 ± 2.5 Ma from Los Reyunos Formation, lower section of the Choiyoi volcanic rocks, Rocha Campos et al. (2011) correlated these rocks with the older tuffs of the Paraná Basin. This correlation is supported by the northeast paleocurrent directions measured in the aeolian sandstones of Los Reyunos Formation by Pazos et al. (2011). However, if we want to use the same Choiyoi source for the pyroclastic deposits of Las Tunas Formation, even with similar ages, the dominant winds should be to the southeast, different from what was measured in the Choiyoi intercalated aeolian sandstones. The distance is closer from Somún Cura, the ages are similar, and the required paleowind direction is also to the northeast. Therefore, we prefer as a potential source the Early Permian widespread calderas and rhyolites of the same age found in the Somún Cura Massif. This interpretation also explains the source of the large amount of volcanic debris and igneous Carboniferous detrital zircons found in Las Tunas Formation.

6. Lu-Hf-Isotope analyses

Hf isotopes have been analyzed in 65 detrital zircons of samples from the Cambrian paragneiss (SLV-VE-02), and from the Lolén (SLVE-01) and Tunas (SLV-VE 20/21) Formations, in order to understand the characteristics of the source region (Fig. 16).

Several zircons from different representative sources have been analyzed in the sample of metamorphic basement (SLV-VE-02). Two Neoarchean zircons yielded negative values of $\varepsilon Hf(t)$ of -7.06 and -5.11 and TDM ages 2.98 and 3.22 Ga; one Mesoarchean zircon has an $\varepsilon Hf(t)$ of +1.73 with a TDM age of 3.06 Ga. The Paleoproterozoic source was analyzed in eight zircons, which yielded values of $\varepsilon Hf(t)$ between + 2.19 and -1.8. These values are typical of the juvenile arc granitoids of Tandilia (Fig. 16). The younger zircon of 1,782 Ma gave a quite negative value of -5.57 far from the previous ones; the TDM ages yielded between 2.57 and 2.19 Ga. This 1.78 Ga corresponds to the age of post-collisional granites in the Tandilia area (Cingolani, 2011), which clearly shows important crustal recycling (Fig. 16).

A few Mesoproterozoic zircons analyzed have disperse εHf(t) values from -14.8 and an TDM age of 2.05 Ga, to εHf(t) positives and TDM ages 1.87 and 1.62 Ga. The other well represented fraction is the Neoproterozoic (ca. 552 Ma) with εHf(t) values between -5.4 and -3.08 with similar TDM Mesoproterozoic ages between 1.34 and 1.26 Ga within the range described for the Sierras Pampeanas by Dahlquist et al. (2013).

FIGURE 16 NEAR HERE

In the Lolén Formation 35 zircons have been analyzed from sample (SL-VE-01) representing different sources (Fig. 16). The Paleoproterozoic source yielded values of εHf(t) of +2.86 and -1.57 and TDM ages between 2.49 and 2.31 Ga; however, a few zircons yielded εHf(t) values more negatives between -4.04 and -20.68 and older TDM ages between 2.81 and 2.59 Ga. Grenville-age zircons yielded similar εHf(t) values, but highly positive, between +12.75 and +7.22, and model ages close to the crystallization ages, between 1.27 and 1.50 Ga, showing their juvenile nature (Fig. 16). The Neoproterozoic zircons have variable characteristics with a group of highly negative εHf(t) values between -35.17 and -18.22 and model ages between 2.52 and 1.80 Ga; a second group has less negative εHf(t) values between -5.64 and -0.73 and younger TDM ages between 1.16 and 1.35 Ga. The Paleozoic sources can also be grouped in two sets, a group of Cambrian, Ordovician, and Devonian zircons with very negative εHf(t) values (-43.93 and -11.09) and TDM ages between 2.61 and 1.47 Ga; the other group has more positive εHf(t) values (+28.71 and -5.01) and younger TDM ages (1.26 and 1. 03 Ga).

The last samples from the Tunas Formation (SLV-VE 20/21), which have late Paleozoic zircons (290-340 Ma) yielded εHf(t) values between +10.51 and -1.87, with TDM ages restricted between 0.98 and 0.80 Ga. These zircons probably belong to the juvenile magmatic arc of northern Patagonia (see Ramos, 2008). There is also a crystal with highly negative εHf(t) value (-30.82) and a model age of 1.82 Ga, very distinct of the rest of the group (Fig. 16). Those highly negative values were also recorded by Chernicoff et al. (2012 a).

7. Analyses of the provenance

Based on the previous detrital zircon analyses, together with conventional petrographic and paleocurrents studies performed by Reinoso (1968), Andreis and Cladera (1992) and López Gamundí and Rossello (1998), among others, a tentative paleogeography can be reconstructed along a series of stages.

7.1 Cambrian-Ordovician

The provenance at this stage looks simple and conditioned by the basement exposed at that time. The Paleoproterozoic of Tandilia is the main source, a clear indication that these mountains were conspicuous at that time. Through time, the Pampean basement of Ventania starts being exhumed and Cambrian and Neoproterozoic granitoids became the main source (Fig. 17).

FIGURE 17 NEAR HERE

The proposed paleogeography shows an old mountain system being exhumed, represented by the Tandilia mountains, surrounded to the west (present coordinates) by the Pampean orogenic belt of Eastern Sierras Pampeanas. The exhumation of this belt produced an increased participation of this source through time. At the eastern side the Punta Mogotes Belt, a Brasiliano orogen related to the final closure of Adamastor Ocean at Early Cambrian times (Gaucher et al., 2005), was one of the last events related to the amalgamation of Gondwana. However, this orogen was not source of the analyzed samples of Ventania. The comparison of the different units of the Curamalal Group (Figs. 7 and 8) with the Mogotes Formation detrital zircon patterns shows striking differences (Fig.18).

FIGURE 18 NEAR HERE

The Cambrian-Ordovician paleogeography is illustrated in Fig. 19. The drainage should have an important component from the west or northwest to explain the lack of zircons from the Punta Mogotes Belt seen in the frequency peaks of Fig. 18. Note that these peaks are partially recognized in the younger Balcarce Formation (Fig. 11).

FIGURE 19 NEAR HERE

7.2 Silurian-Devonian

At this time the main dominant provenance was from the west and northwest. The Pampean basement of Eastern Sierras Pampeanas as described by Rapela et al. (1998), Ramos et al. (2010) and Chernicoff et al. (2009, 2012 b), was the main source of the lower Ventana Group (Fig. 17). The angular unconformity between the Balcarce Formation and the Neoproterozoic and Early Cambrian sedimentary cover of Tandilia (Cingolani, 2011) may be either the result of the collision of Pampia with the Río de la Plata Craton (Early Cambrian), or the Famatinian collision (Middle Ordovician). The sedimentary record of Balcarce Formation indicates a post Hirnantian glaciation age (Late Ordovician). The Pampean unconformity is seen in different places of Eastern Sierras Pampeanas and was dated in 530 Ma by Escayola et al. (2007) and Ianizzotto et al. (2013). But, as the main source is coming from Eastern Sierras Pampeanas which is closer to Tandilia, it is more probable that deformation is related to the Pampean orogen (see further details in Pazos and Rapalini, 2011).

Through time, the Pampean Belt had the relief partially eroded, and during Silurian times the first Ordovician zircons were recorded, indicating that either the Famatinian Belt was supplying zircons to the area, or some scarce Ordovician granitoids in the Eastern Pampean Belt were exhumed. Also, Grenvillian-age zircons began to appear in the pattern of provenance, suggesting that the Mesoproterozoic basement of Cuyania and/or Pampia was also exhumed (Sato et al., 2000). The relief of Tandilia was almost non-existent as a source. At this time, an important source from Punta Mogotes Belt is recorded in the Balcarce Formation, indicating that this belt was actively exhumed. In Silurian times the paleogeography was characterized by higher mountains in the Famatinian Belt in the west, a partially eroded Pampean Belt, almost non-existent Tandilia Mountains, and an important relief in the Punta Mogotes Belt. Some sort of by-pass existed through the Pampean Belt in order to register Ordovician zircons in the Balcarce and Lolén Formations. The continental margin was opened to the present south (Fig. 19).

7.3 Late Paleozoic

A drastic change in paleogeography was produced at this time. A volcanic relief associated with a magmatic arc was located to the south, in present northern Patagonia. Volcanic debris (Andreis and Cladera, 1992) together with magmatic zircons were recorded in Ventania from 320 to 270 Ma. Classic petrographic provenance studies in Ventania and Cape Fold Belt of South Africa indicate a dissected arc source for these rocks (López Gamundí and Rossello, 1998). The older data of Late Carboniferous age observed as detrital zircons are in agreement with their derivation from the northern late Paleozoic magmatic arc proposed by Ramos (2008) in northern Patagonian along the Somún Cura Massif. Recent studies of Chernicoff et al. (2012 a) in the Yaminué region in the Somún Cura Massif show that a biotite paraschist has a maximum U/Pb SHRIMP age of 318 ± 5 Ma coherent with the frequency peaks of several units of the Pillahuincó Group of the Ventania System. On the other hand, the tonalitic orthogneiss has a crystallization age of 261.3 ± 2.7 Ma, which is broadly coeval with deformation, and Neoarchean-Paleoproterozoic inheritance, indicating the occurrence of Archean crust in this sector of Patagonia. Hf TDM ages of Permian zircons are mainly Meso-Paleoarchean (2.97–3.35 Ga) with highly negative ε(Hf) values (ca. –33) according to Chernicoff et al. (2012 a). It is interesting to remark that the first Archean zircons observed in

Ventania are the 2729, 2990 and 3200 Ma frequency peaks of Sauce Grande Formation, within the range of inherited Archean zircons of the Yaminué region described by these authors.

The obtained zircon dates of the ash-fall tuffs of the Tunas Formation indicate an Early Permian age, close to the depositional age of this unit (López Gamundí et al., 1995), which was interpreted as synorogenic deposits based on the occurrence of growth strata. The age of deformation is consistent with the deformation ages of the orthogneisses in north Patagonia in the adjacent Somún Cura Massif (Chernicoff et al., 2012a).

A Permian very juvenile poorly dissected relief dominated the Somún Cura Massif and the uplifted Ventania fold belt providing immature detritus to the Claromecó Basin. The Ventania fold and thrust belt continues in the offshore in the Colorado syntaxis (Pángaro and Ramos, 2012), a mirror image of the Cape Syntaxis (Fig. 20).

8. Correlation with the Cape Fold Belt in South Africa

It is important to note that in South Africa, the Cape Fold Belt was developed at the same time that the Ventania Belt (Fig. 20) as parts of the Gondwanides Orogen (Keidel, 1916, 1921). There is consensus in the correlation of the different units of the Neoproterozoic-Cambrian basement and the Paleozoic sedimentary sequences since the early work of Keidel (1916) and DuToit (1927) followed by Harrington (1947). This correlation was based on the rock types and age of the basement as proposed by Rapela et al. (2003), Milani and DeWitt (2008), and Chemale et al. (2011b). On fossiliferous grounds the correlation was based on the *Eurydesma* fauna and the *Glossopteris* flora, as well as in the Devonian marine fossils (Harrington, 1955; Benedetto, 2010). Another piercing point is the correlation of the glacial deposits of Sauce Grande and the Dwyka Tillite, which has been identified since the early work of Keidel (1913), and corroborated several times by more recent works (López Gamundi and Rossello, 1998).

FIGURE 20 NEAR HERE

A recent study on the detrital zircons of several pre-Carboniferous units of the Cape Supergroup shows striking differences and similarities with the Ventania System (Fourie et al., 2011). The main difference is the dominant Mesoproterozoic (1.0-1.2 Ga) provenance of the Cape Supergroup that points out to the Namaqua Belt as the source area. The Curamalal and Ventana Groups have the Paleoproterozoic ages from Tandilia Belt (2.2-2.0 Ga) as the main Precambrian source. The similarities are the Neoproterozoic-Cambrian ages derived in the present study from the Eastern Sierras Pampeanas, and from the pan-African belts and the

Cape Granites for Fourie et al. (2011). Both studies have also a striking coincidence in the Ordovician ages. The analyses performed in the pre-Carboniferous rocks of the Cape Fold Belt have a noticeable frequency peak at 469 Ma, similar to the frequency peak of 475 Ma of Lolén Formation in the Ventania Belt that in the present study is straight forward derived from the Famatinian Belt of Western Sierras Pampeanas. A similar Ordovician peak (478 Ma, see Fig. 11) was identified in the Balcarce Formation by Rapela et al. (2011). Nonetheless, Fourie et al. (2011) assumed that the source area could be either the Ross Orogen in Antarctica or the Patagonian Deseado Massif of Argentina. As we noticed, the abrupt change in provenance occurred after the collision of Patagonia, where a very different provenance is recorded for the first time.

Based on the evaluation of both detrital zircon data bases we consider the Ordovician (480-460 Ma) provenances in both Ventania and Cape belts, as derived from Western Sierras Pampeanas, while the Neoproterozoic-Cambrian (560-530 Ma) zircons have local sources. Zircons are derived in the Ventania Belt from Eastern Sierra Pampeanas, but in the Cape Fold Belt come from local pan-African belts.

9. Concluding remarks

The obtained data permit to confirm some hypotheses and discard some previous interpretations. The comparison of the provenance between the Curamalal and Ventana Groups allows once more to confirm the stratigraphy of Harrington (1947), and to reject some hypotheses that interpreted these units as tectonic repetitions of the same succession. These pre-Carboniferous sequences of the Ventania Belt have a pattern derived from the Tandilia Belt, as well as from Eastern and Western Sierras Pampeanas. These characteristics can be compared with the detrital zircon pattern of the pre-Carboniferous Cape Fold Belt sequences. Differences and similarities can be explained with common and local sources; both belts share a similar Early to Middle Ordovician age zircons, which seem to be derived from the Sierras Pampeanas Belt.

The change in provenance between the early Paleozoic deposits of the Ventana Group and the late Paleozoic foreland sequences of the Pillahuincó Group indicates a different source region from these deposits. A series of Carboniferous to Permian zircons, absent in the previous units, together with the drastic change in paleocurrents indicate their derivation from northern Patagonia as part of the Gondwanides Belt. The source area for the Pillahuincó Group matches one to one the lithological characteristics of the Somún Cura Massif (see location in Fig. 1), and the U-Pb ages of the main igneous and metamorphic rocks.

The occurrence of clasts with archeocyathids in the Somún Cura Massif sequences, together with the detrital zircon patterns, are compatible with a source in Eastern Antarctica (González et al., 2011; Naipauer et al., 2011; Ramos and Naipauer, 2012; Veevers and Saeed, 2013). The recent finding of archeocyathids in clasts of the Sauce Grande tillites (González et al., 2013), reinforces this provenance. This match indicates that Patagonia should have originated in Eastern Gondwana, and that it was transferred to Western Gondwana during the Gondwanan orogeny. For further details see the recent analysis of Ramos and Naipauer (2013 and cites there in). Although some recent papers proposed a continuation of the magmatic activity in the early Paleozoic from the Sierras Pampeanas to the Somún Cura area (Rapalini et al., 2013), a classic proposal advanced by Bracaccini (1960), it is not able to elucidate the presence of archeocyathids (see discussion in Ramos and Naipauer, 2013). Rapalini et al. (2013) follow the arguments of Dalziel et al. (2013) who propose a continuous archeocyathid reef along the margin of Antarctica. However, this argument needs a magmatic arc located in the Somún Cura arc more than thousand kilometers away from the Pacific margin (see discussion in Ramos, 2008).

The integrated evolution of the Gondwanides in this sector of the southwestern Gondwana margin with the general evolution of the Terra Australis Orogen as defined by Cawood (2005) and modified by Ramos (2009), shows some interesting features. The early Paleozoic continental margin of Ventania interrupts the almost continuous Famatinian-Ross orogens. The Famatinian Orogen characterizes an active continental margin with a voluminous magmatic arc developed along the proto-Andean margin of Western Gondwana from Venezuela and Colombia through most of Argentina down to Ventania, during latest Cambrian and Middle Ordovician times. The Ross Orogen (Stump, 1995; Myrow et al., 2001) continues to the present east from Patagonia all along the Transantarctic Mountains and Australia, and has a latest Cambrian to Early Ordovician magmatic arc. The Ventania early Paleozoic basin is devoid of any magmatic activity in these intervals, representing a passive continental margin. The tectonic causes of such differences are beyond the present research.

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Figure captions

Figure 1: Location of the Ventania and Tandilia systems in the province of Buenos Aires, localities mentioned in the text, and main basement provinces of central Argentina and Uruguay (based on Ramos, 2009 and Cingolani, 2011).

Figure 2: Main geological features of the Ventania System in the province of Buenos Aires. Numbers indicate the samples with detrital zircon U/Pb Laser ablation analyses (geology after Schiller, 1930; Harrington, 1947; Suero, 1972).

Figure 3: Main basement exposures of the Ventania System with available ages based on Varela et al. (1987), Rapela et al. (2003), Rapela and Kostadinoff (2005), and Tohver et al. (2012).

Figure 4: Stratigraphic column of the Paleozoic sedimentary rocks of the Ventania System (based on Harrington, 1947), with the stratigraphic positions of the analyzed samples. Paleocurrents after Reinoso (1968), Andreis and Cladera (1992), and López Gamundí and Rossello (1998).

Figure 5: Structural cross section of the Gondwanides of northern Patagonia restored for the end of the Paleozoic. The hinterland region developed in present Somún Cura Massif with exhumed late Paleozoic arc-granitoids is shown as well as the Ventania System with the fold and thrust belt and associated Claromecó Basin (based on Von Gosen et al., 1991; Tomezzoli and Cristallini, 1998; Ploskiewicz, 1999; Ramos, 2008; Pángaro and Ramos, 2012). The location of potential sutures among Patagonia, Tandilia and Cortijo terranes, as well as the Tandilia magmatic arc further north, are indicated after Teruggi et al. (1988), Max et al. (1999), Ramos, (2008) and Cingolani (2011).

Figure 6: a) Detail of the sample site; b) U-Pb frequency plot ages from zircons of a paragneiss (sample VE-02) of the metamorphic basement in the eastern slope of Cerro Pan de Azúcar, western Sierra de Curamalal (see location in Fig. 2).

Figure 7: a) Tectonic lense of mylonitic granite within quartzite layers of La Lola Formation; b) LA-ICP-MS from concordant zircons of this mylonitic granite (sample SLV-VE-04, see location in Fig. 2 and analytical data in the supplementary material).

Figure 8: U/Pb frequency plot ages from detrital zircons of the Curamalal Group: SLV-VE-03 from a quartzite clast of the basal conglomerate of the La Lola Formation, and SLV-VE-05, quartzitic sandstones interfingered in the upper part of the conglomerates; SLV-VE-09 from Mascota Formation from Cerro Colorado area; SLV-VE-10 from Mascota Formation east of Tornquist (location in Fig. 2).

Figure 9: U/Pb frequency plot ages from detrital zircons of lower part of the Ventana Group. Note the up-sequence decrease of the Paleoproterozoic ages (sample location in Fig. 2) and clear dominance of Late Neoproterozoic to Cambrian zircons.

Figure 10: U/Pb frequency plot ages from detrital zircons of upper part of the Ventana Group. Note that the samples from the Lolén Formation are more than 10 km distant, but have coherent patterns (see sample location in Fig. 2).

Figure 11: U/Pb frequency plot ages from detrital zircons of Balcarce Formation (samples FBA 264 and PMOG 233) based on Rapela et al. (2007, 2011). Note the important frequency peaks of Early Ordovician and Early Cambrian ages (location in Fig. 1).

Figure 12: Comparison of the detrital zircons provenance based on between Curamalal Group and lower and upper Ventana Group. Note the prominent frequency peak of Paleoproterozoic zircons in the Curamalal Group which is poorly developed in the Ventana Group, and the Famatinian peak (475 Ma) in upper Ventana Group, which does not occur in the older units. (FAM: Famatinian; BRAS: Brasiliano-Pampean; GRENV: Grenvillian, and TRANS: Transamazonian).

Figure 13: U/Pb frequency plot ages from detrital zircons of the fine sandstones and shales of Pillahuincó Group. Note the prominent frequency peaks of 322-304 Ma and the 291-282 Ma peaks may be correlated with igneous ages in the northern Somún Cura Massif (Chernicoff et al., 2012a, and cites therein).

Figure 14: U/Pb frequency plot ages from zircons from the northern Somún Cura Massif of the, a) Sedimentary cover of Sierra Grande Formation (Silurian-Devonian), and b) pre-Ordovician metasedimentary basement of the El Jagüelito, Mina Gonzalito, and Nahuel Niyeu Formations (after Pankhurst et al., 2006; Naipauer et al., 2011 and Uriz et al., 2011).

Figure 15: U/Pb frequency plot ages from detrital zircons of the fine sandstone of González Chaves locality. Note the prominent frequency peak at 316 Ma (Late Carboniferous).

Figure 16: Hf isotopic analyses of selected samples from the Ventania System. See supplementary material for sample number and figure 2 for location.

Figure 17: U/Pb frequency plot ages from zircons from the Sierra de La Ventana region obtained in the present study and the main orogenic events ((FAM: Famatinian; BRAS: Brasiliano-Pampean; GRENV: Grenvillian, and TRANS: Transamazonian).

Figure 18: U-Pb frequency plots of detrital zircons of Mogotes Formation. Note the different pattern with the Balcarce Formation of Fig. 11(after Rapela et al., 2007, 2011).

Figure 19: Paleogeography of the Ventania System through time; a) Cambrian-Ordovician; b) Silurian-Devonian; and c) late Paleozoic times. The Pampean Orogen depicted after Ramos (1988), Rapela et al. (1998), and Tohver et al. (2012); the Punta Mogotes Belt based on

Gaucher et al. (2005); the Gondwanides Orogen based on Ramos (2008) and Pángaro and Ramos (2012).

Figure 20: Location of the Ventania Fold Belt in the province of Buenos Aires, Argentina and its correlation with the Cape Fold Belt of South Africa as part of the Gondwanides. Tectonic framework of the pre-break up of Western Gondwana is based on the reconstruction of Pángaro and Ramos (2012).

Figure 1

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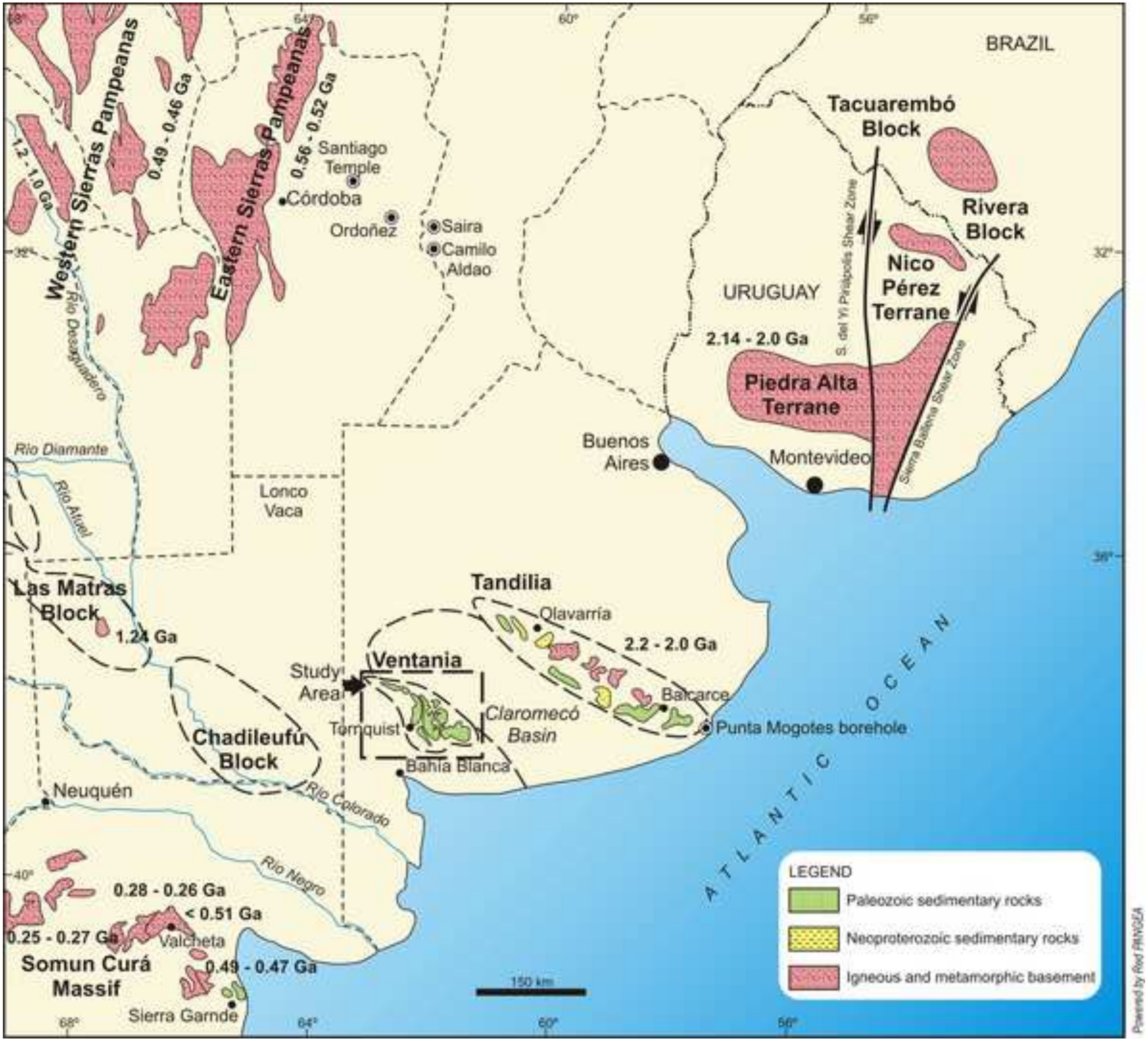

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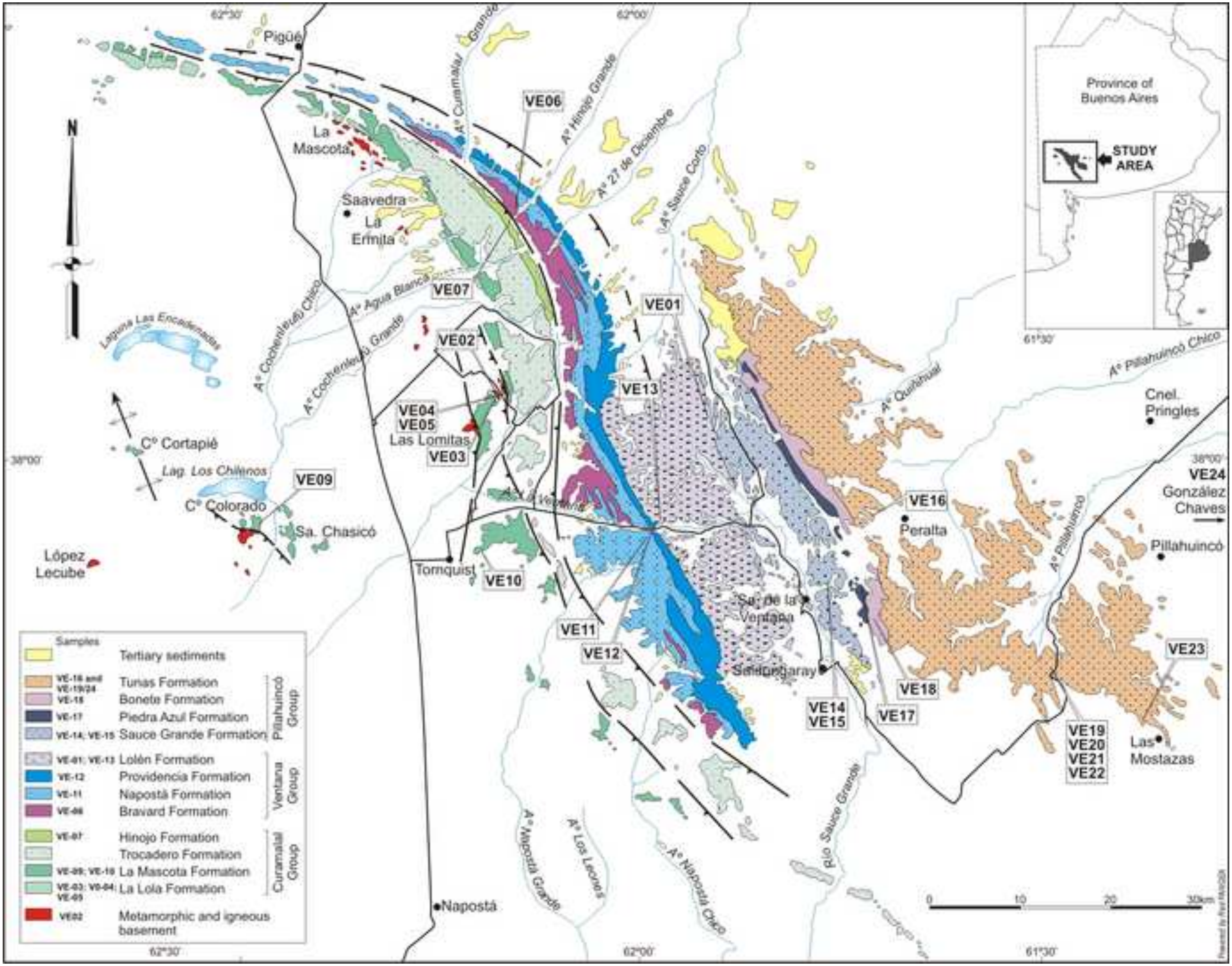

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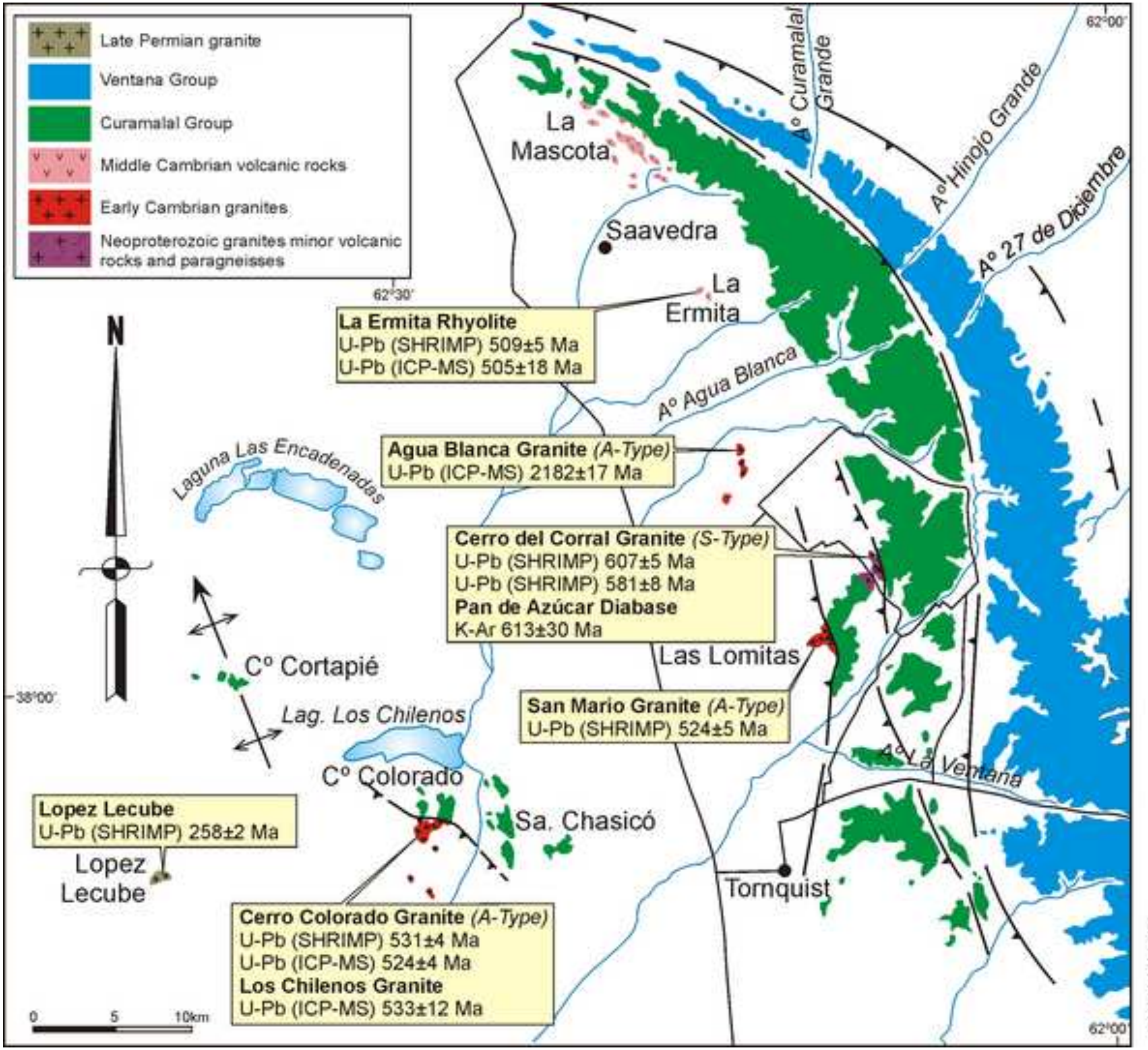

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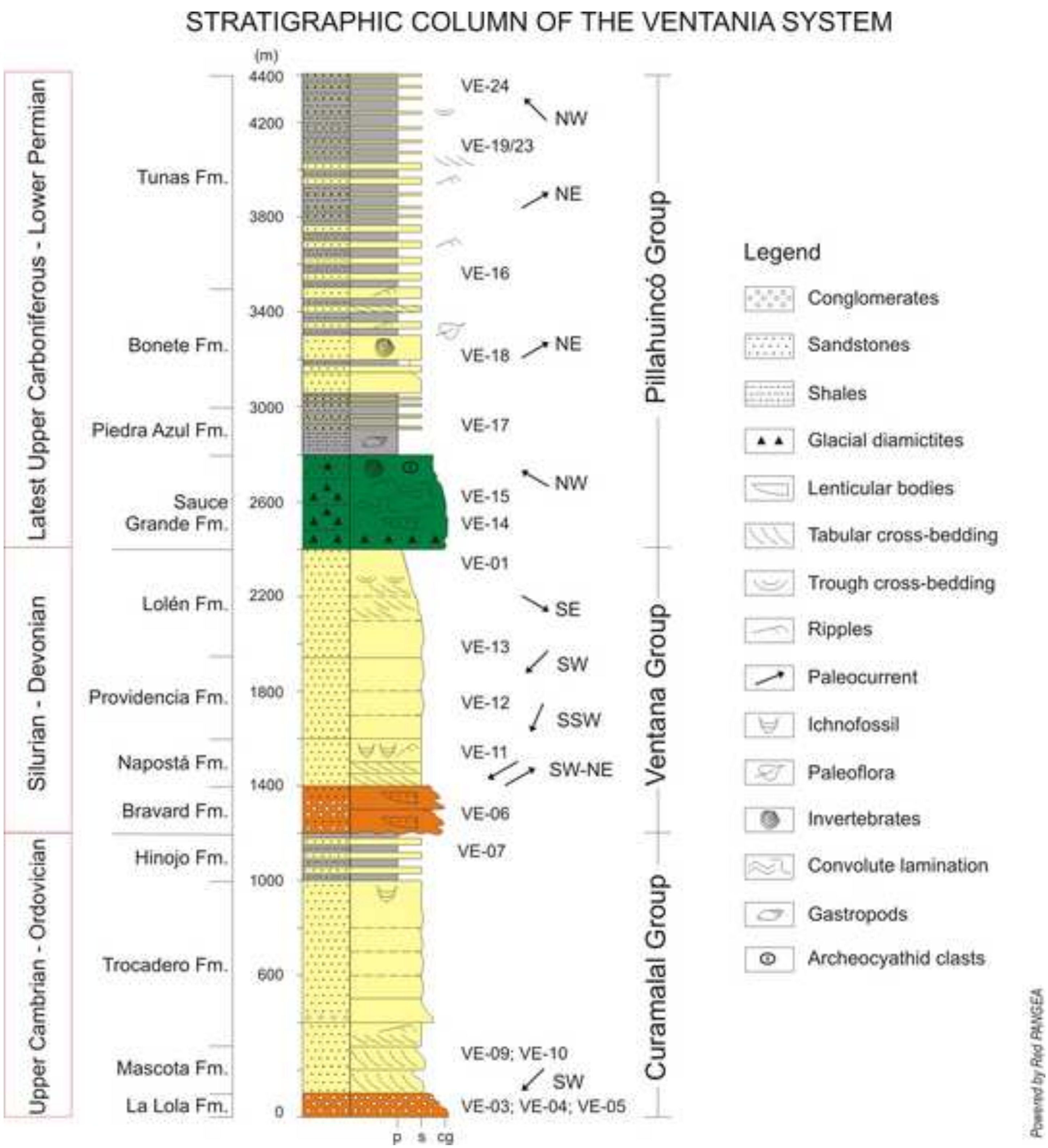

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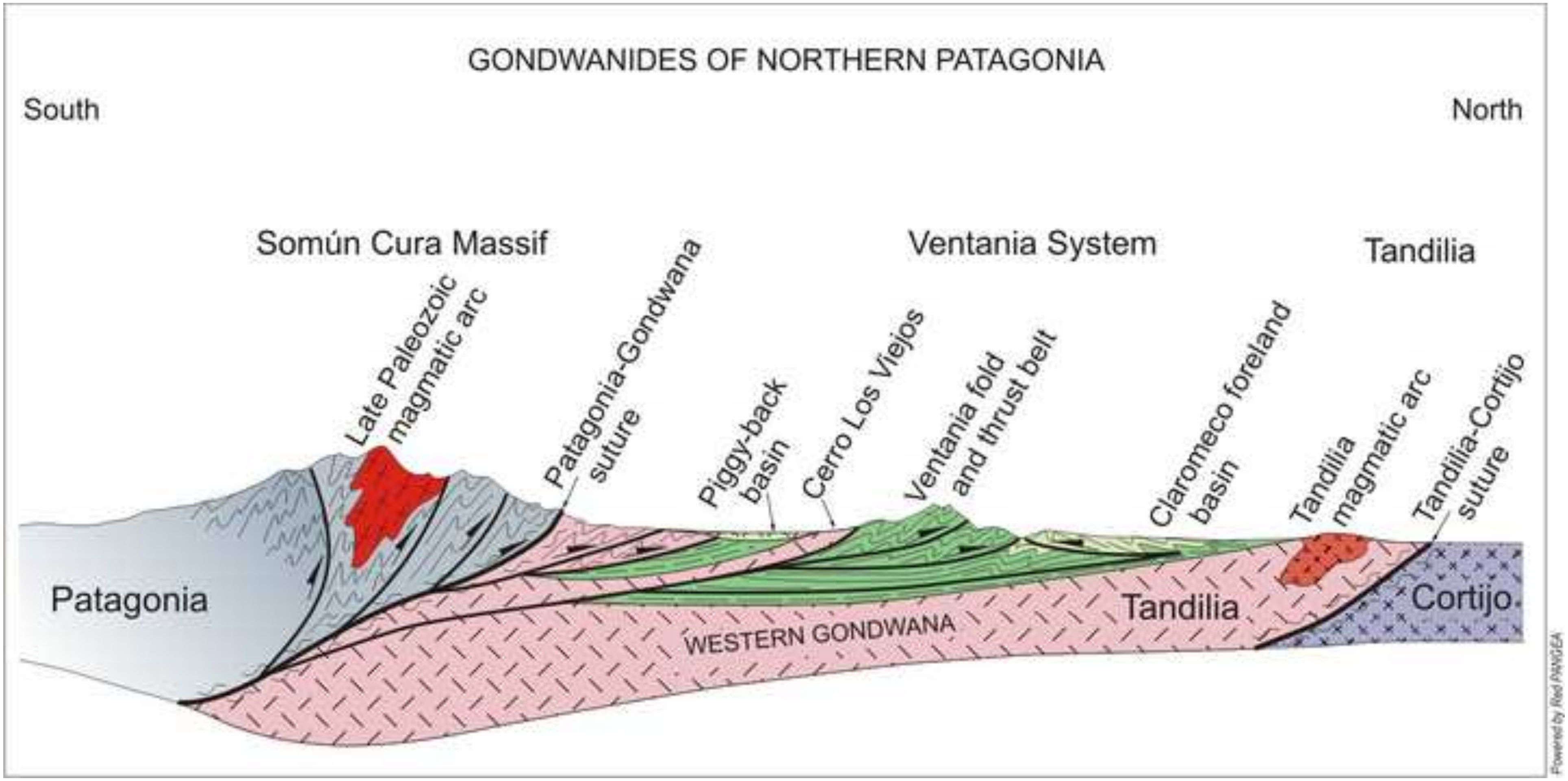

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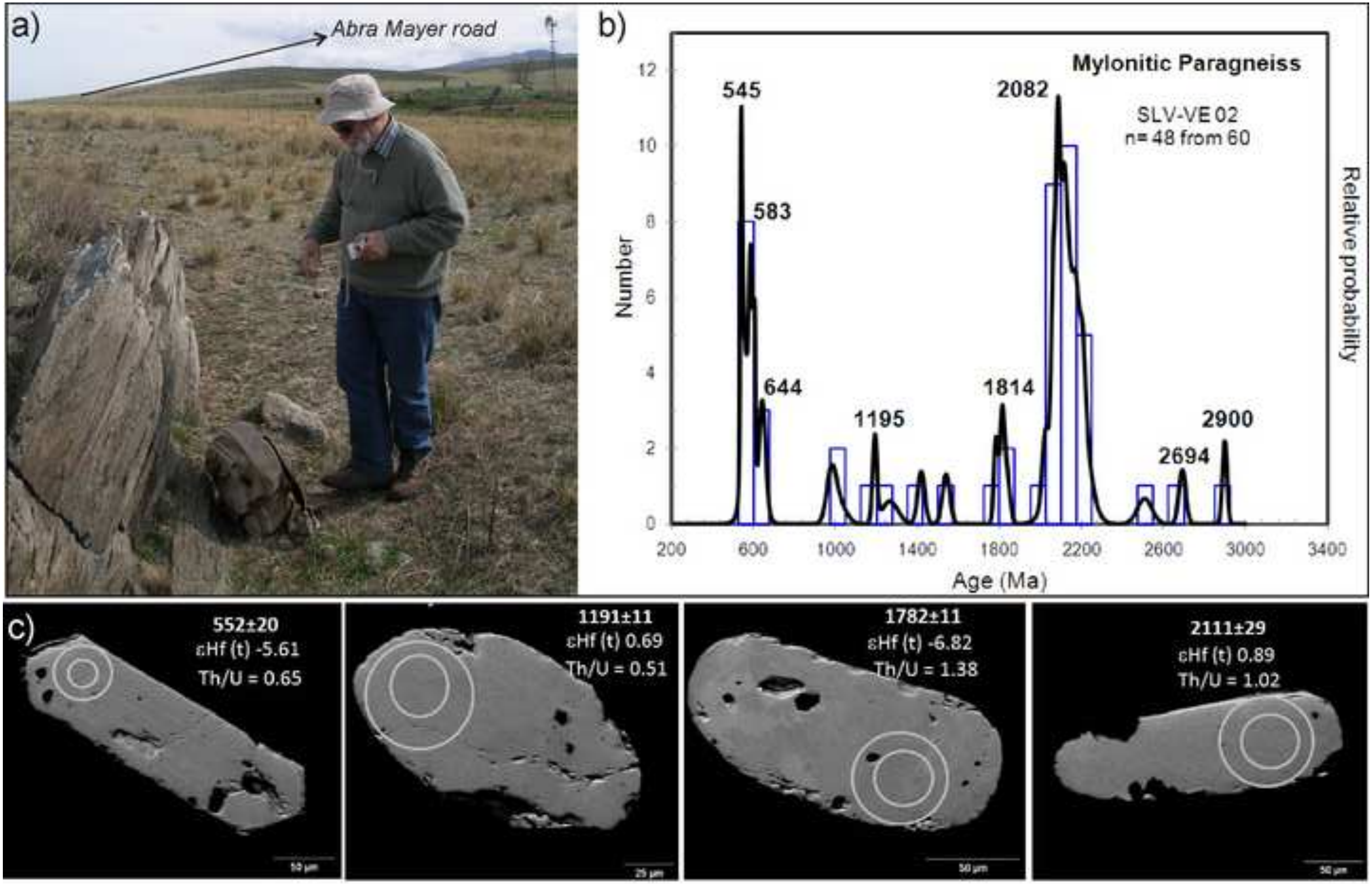

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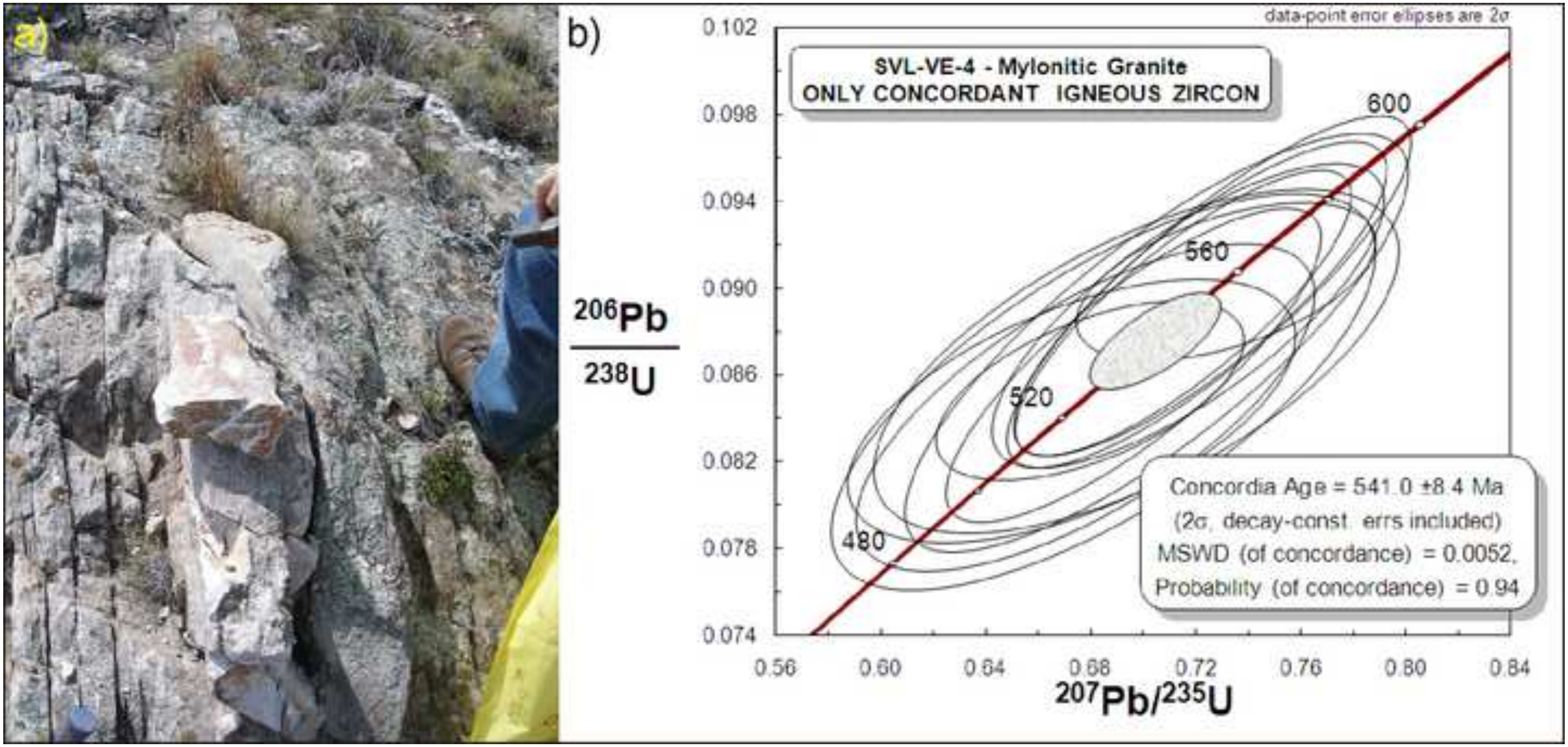

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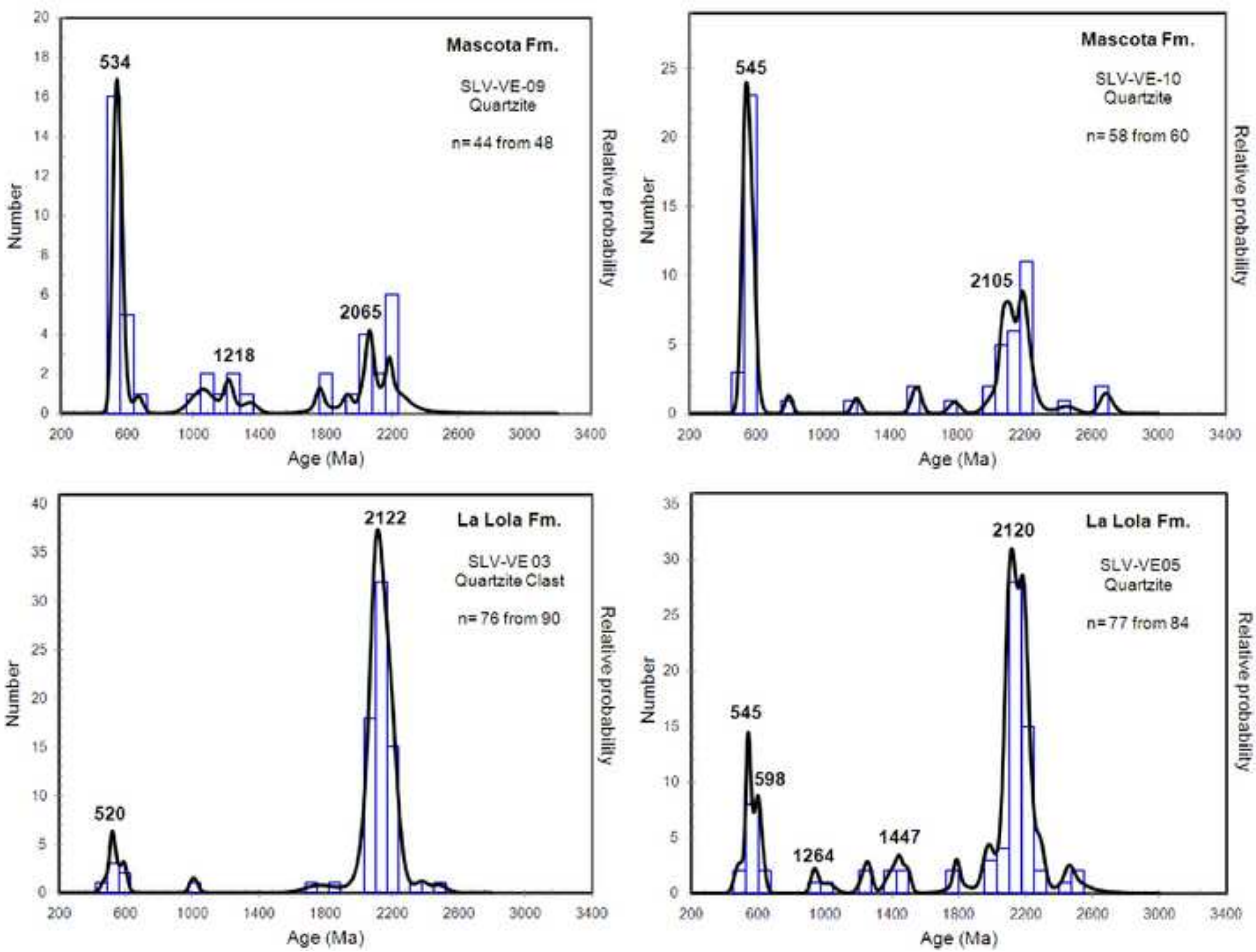

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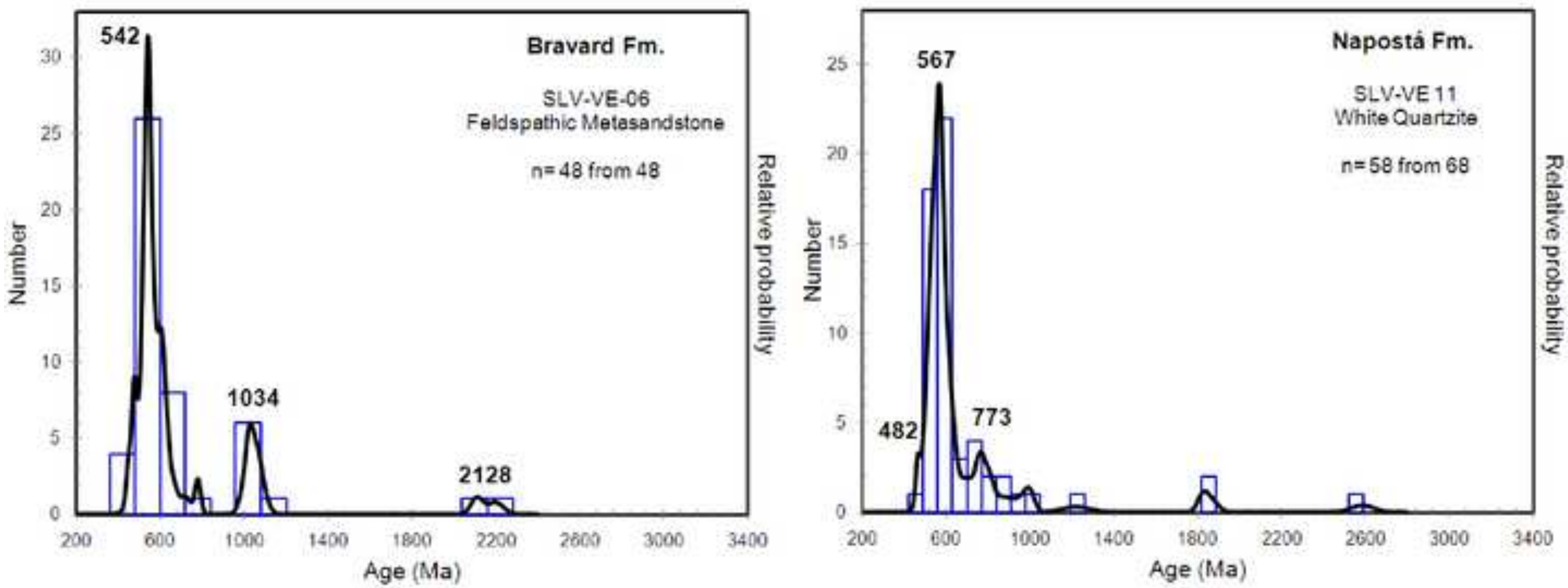

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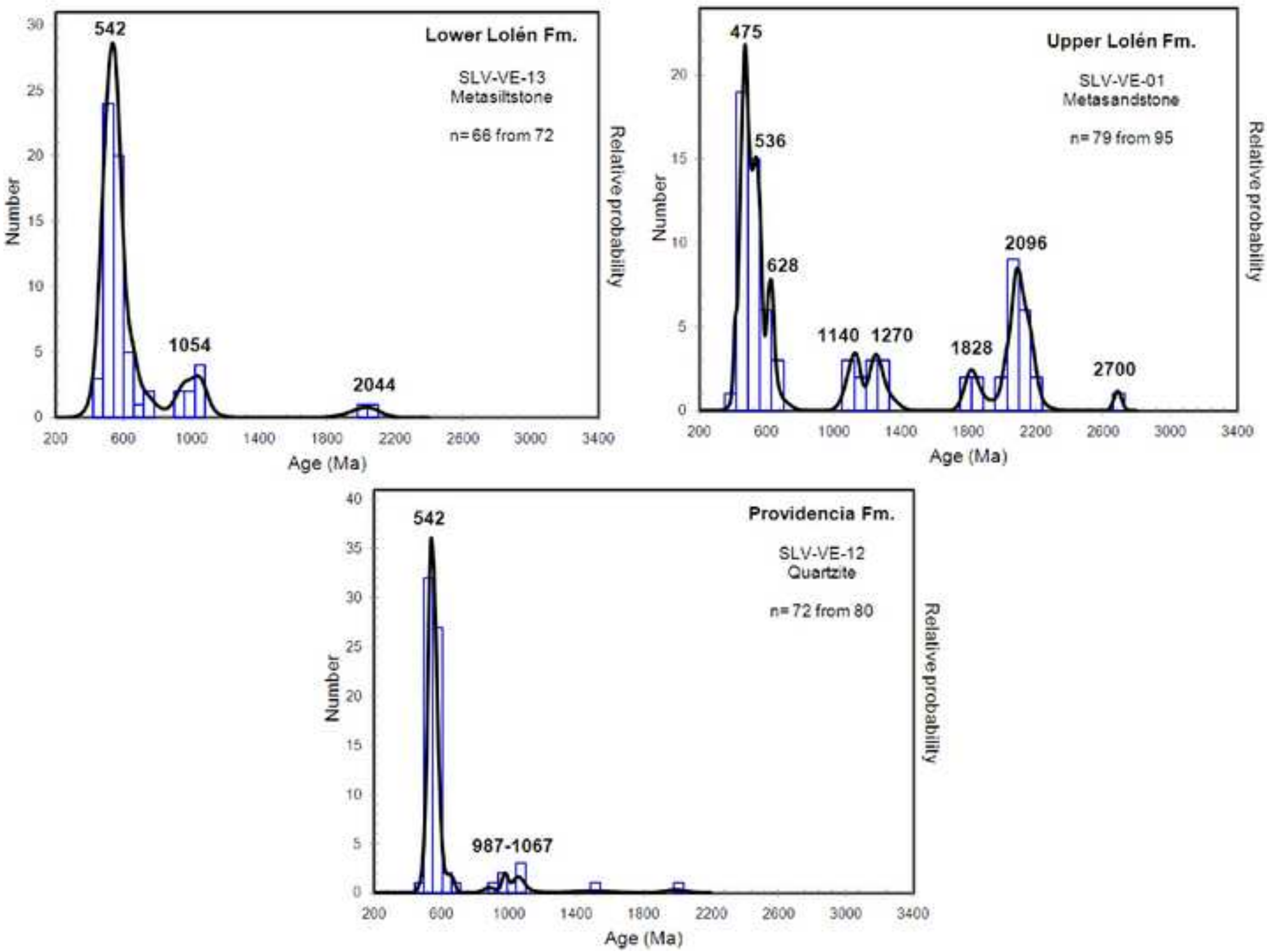

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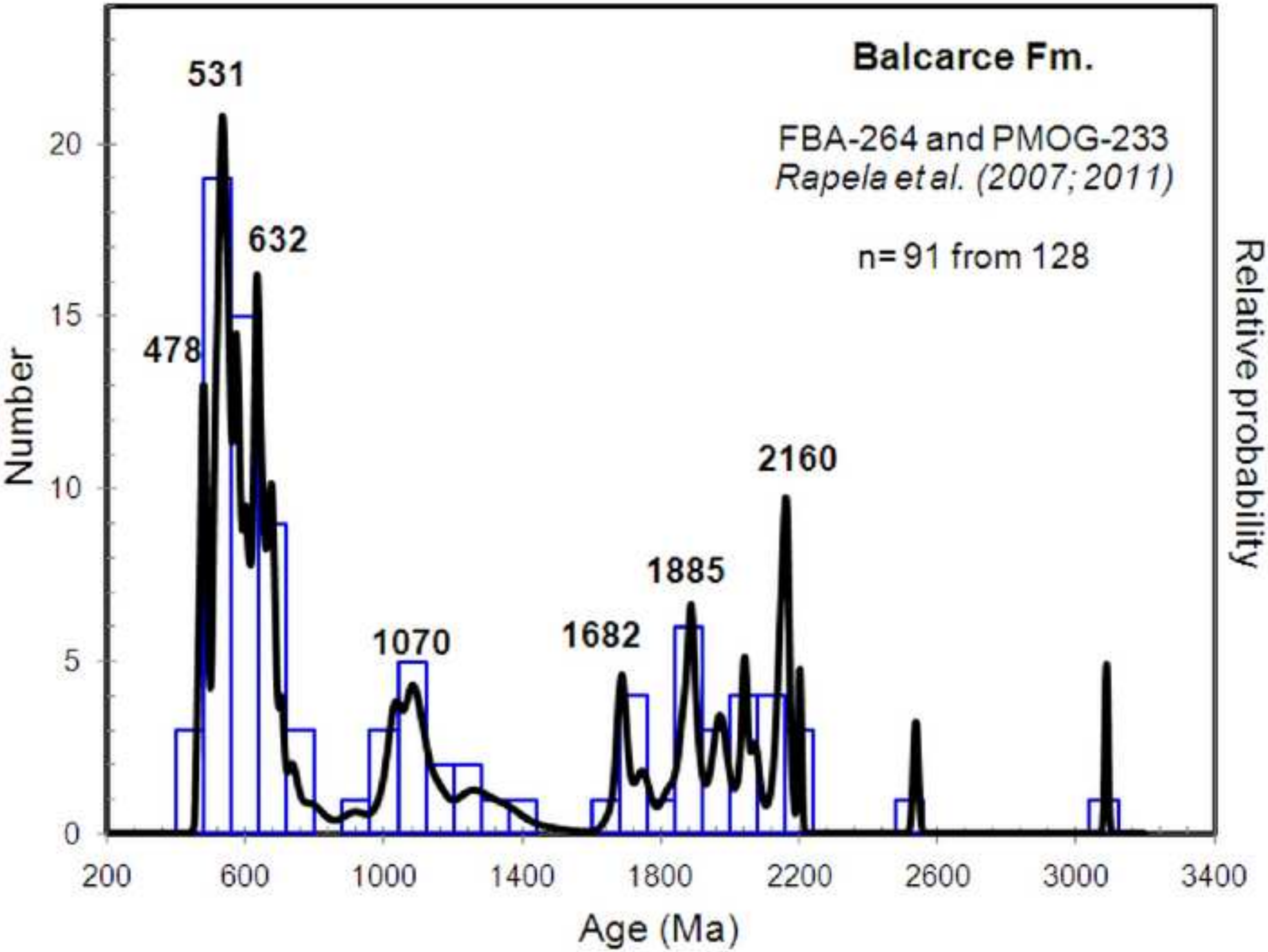

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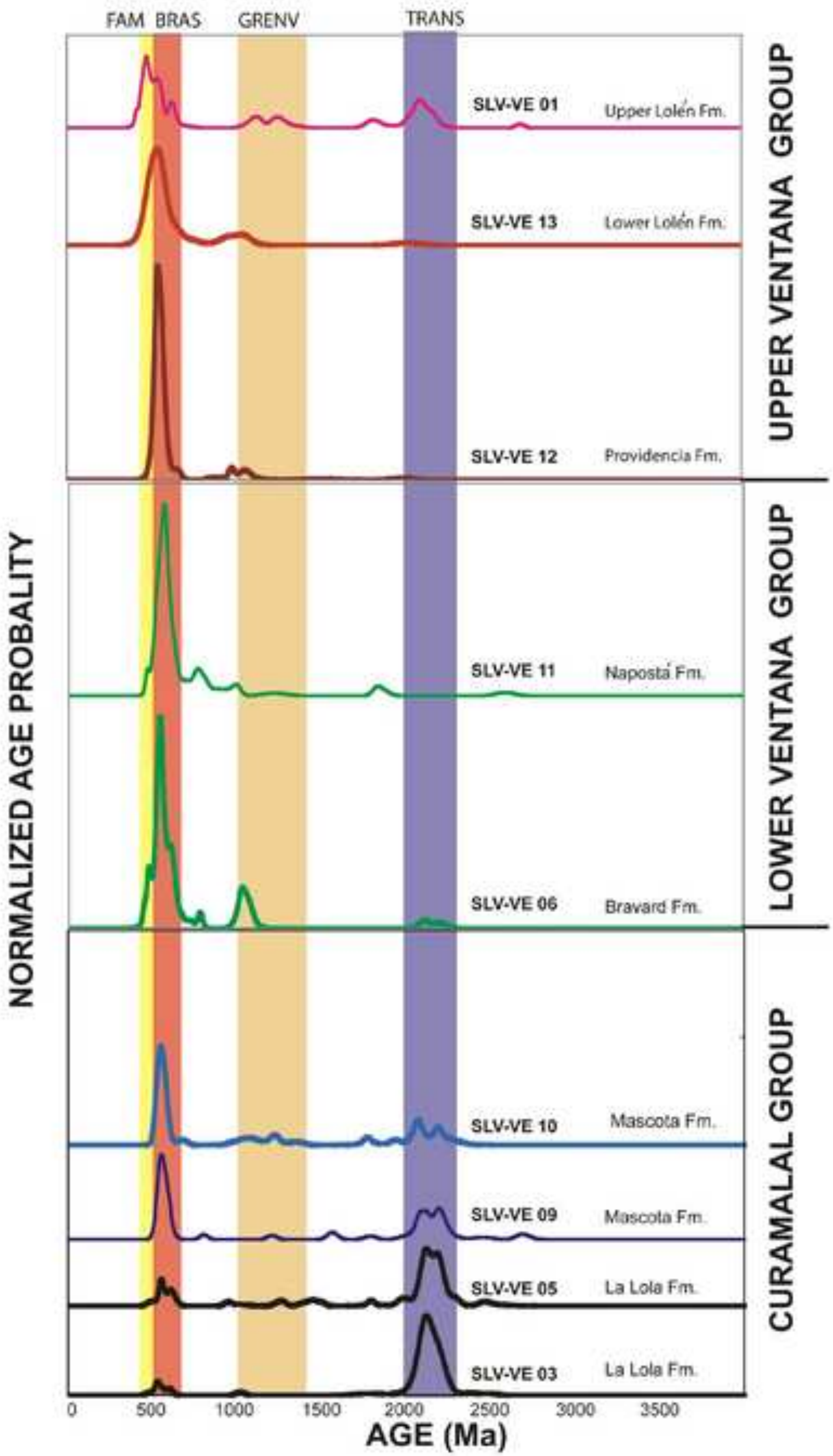

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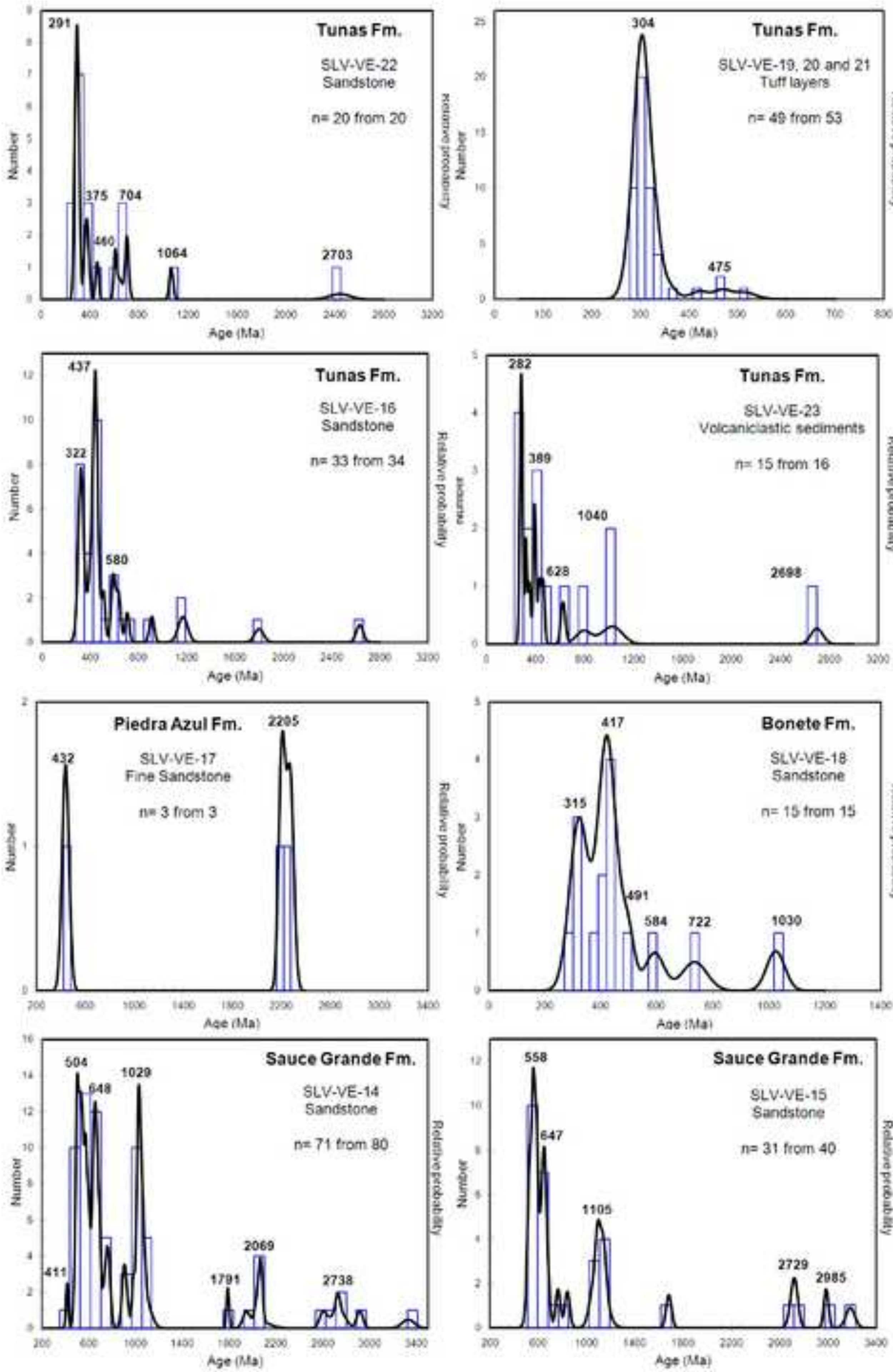

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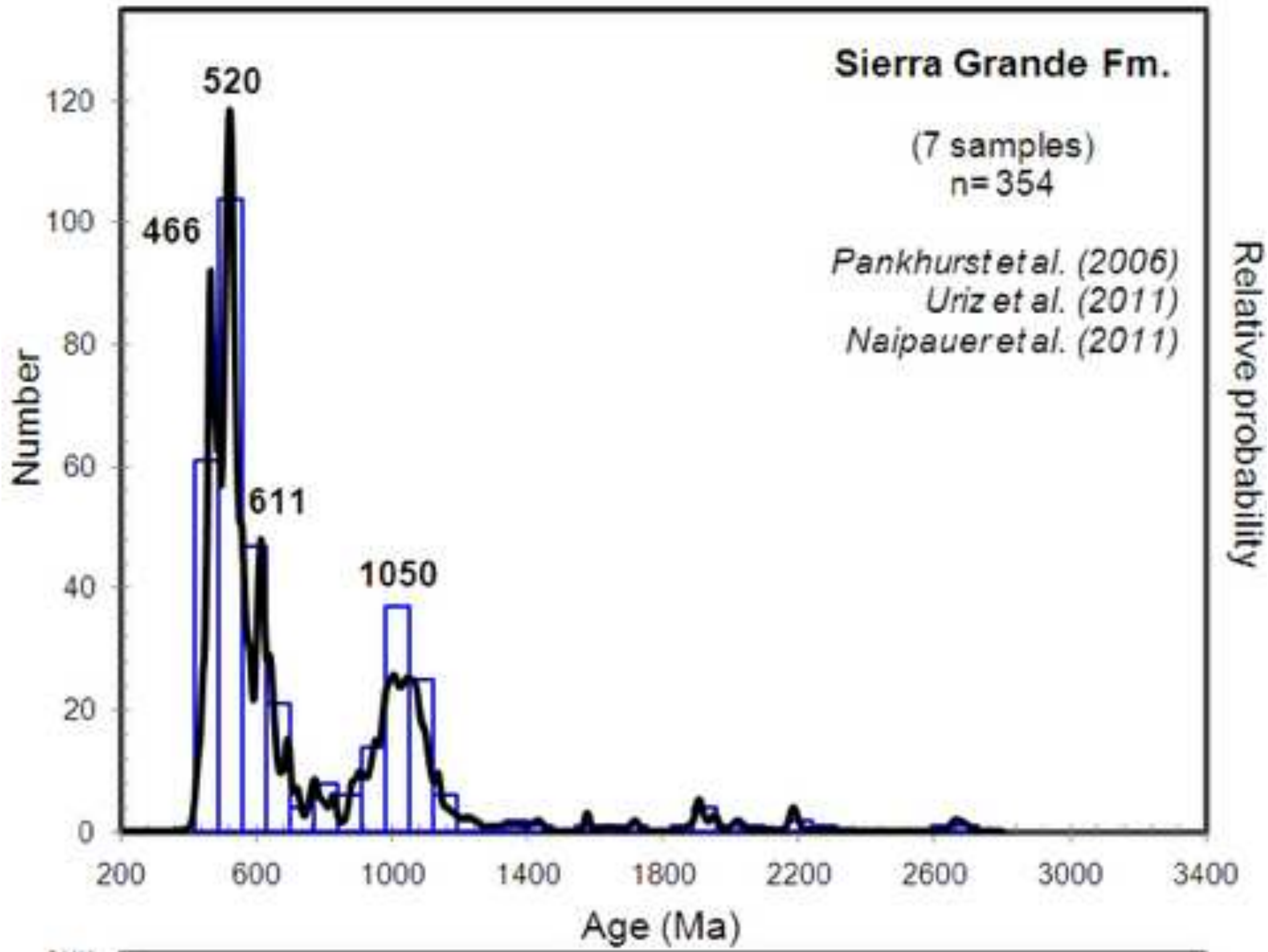

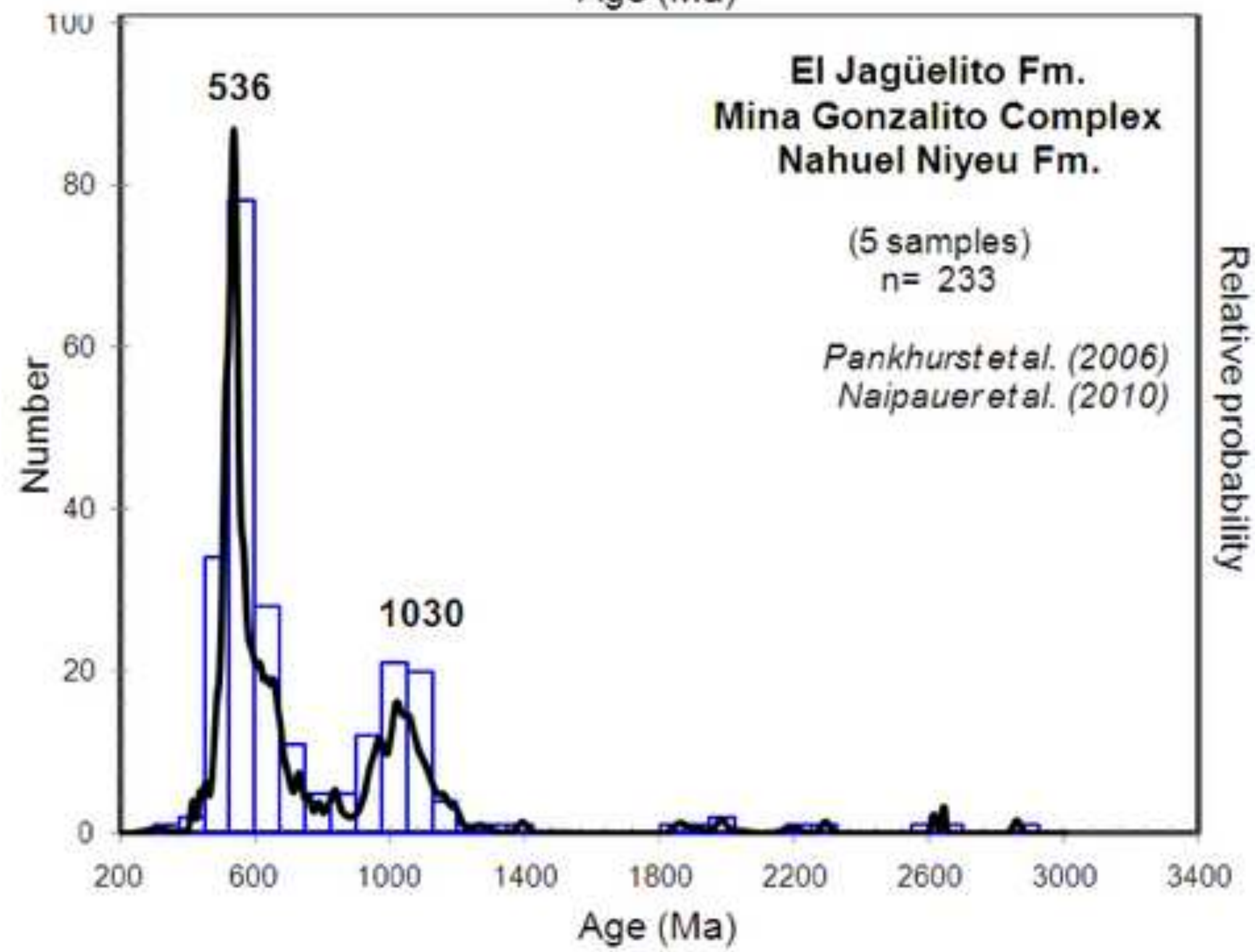

New Figure 15
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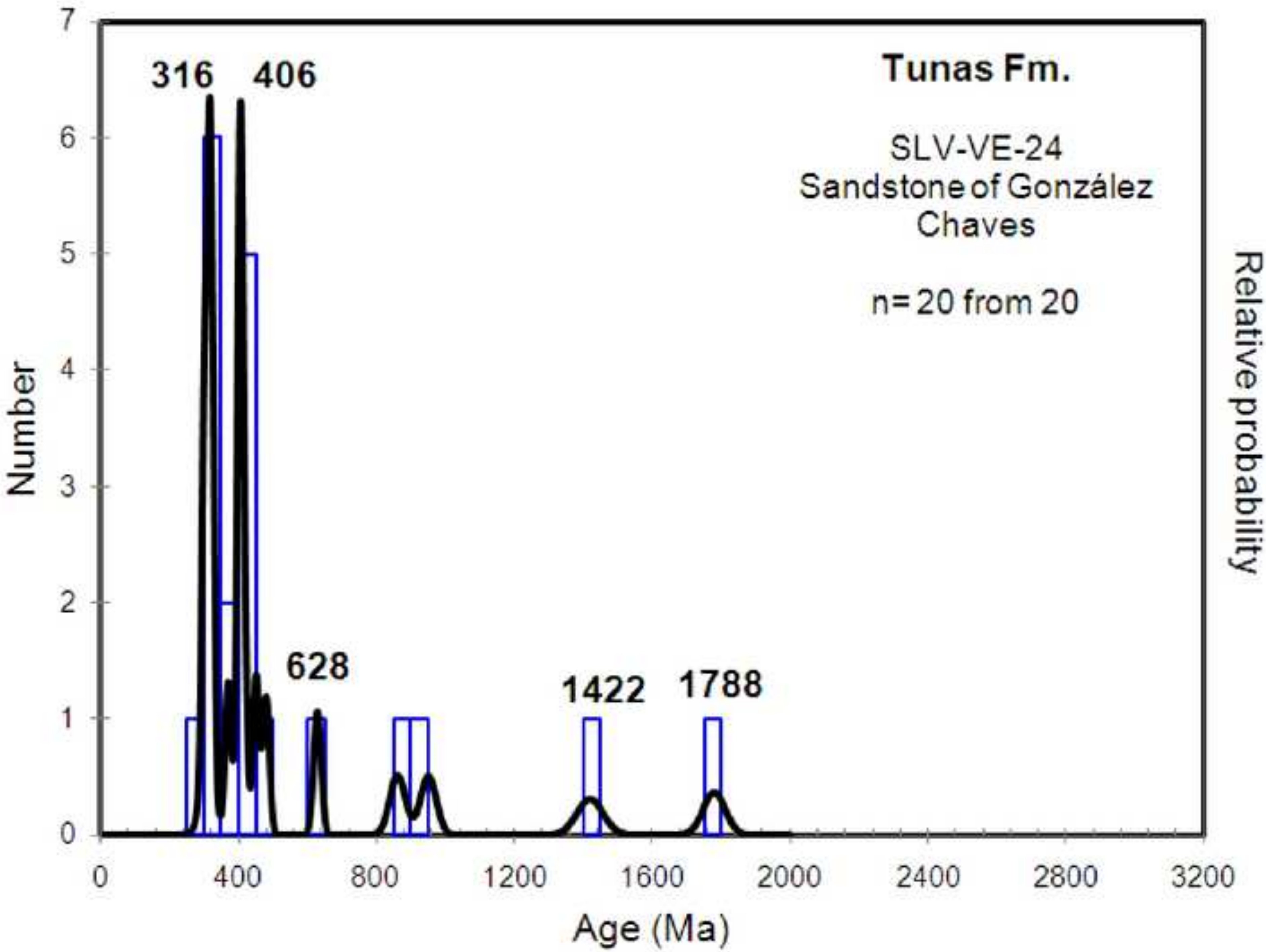

New Figure 16

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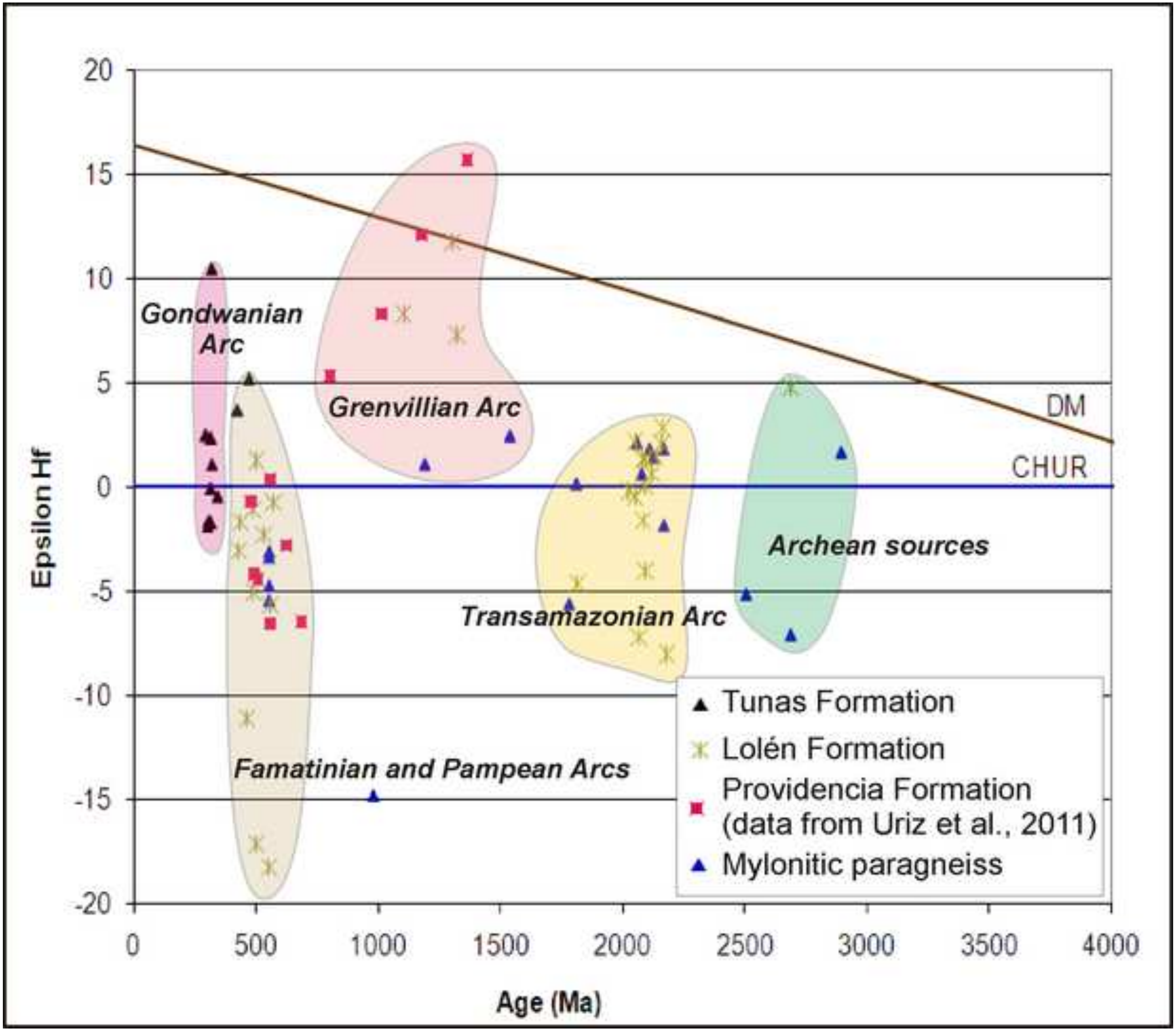

Figure 17
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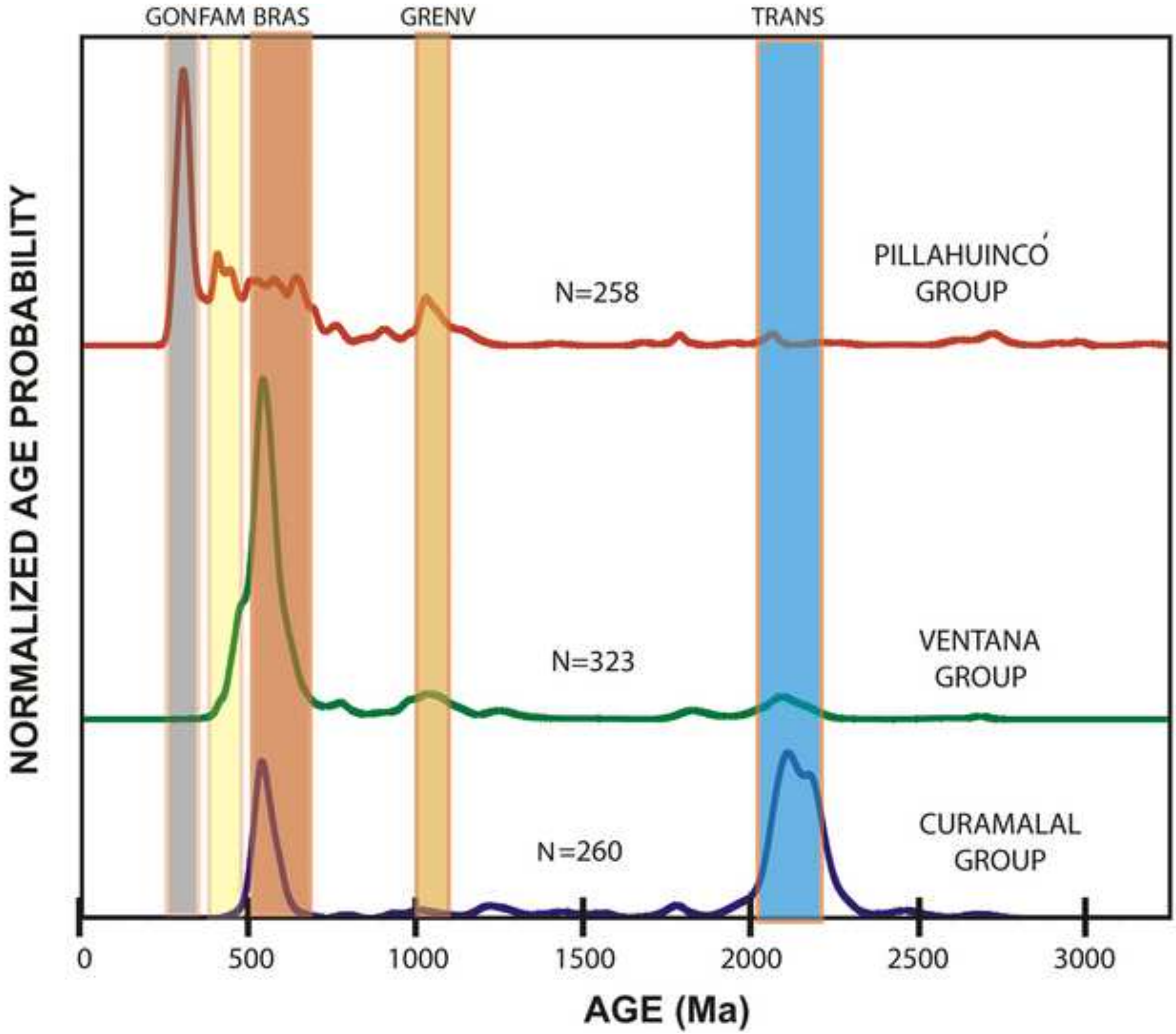

New Figure 18
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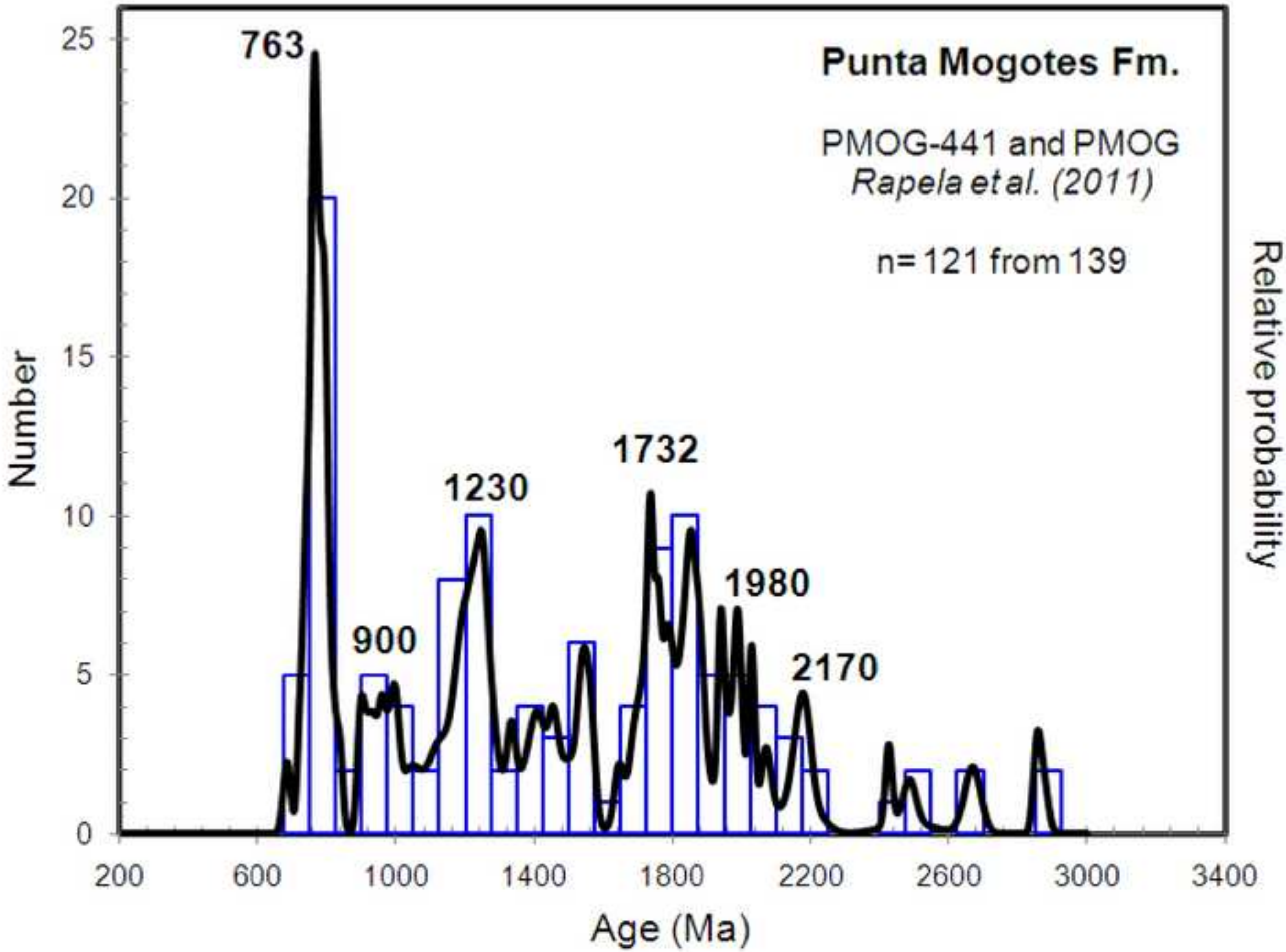

New Figure 19

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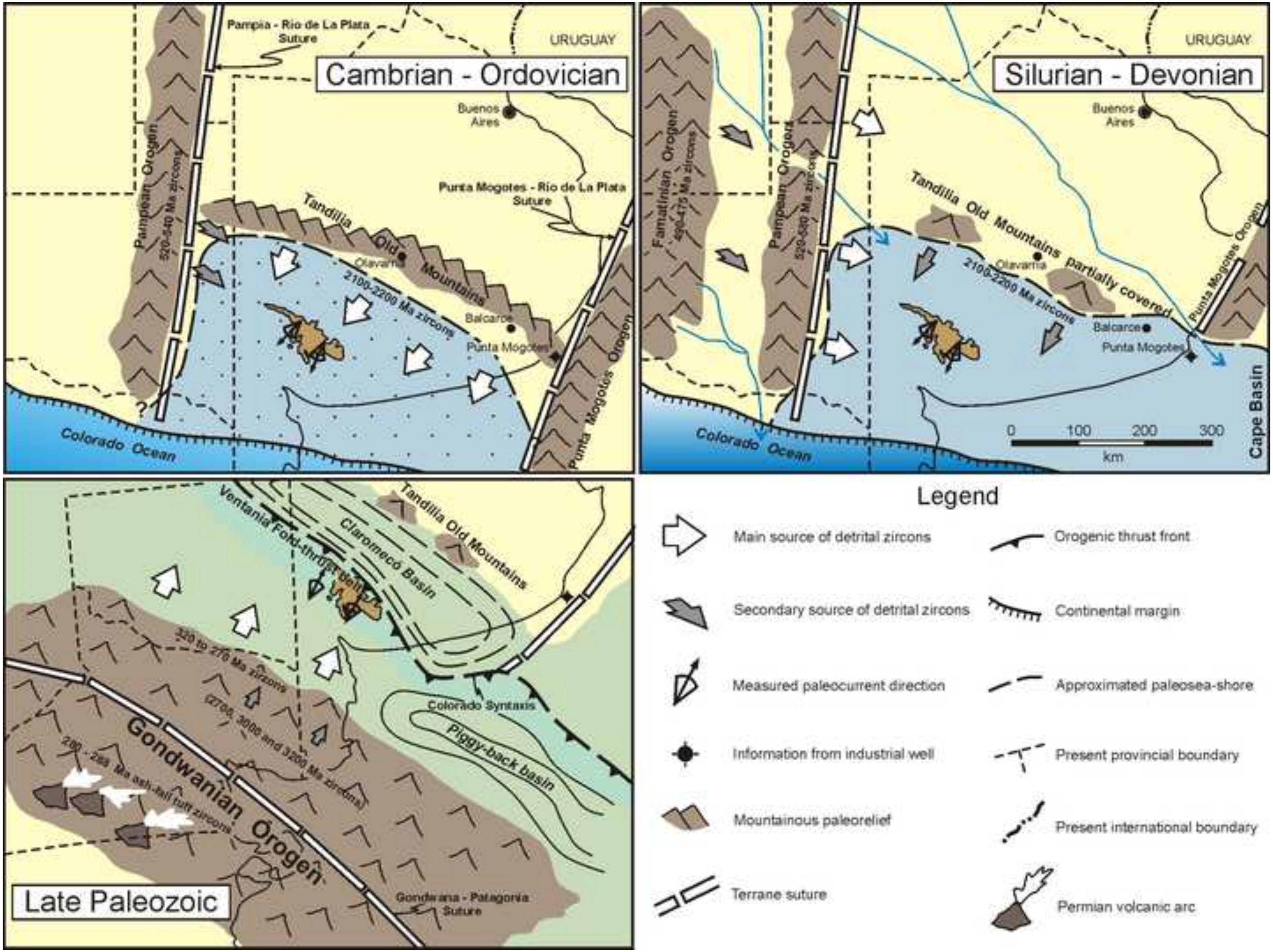

Figure 20
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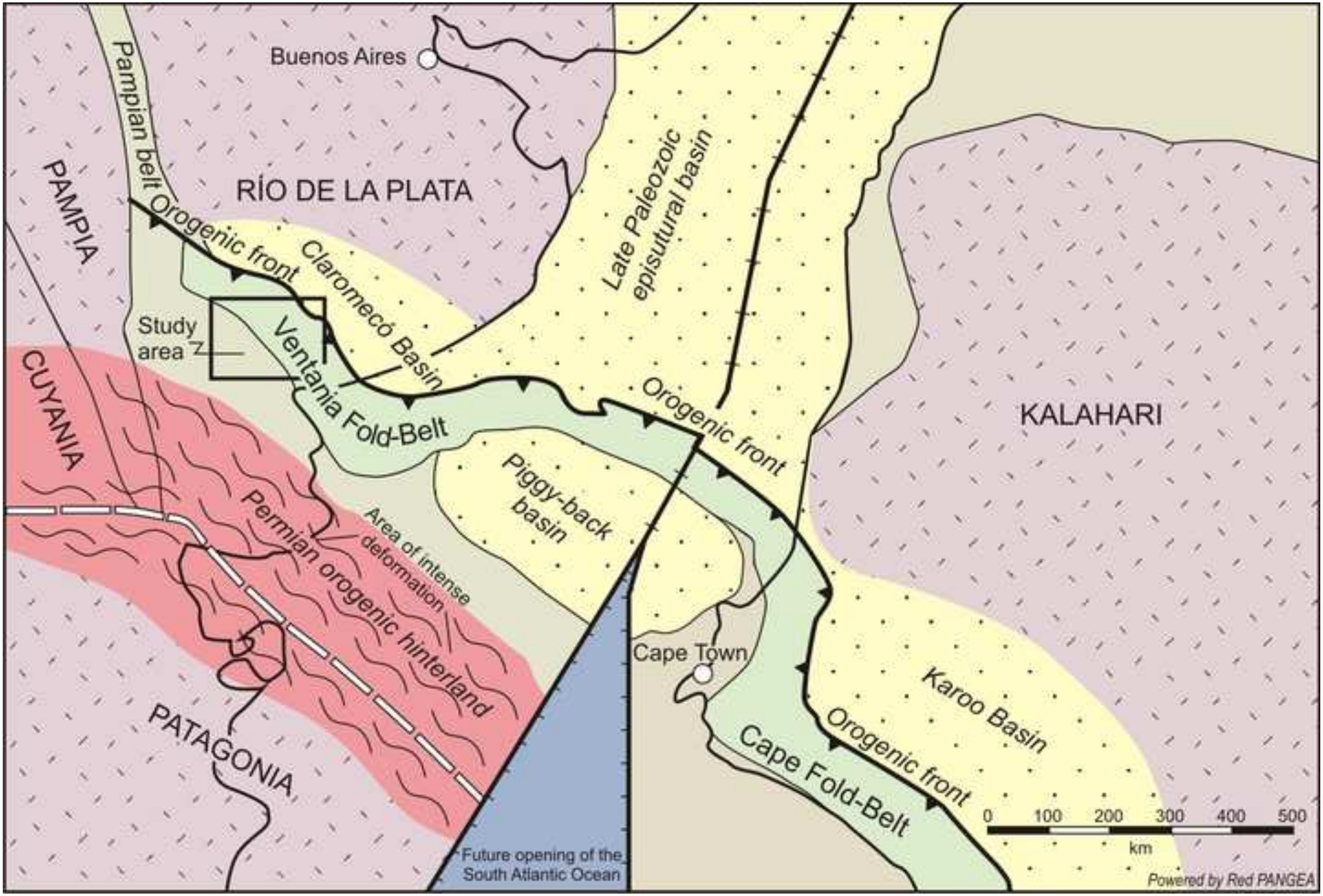

Supplementary Table 1

Click here to download e-component: Supplementary Table_1_Sample list.pdf

Supplementary Table 2
Click here to download e-component: Supplementary Table_2_U-Pb data.pdf

New Table 3

Table 3: Lu-Hf data

Lu-Hf data obtained by MC-ICPMS in detrital zircons from the quartzite of Lolén Fm, Sierra de la Ventana (**sample SLV-VE-01**)

Name	U/Pb Age (Ma)	±2σ	Sample (Present day ratios) $^{176}Hf/^{177}Hf$	±2SE	$^{176}Lu/^{177}Hf$	±2SE	Sample Initial Ratios $^{176}Hf/^{177}Hf$ (t)	εHf(0)	εHf(t)	±2SE	T DM Ga
002-A-I-03	2093	106	0.281346	3.61E-05	0.000343	1.93E-05	0.281332	-50.88	-4.04	0.43	**2.59**
003-A-I-05	2157	53	0.281476	2.66E-05	0.000319	9.70E-06	0.281463	-46.29	2.08	0.11	**2.41**
004-A-I-08	2023	43	0.281510	2.84E-05	0.000608	1.16E-05	0.281487	-45.09	-0.18	0.01	**2.39**
005-A-I-09	2165	62	0.281498	2.99E-05	0.000462	1.44E-05	0.281479	-45.49	2.86	0.17	**2.39**
006-A-I-10	461	54	0.282186	3.61E-05	0.000517	1.88E-05	0.282181	-21.19	-11.09	1.70	**1.47**
009-A-I-11	2066	59	0.281272	3.67E-05	0.000320	5.66E-06	0.281260	-53.49	-7.23	0.34	**2.68**
010-A-I-14	2178	63	0.281183	3.14E-05	0.000432	4.32E-06	0.281165	-56.66	-8.01	0.31	**2.81**
011-A-I-18	569	40	0.282413	3.98E-05	0.000728	1.92E-05	0.282406	-13.14	-0.73	0.07	**1.16**
012-A-I-22	2118	90	0.281476	4.59E-05	0.000703	4.74E-05	0.281447	-46.30	0.63	0.07	**2.44**
013-A-I-26	551	26	0.281929	4.09E-05	0.000571	1.23E-05	0.281923	-30.28	-18.22	1.25	**1.82**
014-A-I-34	2083	120	0.281417	5.72E-05	0.000228	1.91E-05	0.281408	-48.36	-1.57	0.22	**2.49**
015-A-I-36	2136	87	0.281480	2.99E-05	0.000476	3.88E-05	0.281460	-46.16	1.50	0.18	**2.42**
016-B-II-02	557	56	0.282283	4.73E-05	0.000812	3.15E-05	0.282275	-17.75	-5.64	0.79	**1.35**
017-B-II-08	2092	87	0.281503	3.56E-05	0.000428	1.62E-05	0.281486	-45.35	1.38	0.11	**2.39**
018-B-II-14	2092	87	0.281467	4.59E-05	0.000468	7.61E-06	0.281449	-46.60	0.07	0.00	**2.43**
033-D-IV-02	433	40	0.282470	3.89E-05	0.000510	2.86E-05	0.282466	-11.15	-1.66	0.25	**1.08**
034-D-IV-03	499	64	0.282518	3.77E-05	0.001187	1.47E-05	0.282507	-9.44	1.29	0.18	**1.03**
035-D-IV-07	427	56	0.282436	3.97E-05	0.000740	9.41E-06	0.282430	-12.33	-3.04	0.44	**1.13**
036-D-IV-22	2688	46	0.281218	5.78E-05	0.000554	1.47E-05	0.281189	-55.42	4.76	0.21	**2.77**
037-E-V-11	1320	113	0.282167	5.85E-05	0.000574	4.70E-06	0.282153	-21.84	7.32	0.69	**1.50**
038-E-14	486	81	0.282345	6.08E-05	0.000894	3.78E-05	0.282337	-15.54	-5.01	1.05	**1.26**
039-F-VI-01	1300	118	0.282310	4.95E-05	0.000767	2.33E-05	0.282291	-16.80	11.77	1.42	**1.31**
040-F-VI-04	1104	52	0.282330	4.07E-05	0.000444	6.66E-06	0.282319	-16.10	12.75	1.35	**1.27**
041-G-VII-05	1814	54	0.281510	2.98E-05	0.000379	3.06E-05	0.281502	-45.08	-20.68	2.64	**2.37**
042-G-VII-06	485	65	0.282454	3.34E-05	0.000524	1.73E-05	0.282436	-11.70	28.71	1.81	**1.10**
021-B-II-16	2051	170	0.281480	4.15E-05	0.000482	3.43E-05	0.281461	-46.15	-0.44	0.07	**2.42**

Assumed Values	
t (Ma)	4560
λ (Ga-1) [a]	0.01867
$(^{176}Hf/^{177}Hf)^{0}$chur [b]	0.282785
$(^{176}Hf/^{177}Hf)^{i}$ chur	0.279718
$(^{176}Lu/^{177}Hf)^{0}$ chur [b]	0.0336
$(^{176}Hf/^{177}Hf)$DM [c]	0.28325
$(^{176}Lu/^{177}Hf)$DM [c]	0.0388
$(^{176}Lu/^{177}Hf)$BSE [d]	0.015
$^{176}Lu/^{177}Hf$ [e]	0.022
$^{176}Lu/^{177}Hf$ [e]	0.010

022-B-II-21	597	67	0.281529	1.06E-04	0.001158	9.05E-05	0.281516	-44.41	-31.59	6.03	**2.39**
023-B-II-25	2051	170	0.281570	4.17E-05	0.000882	4.67E-05	0.281536	-42.97	2.21	0.30	**2.32**
024-B-II-26	500	30	0.281888	3.46E-05	0.000345	1.84E-05	0.281885	-31.72	-20.72	2.35	**1.86**
025-B-II-31	2082	152	0.281515	4.74E-05	0.000598	1.05E-05	0.281491	-44.92	1.35	0.12	**2.38**
026-B-II-37	531	37	0.282397	4.55E-05	0.001041	5.61E-05	0.282386	-13.74	-2.27	0.28	**1.20**
027-C-III-06	500	15	0.281987	3.48E-05	0.000130	1.65E-05	0.281986	-28.21	-17.13	2.69	**1.72**
028-C-III-18	464	15	0.281527	5.39E-05	0.000409	1.70E-05	0.281523	-44.49	-34.32	2.55	**2.35**
029-C-III-21	362	15	0.281317	3.22E-05	0.000164	2.98E-06	0.281316	-51.91	-43.93	2.62	**2.61**
030-C-III-27	617	15	0.281410	1.61E-04	0.000676	1.42E-05	0.281403	-48.61	-35.17	1.61	**2.52**

Lu-Hf data obtained by MC-ICPMS in detrital zircons from the mylonitic paragneiss of Pan de Azúcar area, Sierra de la Ventana (**sample SLV-VE-02**)

Name	U/Pb Age (Ma)	±2σ	Sample (Present day ratios) ^{176}Hf/^{177}Hf	±2SE	^{176}Lu/^{177}Hf	±2SE	Sample Initial Ratios ^{176}Hf/^{177}Hf (t)	εHf(0)	εHf(t)	±2SE	T DM Ga
065-A-1	979	29	0.281755	4.45E-05	0.000423	7.75E-06	0.281747	-36.43	-14.82	0.71	**2.05**
066-A-6	2690	17	0.280890	3.40E-05	0.000670	6.14E-05	0.280856	-67.00	-7.06	0.69	**3.22**
067-A-9	2079	11	0.281501	4.13E-05	0.000678	6.68E-05	0.281475	-45.39	0.69	0.07	**2.40**
068-A-14	2170	20	0.281352	3.78E-05	0.000168	4.40E-05	0.281345	-50.68	-1.80	0.49	**2.57**
069-A-18	2170	20	0.281472	1.16E-04	0.000548	3.91E-05	0.281449	-46.43	1.90	0.15	**2.43**
070-B-05	1190	11	0.282073	4.30E-05	0.000477	8.15E-06	0.282063	-25.16	1.15	0.03	**1.62**
072-B-06	2128	18	0.281491	4.43E-05	0.000634	6.68E-05	0.281465	-45.77	1.48	0.17	**2.41**
71-B-07	2897	11	0.280988	3.00E-05	0.000388	1.49E-06	0.280966	-63.55	1.73	0.01	**3.06**
075-B-09	2507	36	0.281043	5.70E-05	0.000243	1.99E-05	0.281031	-61.60	-5.11	0.49	**2.98**
076-B-11	1811	10	0.281651	3.02E-05	0.000453	3.91E-06	0.281635	-40.11	0.20	0.00	**2.19**
078-B-17	2059	8	0.281568	4.61E-05	0.000970	5.93E-05	0.281530	-43.04	2.19	0.14	**2.33**
079-C-1	552	20	0.282315	4.55E-05	0.001017	9.96E-05	0.282304	-16.63	-4.70	0.63	**1.31**
080-C-3	552	20	0.282294	4.95E-05	0.000939	4.69E-05	0.282284	-17.36	-5.40	0.47	**1.34**
081-C-4	552	20	0.282366	5.76E-05	0.001587	6.14E-05	0.282350	-14.80	-3.08	0.23	**1.26**
082-C10	1539	18	0.281893	3.73E-05	0.000565	1.23E-05	0.281876	-31.56	2.51	0.08	**1.87**
083-C-16	1782	11	0.281532	5.83E-05	0.001186	4.43E-05	0.281491	-44.33	-5.57	0.24	**2.39**
084-C-17	552	20	0.282353	3.46E-05	0.001000	2.37E-06	0.282343	-15.27	-3.33	0.13	**1.26**
085-D-1	2111	19	0.281505	4.61E-05	0.000442	7.73E-06	0.281487	-45.27	1.88	0.05	**2.38**

Assumed Values	
t (Ma)	4560
λ (Ga-1) [a]	0.01867
(^{176}Hf/^{177}Hf)^{0}chur [b]	0.282785
(^{176}Hf/^{177}Hf)^{i} chur	0.279718
(^{176}Lu/^{177}Hf)^{0} chur [b]	0.0336
(^{176}Hf/^{177}Hf)DM [c]	0.28325
(^{176}Lu/^{177}Hf)DM [c]	0.0388
(^{176}Lu/^{177}Hf)BSE [d]	0.015
^{176}Lu/^{177}Hf [e]	0.022
^{176}Lu/^{177}Hf [e]	0.010

Lu-Hf data obtained by MC-ICPMS in detrital zircons from the tuffs of Tunas Fm., Sierra de la Ventana (**sample SLV-VE-20 and SLE-VE-21**)

			Sample (Present day ratios)				**Sample Initial Ratios**				**T DM**
Name	**U/Pb Age (Ma)**	**±2σ**	**$^{176}Hf/^{177}Hf$**	**±2SE**	**$^{176}Lu/^{177}Hf$**	**±2SE**	**$^{176}Hf/^{177}Hf$ (t)**	**εHf(0)**	**εHf(t)**	**±2SE**	**Ga**
045-ZR-8-A-17	317	15	0.282623	4.38E-05	0.000979	1.97E-05	0.282617	-5.74	1.11	0.07	**0.88**
046-ZR-8-A-40	316	8	0.282888	3.68E-04	0.000824	9.75E-05	0.282883	3.64	10.51	1.52	**0.51**
047-ZR-8-B-II-35	311	20	0.282661	7.86E-05	0.000787	1.21E-05	0.282657	-4.38	2.38	0.19	**0.82**
048-ZR-8 C-III-18	290	20	0.282678	4.89E-05	0.000926	6.47E-05	0.282673	-3.77	2.50	0.35	**0.80**
049-ZR-8-C-III-13	311	19	0.282594	8.77E-05	0.001079	3.57E-05	0.282588	-6.74	-0.05	0.00	**0.92**
050-ZR-8-C-III-6	300	22	0.282547	1.05E-04	0.000664	2.15E-05	0.282543	-8.41	-1.87	0.20	**0.98**
051-ZR-8 E-V-3	303	11	0.282552	3.36E-05	0.000596	1.64E-05	0.282548	-8.25	-1.63	0.10	**0.97**
052-ZR-8 E-V-7	312	9	0.282545	6.66E-05	0.000718	1.06E-05	0.282541	-8.48	-1.69	0.07	**0.98**
053-ZR-8 E-V-9	340	8	0.282565	4.99E-05	0.000991	2.99E-05	0.282559	-7.78	-0.44	0.02	**0.96**
036-Zr 8 E-V-11	303	6	0.281914	2.71E-05	0.000096	1.33E-05	0.281913	-30.82	-24.11	3.81	**1.82**
056-ZR-8 F-VI-18	420	18	0.282633	5.55E-05	0.001006	4.83E-05	0.282625	-5.36	3.71	0.34	**0.87**
057-ZR-8 F-VI-01	468	16	0.282643	3.56E-05	0.000627	1.86E-05	0.282637	-5.02	5.22	0.33	**0.85**

Assumed Values	
t (Ma)	4560
λ (Ga-1) [a]	0.01867
$(^{176}Hf/^{177}Hf)^0$chur [b]	0.282785
$(^{176}Hf/^{177}Hf)^i$ chur	0.279718
$(^{176}Lu/^{177}Hf)^0$ chur [b]	0.0336
$(^{176}Hf/^{177}Hf)$DM [c]	0.28325
$(^{176}Lu/^{177}Hf)$DM [c]	0.0388
$(^{176}Lu/^{177}Hf)$BSE [d]	0.015
$^{176}Lu/^{177}Hf$ [e]	0.022
$^{176}Lu/^{177}Hf$ [e]	0.010

a ^{176}Lu decay constant (Söderlund et al., 2004)

b Chondritic values (Bouvier et al., 2008)

c Present day Depleted Manlte (Griffin et al., 2000; updated by Andersen et al., 2009)

d Goodge and Vervoort, EPSL 243, 711-731 (2006)

e 176Lu/177Hf ratios of mafic and felsic crust from Pietranik et al. (2008)