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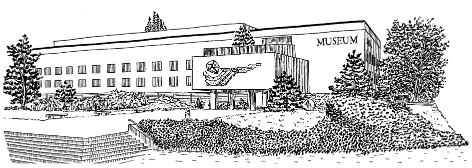

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Palaeomagnetic study of the Jurassic from Argentina: magnetostratigraphy and palaeogeography of South America

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Abstract
A palaeomagnetic study has been carried out in five Lower Jurassic sections from the Neuquén basin, made up mainly of ammonite-bearing sedimentary and, subordinately, volcanic rocks. Sampled sections are located to the north of the basin, along the Atuel river (Hettangian to Toarcian) and to the centre (Pliensbachian to Toarcian) of the basin. The palaeomagnetic study shows two magnetic components carried by titanomagnetites, one soft with a direction in coincidence with the local dipolar field, and another harder that is interpreted as the original Jurassic based on the field tests for palaeomagnetic stability. From the polarity successions obtained in each locality, a composite magnetostratigraphic scale for the Southern Hemisphere has been constructed. The resultant scale bears 11 zones of dominant reverse polarity (JR_1 to JR_{11}), and 12 zones of dominant normal polarity (JN_1 to JN_{12}), which have been tied to 19 ammonite zones of the Andean Region. The regional scale has, in turn, been correlated to the international geomagnetic time scale. A good fit between the two scales is observed, allowing to date intervals with no diagnostic fossils. On the other hand, two palaeomagnetic poles have been calculated, one for the Hettangian-Sinemurian interval (223°E, 51°S, A_{95}= 6°, N = 25) and the other for the Pliensbachian-Toarcian (67°E, 74°S, A_{95}= 5°, N = 52). Such poles were combined with others from the literature to obtain the apparent polar wander (APW) path for South America, which turns out to be remarkably dissimilar from the classical ones that show the continent in a stationary position throughout the Mesozoic. From the new APW path, it has been interpreted that South America may have rotated clockwise while it moved to the north. Eurasia's path is also presented in this study, revealing the same shape and chronology of tracks. These latitudinal changes that we observed from the palaeomagnetic data are supported by palaeoecological data.

Keywords
Magnetostratigraphy, palaeogeography, apparent polar wander path, Jurassic, Argentina.

INTRODUCTION

Magnetic polarity scales younger than 160 Ma are derived from sea-floor magnetic anomalies M37 to C1. For older times, such scales are derived from polarity successions obtained in the continents yielding a precise age control such as that provided by ammonites, i.e. 1 m.y. In order to carry out this study, OGG's (2004) geomagnetic time scale has been used, that has been constructed on the basis of sections in the northern hemisphere only. This scale however, bears different degrees of reliability. This is particularly poor in the Lower Jurassic, due to problems either in the magnetic or chronostratigraphic age. Hence, by sampling sections of this age from western Argentina, we intended to refine the somewhat unreliable intervals of the international scale. From the polarity successions obtained, a composite magnetostratigraphic scale has been constructed, that was tied to OGG's reference scale by means of the correlation between the Andean and Tethyan ammonite Zones.

Palaeomagnetic studies for the Jurassic in South America started with the poles obtained in Argentina (e.g. VALENCIO & VILAS, 1970; CREER *et al*., 1972; VILAS, 1974) from volcanic rocks. The fact that palaeopoles clustered around the geographic pole led to the generalised interpretation that South America underwent negligible polar wander. In other words, it has been long considered that the continent remained more or less in fixed palaeolatitudes from the Upper Palaeozoic and throughout the Mesozoic (e.g. VALENCIO *et al*., 1983; OVIEDO & VILAS, 1984; RAPALINI *et al*., 1993; BECK, 1999; BESSE & COURTILLOT, 2002). Nonetheless, it should be noted that the number and quality of South American palaeopoles at that time was rather poor due to problems with the magnetic and/or chronostratigraphic ages, and the fact that some of them are no representative of cratonic poles. More recent palaeomagnetic studies performed in Lower Jurassic sedimentary rocks would indicate that the continent was subjected by then, to considerable polar wander (IGLESIA LLANOS, 1997; VIZÁN, 1998; IGLESIA LLANOS *et al*., 2006), and changed its palaeolatitudinal position rather fast.

In order to thoroughly analyse this issue, two palaeomagnetic poles were derived for this study, one corresponding to the Hettangian-Sinemurian (197 Ma) and the other to the Pliensbachian-Toarcian (185 Ma).

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Thus, five different sections cropping out in the Neuquén basin, made up of mainly ammonite-bearing sedimentary rocks and subordinately, volcanic rocks, have been sampled for palaeomagnetic purposes.

GEOLOGY AND SAMPLING METHODOLOGY

Sampled sections are located to the north (Arroyo Malo, Puesto Araya, Arroyo Blanco) and to the centre (Rajapalo, Chacay Melehue) of the Neuquén basin (Fig. 1). The basin is a back-arc type that originated during the Triassic, in the extensional setting of western South America that finally led to the break-up of Gondwana (e.g. ULIANA & BIDDLE, 1988).

During the Middle Triassic, isolated half-grabens developed in the basement (MANCEDA & FIGUEROA, 1995; VERGANI *et al.*, 1995). Here, c. 7 km-thick of mainly sedimentary rocks have been deposited up to the Cenozoic. Deposition commenced as continental coarse-grained and volcanic rocks, until in the Late Triassic the first Pacific transgression took place along a narrow marine corridor to the north of the basin (RICCARDI *et al.*, 1988). The onset of the thermal sag phase determined the coalescence of the half-grabens and flooding of the basin during the Pliensbachian (LEGARRETA & GULISANO, 1989). Subsequently, during the Andean Orogeny in the Cretaceous-Tertiary, deformation began, leading to the development of N-S- oriented fold and thrust belts.

For this palaeomagnetic study, fine-grained sedimentary and volcanic rocks were preferred (Fig. 2, 3). The mean distance between sites – included those that were discarded – was 10 m, well within the represented biozones. In all cases, at least 2 hand samples were collected, from which a minimum of 2.5 cm cylindrical specimens were obtained, and thus, at least 4 specimens per site were collected. In addition, samples for radiometric dating and petrographical studies were collected. The latter were performed by R. ANDREIS, S. SINGER and M. BRODTKORB, and were very useful to help identifying the different magnetic carriers (IGLESIA LLANOS *et al.,* 2006).

Ammonites from the Andean region found in the sampled localities as well as the correlation with the Tethyan Zones were determined by A.C. RICCARDI and follow (Fig. 4) his most recent classification (RICCARDI, 2008). Thus, palaeomagnetic sampling sites were assigned precise chronological ages. This new classification of ammonites and their correlation with the Tethyan Zones, introduces some changes in the former analysis of the same sections performed by IGLESIA LLANOS *et al.* (2006, 2008), where a previous classification of biozones was used. Among the most remarkable differences with IGLESIA LLANOS *et al.* (2006, 2008) there is Z2

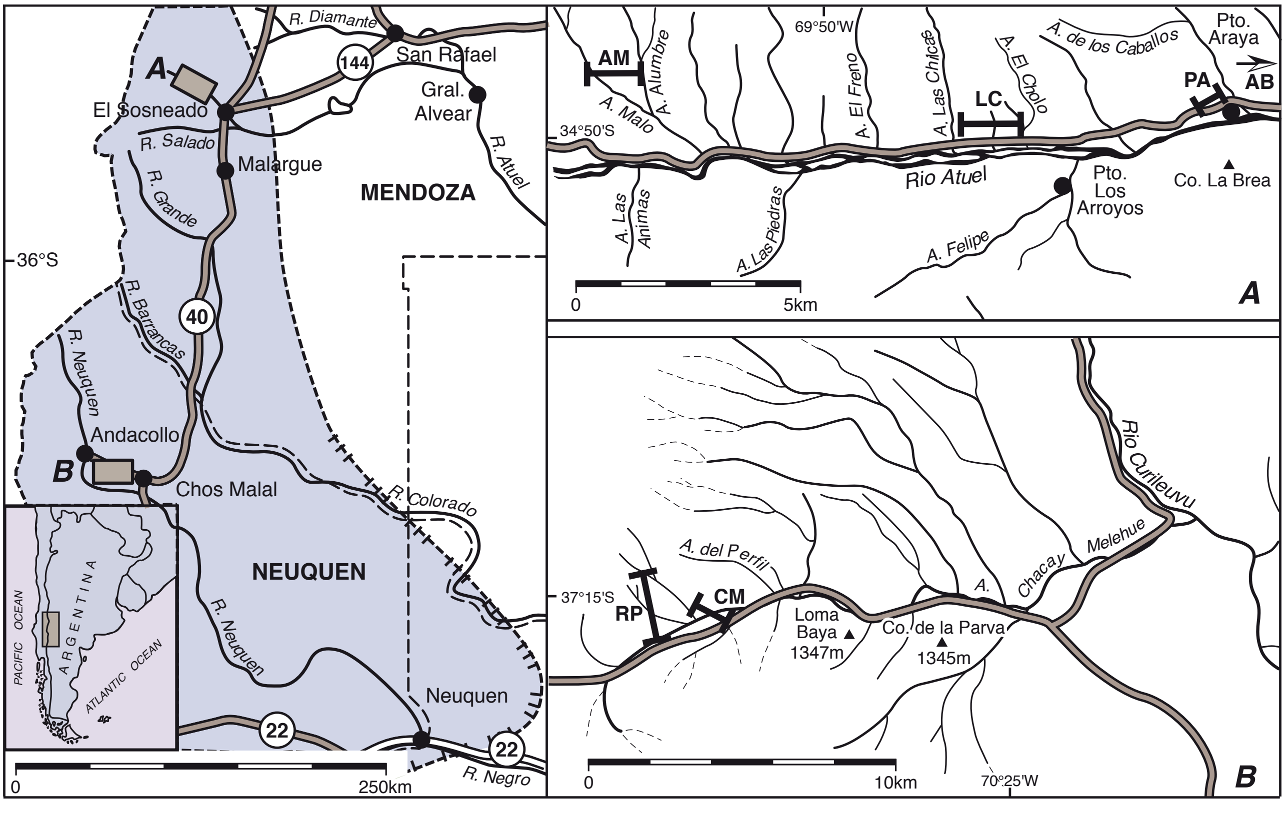


Fig. 1: Sketch map of the Neuquén basin. Sampled localities are, **A**: Arroyo Malo (AM), Las Chilcas (LC), Puesto Araya (PA) and Arroyo Blanco (AB), and **B**: Rajapalo (RP) – Chacay Melehue (CM). Dashed black line marks the basin's borders

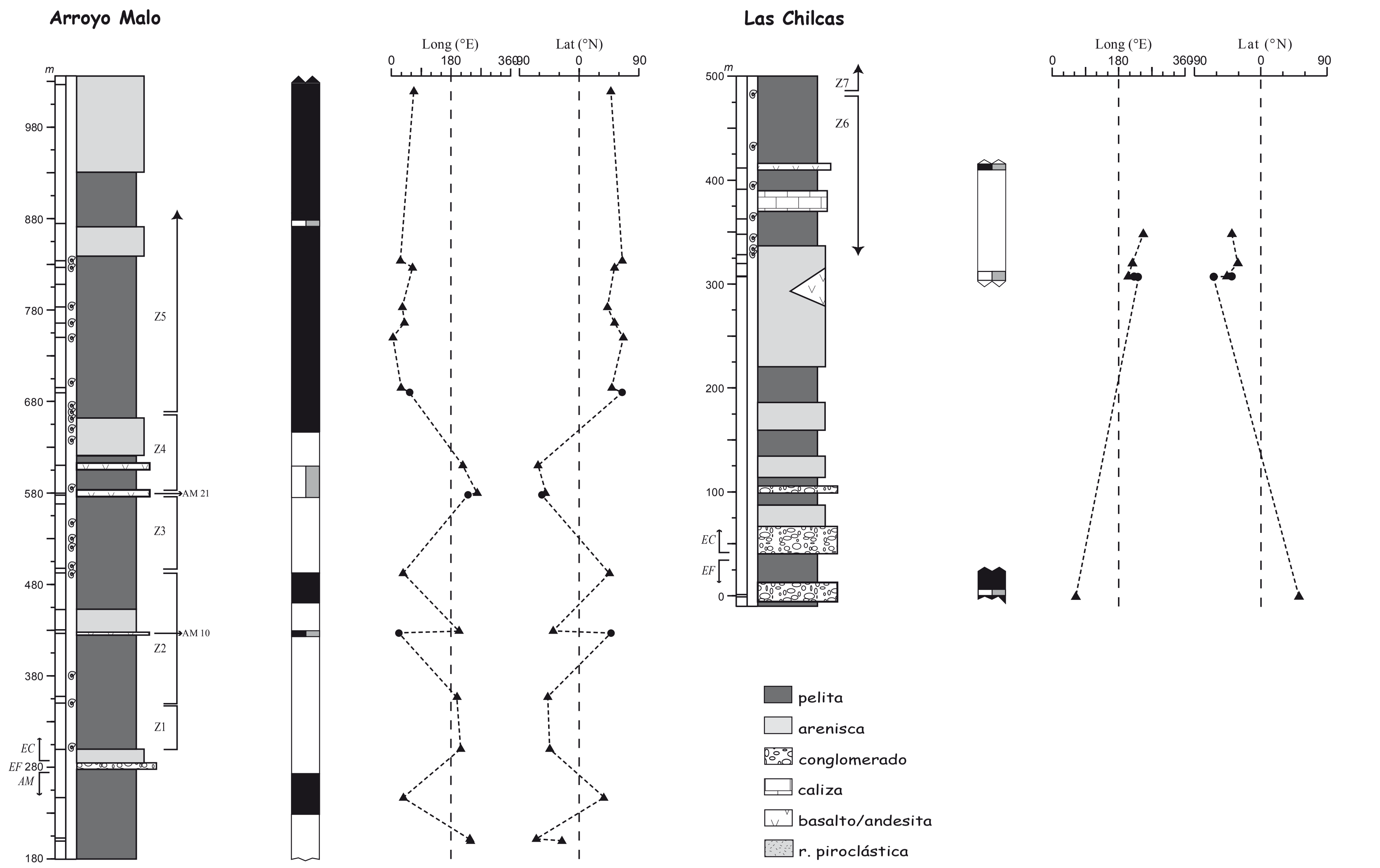


Fig. 2: Stratigraphy, position of sampling sites and virtual geomagnetic poles (VGP) from Arroyo Malo and Las Chilcas (Hettangian-Sinemurian). From left to right: palaeomagnetic and ammonite sites, ammonites zones, polarities and VGP computed per site. Black: normal polarity, white: reverse polarity. Half-column shows polarities isolated in sills that were not considered for magnetostratigraphy but are included in the calculation of the Hettangian-Sinemurian palaeopole. Symbols: palaeomagnetic sites with circles (triangles) indicate a number of samples $\geq$ 3 ($\leq$ 2). *AM:* Arroyo Malo Formation, *EF:* El Freno Formation, *EC:* El Cholo Formation.

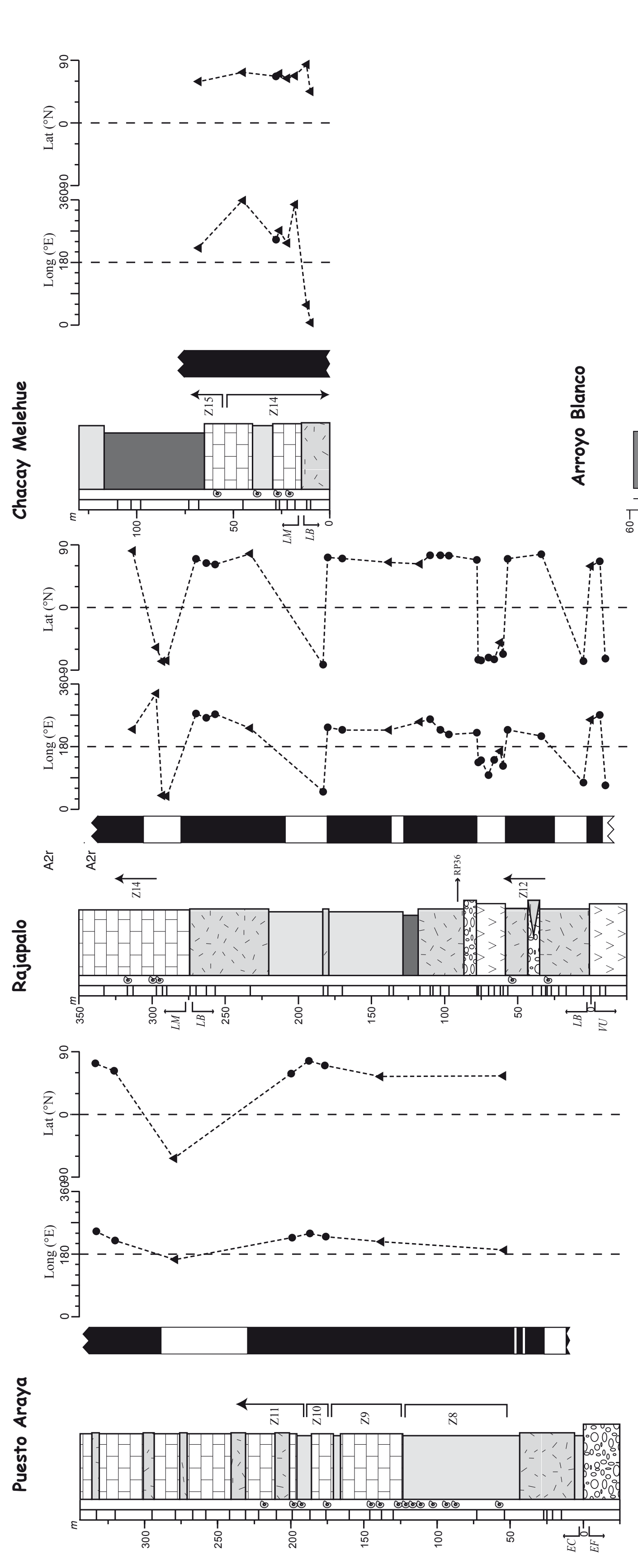
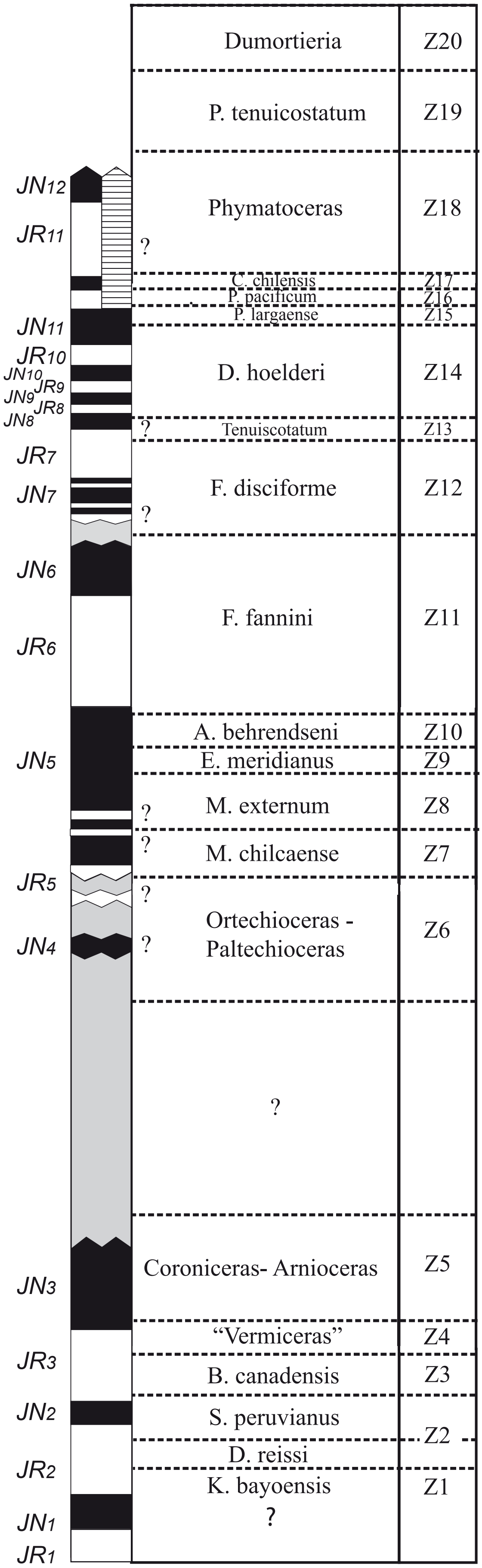


Fig. 3: Stratigraphy, position of sampling sites and virtual geomagnetic poles (VGP) from Puesto Araya, Rajapalo-Chacay Melehue (Pliensbachian-Toarcian) and Arroyo Blanco (polarities only). *UV*: volcanic unit, *LB*: Lista Blanca Fm., *LM*: Los Molles Fm., *ChM*: China Muerta Fm. Symbols as in Fig. 2.



(in Arroyo Malo), which was assigned by RICCARDI to the *Waehneroceras-Scholotheimia* whereas here the same author split Z2 into *S. peruvianus* and *D. reissi*. The other difference is Z5 and Z6, formerly belonging to the "*Agassiceras"* and *"Epophioceras"* respectively, had considerable extension in the older scale, whereas in RICCARDI (2008) both biozones have been notably reduced with an uncertain interval in between.

Hettangian-Sinemurian

Sampled sections of this age are located to the NW, at the northern margin of the Atuel river, between the Arroyo Malo and Arroyo Las Chilcas (Fig. 1a). Successions are made up of 2 km-thick of fine-grained sedimentary and volcanic rocks that become coarser and younger to the east. Deposits in this area conform the synrift phase that correspond to fault-controlled deltas. In Arroyo Malo to the west (Fig. 2), the section is made up of 1 km-thick of fine-grained sedimentary rocks mainly, and subordinate volcanic rocks. It is conformed from bottom to top by the Arroyo Malo Formation, El Freno Formation and El Cholo (= Puesto Araya) Formation (RICCARDI *et al.,* 1988, 1991, 2004). The Arroyo Malo Fm. (Fig. 2, 3) bears ammonites from the Upper Triassic (RICCARDI & IGLESIA LLANOS, 1999), whereas on the upper part of the Las Chilcas Fm., the *Psiloceras rectocostatum* Z1 (Lower Hettangian) to *Coroniceras-Arnioceras* (formerly called "*Agassiceras"*) Z5 Zones (Lower Sinemurian), are represented. In this interval, at least three sills of alkaline composition were recognised and sampled, the one at the bottom (Z2) corresponding to a basalt and the other two (Z3-Z4) to lamprophyres. At Las Chilcas (Fig. 2), a 500 m-thick section was sampled. Here in the El Cholo Fm., ammonites from the *Orthechioceras-Paltechioceras* (formerly called *"Epophioceras"*)- Zone Z6 indicate a Sinemurian age, whereas those from the *M. chilcaense* formerly called *Miltoceras* Zone Z7 are assigned to the Sinemurian-Pliensbachian boundary. At 300 m from the base, alkaline sills are also intercalated in the section,

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Fig. 4: With the isolated polarities in five marine sections, tied to the corresponding ammonite Zones, a composite magnetostratigraphic scale was constructed for the Lower Jurassic. 12 dominant normal polarity zones were identified in the scale (JN_1 to JN_{12}) with 11 dominant reverse (JR_1 to JR_{11}). Ammonite zones follow the new biostratigraphic scheme from RICCARDI (2008). Here, Z2 correspond to *D. reissi* and *S. peruvianus* Zones, but in IGLESIA LLANOS & RICCARDI (2000), IGLESIA LLANOS *et al.* (2006), Z2 identified the *Waehneroceras-Schlotheimia* Zone. The interval in the scale shown in grey and with question mark located between Z5 and Z6, formerly corresponded to part of Agassiceras and part of Epophioceras Zones, although in the present scheme it is uncertain (RICCARDI, 2008). Question marks display intervals with uncertain polarities and/or biozones.

and have been sampled (Fig. 2) for palaeomagnetic and petrographical purposes. These sills disappear in the sag deposits, indicating that they were injected during the first stages of the rift formation. Based on the geology, composition and petrography of these sills, they have been interpreted as of Hettangian-Sinemurian age. Moreover, the undeniable primary origin of the magnetic carriers made the sills injected in the El Cholo Fm., optimal recorders of the palaeomagnetic field. Therefore, they were used as reference palaeomagnetic directions in relation with coeval sedimentary rocks (IGLESIA LLANOS *et al.,* 2006).

In addition, in the El Cholo Fm., flattened ammonites and concretions, along with sedimentary structures, prove that the sequence was subjected to considerable compaction. Measurements of the axis of fossils indicate compaction values of around 66% with respect to the same undeformed ammonites from northern Chile (A.C. RICCARDI, personal communication).

Pliensbachian-Toarcian

Sampled rocks of this age are located (Fig. 1) to the north (Puesto Araya, Arroyo Blanco) and centre (Rajapalo, Chacay Melehue) of the basin.

In Puesto Araya (Fig. 3), a c. 400 m thick section is made up of a coarser-grained and younger El Freno and El Cholo Formations (Fig. 1a). Here, the El Cholo Fm. bears ammonites (VOLKHEIMER, 1978; RICCARDI, 1983; WESTERMANN & RICCARDI, 1985; HILLEBRANDT, 1987) from the *M. externum* (formerly called *Tropidoceras)*-Z8 to *F. Fannini* Z11, indicate an Upper Sinemurian-Lower Pliensbachian age. On top of Puesto Araya to the east, the section of Arroyo Blanco (Fig. 1a) is 80 m thick and is made up of fine-grained ammonite-bearing sedimentary rocks. They represent the El Cholo and China Muerta Formations. Although ammonites have not been thoroughly identified yet, they were useful enough to determine the Lower-Upper Toarcian boundary, from which the age of polarities could be interpreted.

To the centre of the basin, the Rajapalo-Chacay Melehue section (Fig. 3) is 500 m thick, and is composed (Fig. 3) by a volcanic basement, on top of which lie (CLAVIJO, 1944; DAMBORENEA, 1987; GULISANO & GUTIÉRREZ PLEIMLING, 1995) the Lista Blanca (= La Primavera) Formation and Los Molles Formation. Such formations are conformed by volcanic, sedimentary and pyroclastic rocks that correspond to off-shore facies (Fig. 3). Ammonites belong to the *F. disciforme* Z12 (Upper Pliensbachian) to *P. largaense* Z15 (Lower Toarcian). The Arroyo Blanco section (Fig. 3) on the other hand, is made up of 60 m thick of black shales. Ammonites in this section have not been thoroughly determined, but were of primary importance to tie the isolated polarities.

PALAEOMAGNETIC RESULTS

Treatment and analysis of specimens were performed at the IGEBA, Universidad de Buenos Aires. Samples were demagnetised using a TSD-1 Schoensted furnace as well as a 2G alternating field demagnetiser. Residual remanent magnetisation was measured using a 2G (DC squids) cryogenic magnetometer. Analysis of magnetic components was carried out using software from Utrecht University and Universidad de Buenos Aires.

Demagnetisation involved at least 10 steps, of up to 550-580°C and/or 130 mT. After each step, magnetic susceptibility (*X*) was measured in order to monitor that no mineralogical change had taken place. *X* is in the order of 1x 10^{-4} SI for sediments and 6x 10^{-4} SI for volcanics, except for basalts in Rajapalo where this parameter is considerably higher (up to 1x 10 SI).

Palaeomagnetic behaviour of specimens was quite variable. In this study, only reliable components were considered, that is, with trajectories to the origin and/or stable components not fully removable, i.e. titanohaematite (Fig. 5). The study of magnetic directions was carried out using principal component analysis (KIRSCHVINK, 1980).

In general terms, two (Fig. 5) or three magnetic components were isolated, carried by *A* secondary titanomagnetite which can be deleted between 200 and 400°C or 20 mT, *B* titanomagnetite of primary origin that was removed between 550 and 580°C or 50 and 60 mT, and *C*, a high temperature / coercivity mineral such as titnohaematite that at around 700°C/ > 130 mT, could not yet be removed. Component *A* bears northern directions with negative inclinations that coincide with the dipolar field of the region (Fig. 6, 7). *B* and *C* on the other hand, yield N-NE directions with negative inclinations and S-SW directions with positive inclinations (Fig. 6, 7). Mean site directions were computed using FISHER (1953) statistics. Given that c. 50% of the specimens were discarded, in Figures 2-3, different symbols have been used to identify sites with number of accepted specimens (N) ≥ 3 (dots) and ≤ 3 (triangles).

Hettangian-Sinemurian

When the bedding-correction is applied to the mean direction of components *B-C*, two distinct groups emerge yielding the same declination but different inclinations (Fig. 6d). The cluster yielding the lowest inclination values is derived from sedimentary rocks (Decl= 231°, Incl= 40.5°), whereas the one with the highest inclinations belongs to the coeval sills (Decl=226.3°, Incl= 58.8°). Such difference in the inclination is the result of inclination shallowing due to compaction by overload. This process makes magnetic carriers rotate toward the horizontal plane, and determines the shallowing of the primary inclination in the sedimentary rocks. Hence, a primary conclusion is that the compaction observed in ammonites, concretions and structures is also detected by the palaeomagnetic method. If such a fact is to be assessed, two conditions must be fulfilled: to know the inclination of the original field – here provided by the volcanic rocks – and the flattened inclination of the sedimentary rocks. On this basis, we applied a classic compaction correction (KING, 1955) as follows:

$I_o = \tan^{-1} (\tan I_s/f)$

where f is computed from the relationship between the mean direction of the Hettangian-Sinemurian sedimentary rocks and the mean direction of the sills. The resultant value of f was applied each site in order to obtain I_o. Furthermore, we compared these results with those obtained using another method that is applicable to magnetite-bearing fine-grained rocks such as those from this study (K. KODAMA, personal communication). It turned out that both results were identical, i.e. 65-70%, just as the compaction values derived from ammonites.

The bedding and compaction-corrected mean direction from component *B-C* –reverse polarity- is Decl= 230°, 58°, α_{95}= 4.5°, k=41, N=25 (Fig. 6c). Such component passes MCFADDEN's (1990) fold test with the minimum test value displayed at 100% of unfolding, which is indicative that the magnetisation isolated in Arroyo Malo and Las Chilcas sections are pretectonic. In addition, it passes MCFADDEN & MCELHINNY's (1990) reversal test in each locality. In Arroyo Malo (Fig. 1A), the latter test was positive class C which indicates that the reverse and normal directions correspond to the same population, while in Las Chilcas (Fig. 1A) the test turned out indeterminate due to the low number of data. In addition, in Arroyo Malo a baked test was performed with one of the sills located at c. 430 m from the base, and the host sedimentary rocks. The latter carried two components: one soft of normal polarity that was easily removed and coincided with the direction of the sill, and the other a reverse polarity hard component which corresponded to the characteristic of the sedimentary rocks. This demonstrates that the injection of the sills was unable to totally remove the characteristic magnetisation. On the basis that component *B-C* passes all field tests for palaeomagnetic stability and the petrographical studies that prove the primary origin of the magnetic carriers, it is interpreted that component *B-C* was acquired during or shortly after the deposition (cooling) of the sedimentary rocks (volcanic rocks).

The palaeomagnetic pole (PP) for component *B-C*, was computed. It is located (Table 1, Fig. 8) at: 223°E, 51°S, A_{95}= 6°, N=25.

Pliensbachian-Toarcian

In Rapalo-Chacay Melehue (Fig. 1B), the best palaeomagnetic behaviours were observed, most likely due to the greater volume of volcanic rocks (Fig.7).

In sections of this age, no signs of compaction – either in the structures or in the fossils – have been observed in the field. Thus, mean site directions from Puesto Araya,

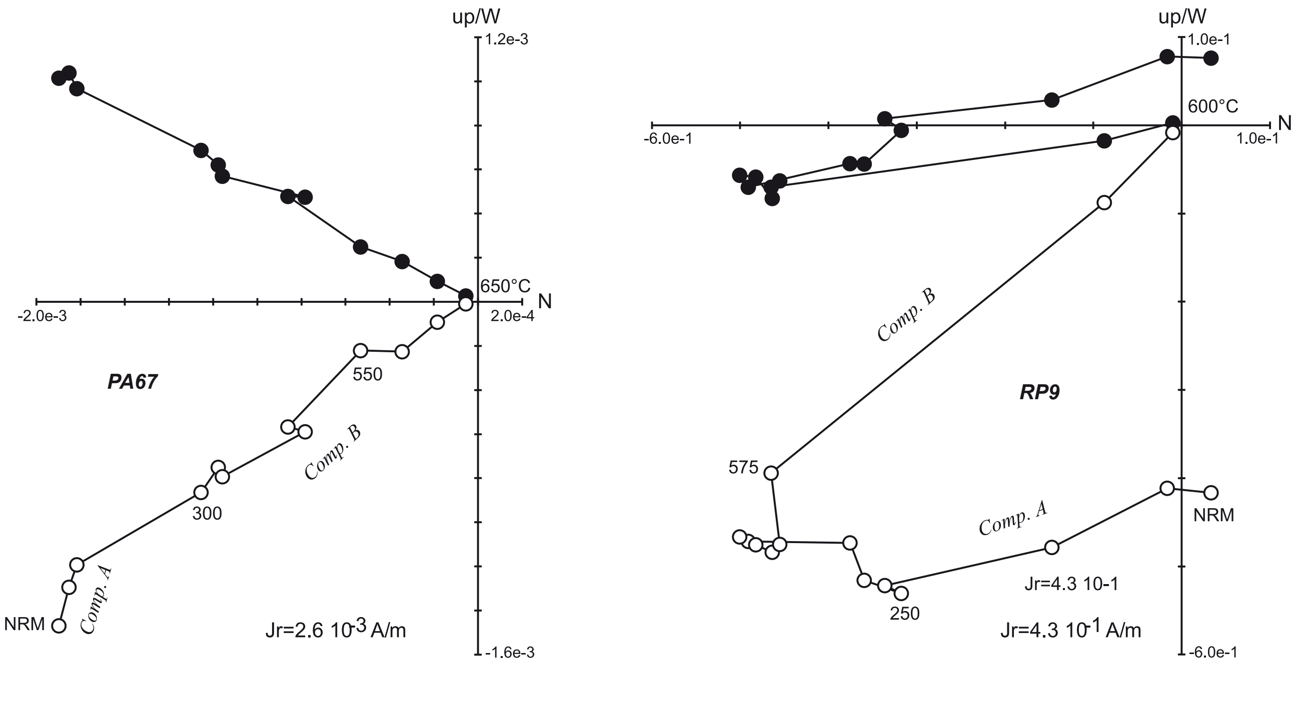


Fig. 5: Orthogonal plots showing representative palaeomagnetic behaviours in Puesto Araya (PA67) and Rajapalo (RP9) (Pliensbachian-Toarcian). Specimens correspond to a sedimentary rock (PA67) and a basaltic flow (RP9) located at 60-75 m from the base. Both diagrams reveal that components *A* and *B* have been removed. Symbols: black (white) circles= declination (inclination), *Jr*= intensity of the natural remanent magnetisation. Directions are bedding-corrected.

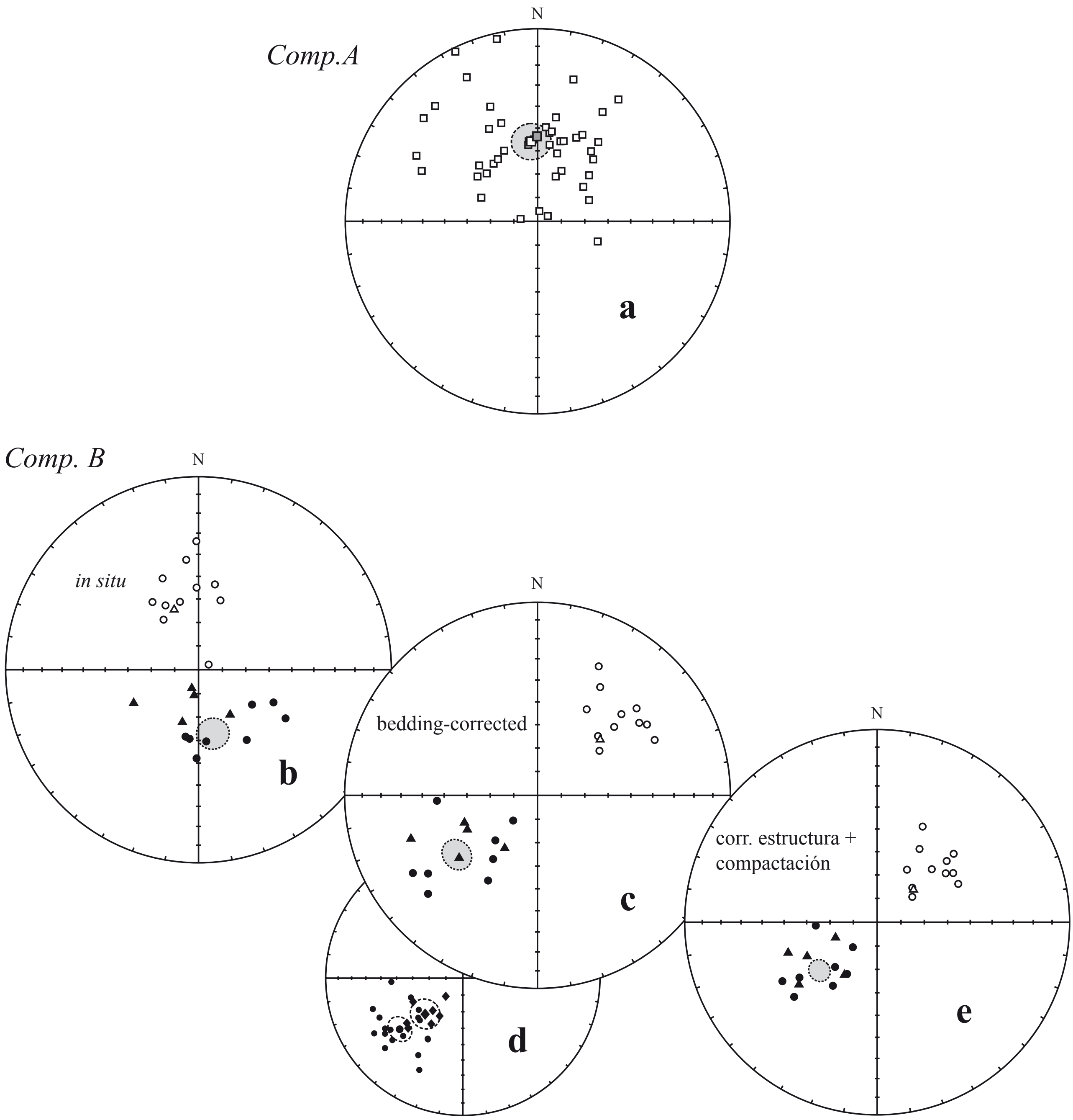
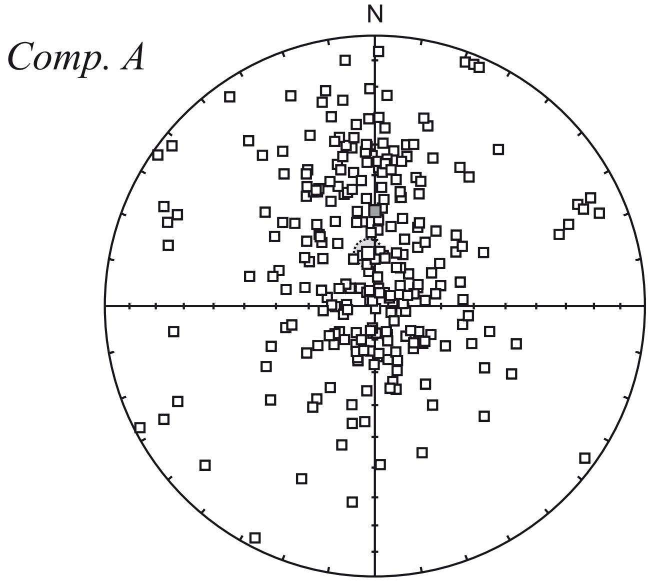


Fig. 6: Stereoplots showing magnetic directions from the Hettangian- Sinemurian localities. Component A yields **a)** *in situ* directions with normal polarity only which is very similar (Dec= 355, Inc= -56, α_{95}= 8°) to the present-day local field, whereas B is depicted **b)** *in situ* **c)** bedding-corrected and **e)** bedding- and inclination error- corrected, with opposite polarities and antiparallel directions. Note that bedding-corrected directions (here shown in reverse polarity) fall **d)** into two well-distinguishable groups, one with high inclinations recorded in the sills (diamonds) and the other with lower inclinations recorded in the sediments (circles). Symbols: full (open) symbols = lower (upper) hemisphere; circles (triangles) = directions at Arroyo Malo (Las Chilcas); gray square= direction of present-day local magnetic field; gray circle= 95% confidence circle in reverse polarity (component B).



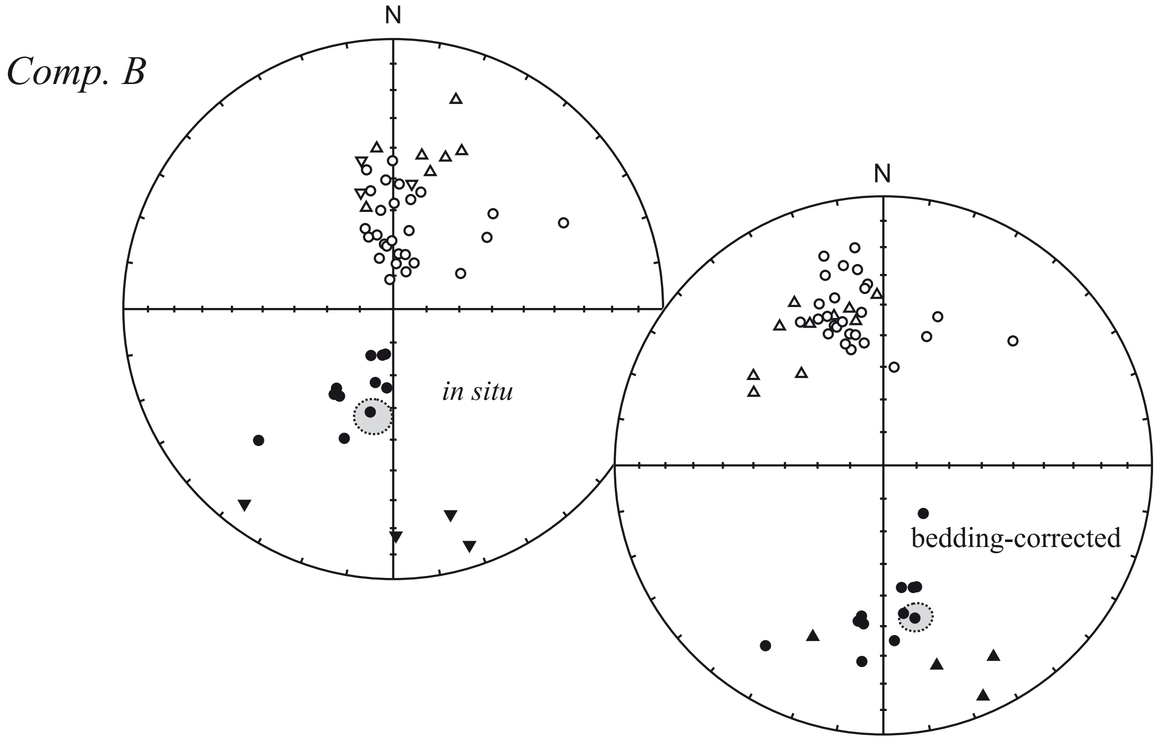


Fig. 7: Stereoplots from the Pliensbachian-Toarcian localities. Component A shows *in situ* sample directions with normal polarity only which is very similar (Dec= 353, Inc= -74, α_{95}= 4.5°) to the expected present-day local field, whereas those of B yields b) *in situ* and c) bedding-corrected, with opposite polarities and antiparallel directions. Symbols: as in Fig. 7; circles (triangles)= mean site directions at Rajapalo-Chacay Melehue (Puesto Araya).

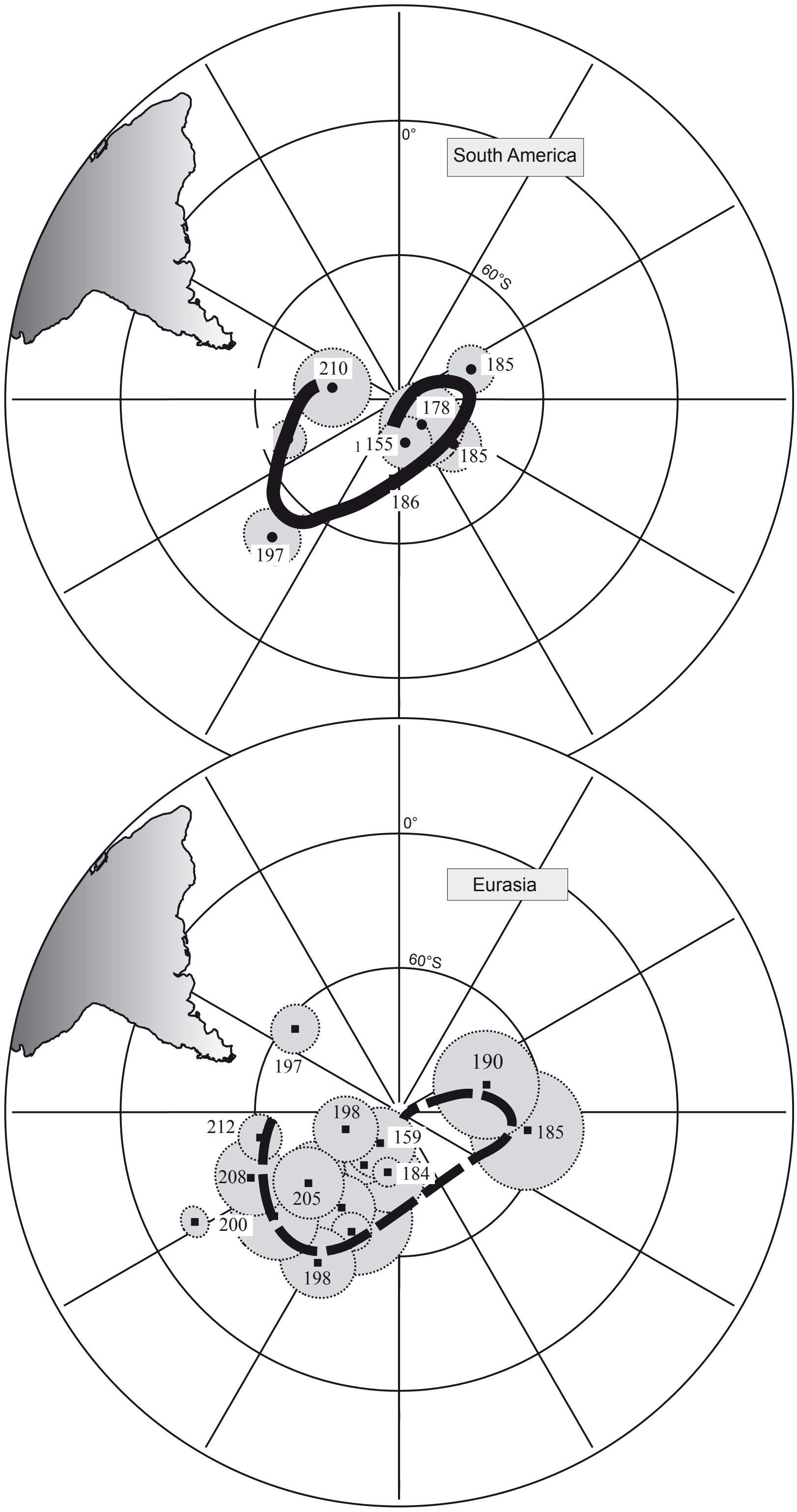


Fig. 8: Late Triassic-Jurassic APW path for South America (solid line) proposed in this study. The APW path of Eurasia (dashed line) constructed using the data in TORSVIK *et al.* (2001), turn out consistent with that of South America. Eurasian PP have been rotated to South American coordinates through two kinematic models, that varied with pole ages. Paths suggest important polar wander during the Early Jurassic.

Kinematic Model 1 (220-193 Ma): EUR-NAM= FREI & COX (1987); NAM-SAF= KLITGORD & SCHOUTEN (1986); SAF-SAM= RABINOWITZ & LA BRECQUE (1979).

Kinematic Model 2 (183-165 Ma): EUR-NAM= ROYER *et al.* (1992); NAM-SAM= PINDELL *et al.* (1988)

210-155: ages according to OGG (2004).

Table 1: Selected palaeopoles from the GPDB v. 4.6 (http://www.tsrc.uwa.edu.au/data_bases) and more recent South American poles. A_{95}: 95% confidence interval. References/RefNo: Reference number in the GPDB.

Code/Geologic unit	Age (Ma)	Lat °S	Long °E	A_{95}	Reference	RefNo
South America						
1. Los Colorados Fm.	210	76.0	280.0	8.0°	Vizán *et al*. (2004)	--
2. Anari-Tapirapua Fm. *(1) (2)*	196.6 ± 0.4	65.5	250.0	3.5°	Montes Lauar *et al.* (1994)	3316
3. Neuquén basin 1 *(2)*	197	51.0	223.0	6.0°	Iglesia Llanos *et al*. (2006)	--
4. Lepá-Osta Arena Fm. *(2)*	180-186	75.5	129.5	6.0°	Vizán (1998)	3314
5. Neuquén basin 2 *(2)*	185	74.0	67.0	5.0°	Iglesia Llanos *et al*. (2006)	--
6. Marifil Complex *(2)*	168-178	83.0	138.0	9.0°	Iglesia Llanos *et al*. (2003)	3535
7. El Quemado Complex (N of 48°S) *(1) (2)*	153-157	81.0	172.0	5.5°	Iglesia Llanos *et al*. (2003)	3535
Eurasia						
1. Sunnhordland dikes *(3)*	221	50.0	305	4.5°	*Walderhaug (1993)	--
2. Volc. N Pyrenees1	200-228	62.1	294.2	7.3°	Girdler (1968)	481
3. Pre-Azov	247-200	38.0	278.0	3.0°	Mikhaylova *et al*. (1989)	2622
4. Donbass	200-228	70.0	268.0	4.0°	Rusakov (1971)	919
5. Rhaetian Seds. *(1)*	200-204	50.0	292.0	7.6°	Edel & Duringer (1997)	3141
6. Hett.-Sinem. Limest. *(1)*	190-200	55.0	280.0	9.0°	Edel & Duringer (1997)	3141
7. Paris Basin Seds. *(1)*	190-200	51.3	285.0	3.1°	Yang *et al*. (1996)	3029
8. Kerforne dikes *(1) (2)*	200 ± 8	61.3	258.8	7.5°	Sichler & Perrin (1993)	2743
9. Main Caucasus	183-196	43.0	337.0	5.0°	Sinitsin & Shevlyagin (1986)	2019
10. Liassic Volcs. *(1)*	196-200	64.9	323.6	6.7°	Girdler (1968)	481
11. N Caucasus Volc.	176-200	68.0	72.0	12.0°	Azanidze & Pechersky (1982)	2010
12. E Donbass	210-190	85.0	41.0	11.0°	Mikhaylova *et al.* (1989)	2622
13. Liassic Seds. *(1)*	185-190	76.9	314.7	3.0°	Hijab & Tarling (1982)	1467
14. Thouars and Airvault Sections *(1)*	176-183	70.5	276.3	11.8°	Galbrun *et al*. (1988)	1427
15.Scania Basalts *(1) (2)*	176-183	69.0	282	6.8°	Bylund & Halvorsen (1993)	2720
16. Alsace Bajocian Seds. (1)	168-170	63.0	300	6.0°	Kadzialko-Hofmokl *et al*. (1988)	1514
17. Subtatric Nappe Seds.	151-168	71.7	312.2	4.0°	Kadzialko-Hofmokl & Kruczyk (1987)	1948
18. Limestones. Krakow-Czest. *(1)*	155-165	72.3	330.4	7.3°	Kadzialko-Hofmokl & Kruczyk (1987)	1948
19. Terres Noires *(1)*	155-165	77.6	309.7	7.0°	Aubourg & Rochette (1992)	3156
20. Oxfordian Seds. *(1)*	155-159	70.1	327	4.0°	Kruczyk & Kadzialko-Hofmokl (1988)	616

(1) also included in*:* van der Voo & Torsvik (2004)
(2) also included in Kent & Torsvik (2010)
(3) also in van der Voo & Torsvik (2004)
Ages according to Ogg (2004)

Rapalo and Chacay Melehue sections have been bedding-corrected only, yielding a mean directions for component *B-C* of Decl=168.5°, Incl=41, α_{95}=4.5°, N=52 (Fig. 7).

In the basaltic interval in Rajapalo at 65-70 m from the base (Fig. 3), at least 5 flows were recognised for the first time, each one bearing different values of *X* (Iglesia Llanos, 1997) that vary between 1 x 10^4 and 1 x 10^2 SI. Magnetic directions from these lava flows were taken as reference directions, such as was the case with the Hettangian-Sinemurian sills.

In Rajapalo-Chacay Melehue, component *B-C* passes the fold test, yielding the minimum test value for 100% of unfolding and thus indicating that the isolated magnetisations are pretectonic. Likewise, it also passes the reversal test (class C), thus revealing that reverse and normal directions belong to the same population. Meanwhile in Puesto Araya (Fig. 1B), the reversal test was indeterminate due to the scarce number of data. In addition in Rajapalo, a conglomerate test was carried out at the level situated c. 80 m from the base (Fig. 3) and turned out positive, which indicates that the section below has not been remagnetised. Therefore, the fact that the Pliensbachian-Toarcian rocks do pass all field tests for palaeomagnetic stability and that petrographical studies

reveal the primary origin of the magnetic carriers, it is interpreted that the isolated magnetisation was acquired during or shortly after the deposition (cooling) of the sedimentary (volcanic) rocks.
From component B-C, a PP was derived, which is located at: 61°E, 88.5°S, A_{95}=3.5° and N= 262.

MAGNETOSTRATIGRAPHY

With the polarities isolated in each section (Fig. 2, 3), a composite magnetostratigraphic scale was constructed (Fig. 4). In the first place, ammonite zones of the Andean region were correlated with those of the Tethyan zone, and subsequently polarities were used to achieve a finer correlation between the geomagnetic time scales (Fig. 9). Results show that in the Andean region, the scale is made up by 12 dominantly normal polarity zones (JN_1 to JN_{12}), and 11 dominantly reverse zones (JR_1 to JR_{11}). This Lower Jurassic 23 polarity zones that have been recognised in the Neuquén basin, are tied to 19 ammonite Zones. The international scale (Fig. 9) on the other hand, yields, in general terms, more polarity reversals than the regional scale, comprised in a similar number of ammonite Zones from the Tethyan Realm.

Hettangian-Sinemurian

Polarities isolated in the sills at Arroyo Malo and Las Chilcas (half-column in Fig. 2) have not been considered in this part of the study, since they clearly were injected after the deposition of the sedimentary rocks.
In general terms, this time interval is assigned a poor reliability in the international scale due to the scarce or null content of ammonites in the sections from the northern hemisphere. In the Hettangian, the quality in the correlation with the local scale depends on the fact that polarities comprised between the Liasicus and Semicostatum Zones of the international scale are moved down until the dominant normal zone in the Semicostatum coincides with JN_3 (Fig. 9). In the Sinemurian, on the other hand (Fig. 9), there is a considerable interval between Z5 and Z6 – comparable with the top of Semicostatum to Raricostatum – devoid of ammonites. In the Upper Sinemurian, polarity correlations are somehow uncertain, due to the great number of reversals in the international scale, just as in the case of JN_4 and JR_5 in Z6 in the base of Las Chilcas. Finally on the top of the Sinemurian, there appears a reverse polarity (JR_5) that is not recorded in the international scale (Fig. 9).

Pliensbachian-Toarcian

This time interval presents the most solid correlations, both palaeomagnetic and biostratigraphic (Fig. 9). In this sense, minor polarities zones in the regional scale correlate very well with the international scale, just as observed in Z1 and Z12. If the equivalence proposed for JN_5 is correct, then the barren levels from the base of Puesto Araya (Fig. 3) mark the Z7-Z8 boundary. On the other hand, such correlation helped to interpret that at Rajapalo in JR_7, we find in the barren levels at approximately 200 m from the base the Pliensbachian-Toarcian boundary (Fig. 3). The Toarcian encompasses a great number of reversals in the regional scale (Fig. 9). From Z15 on, represented polarities are those isolated in Arroyo Blanco. Here, ammonites only helped to locate the Lower-Upper Toarcian boundary. Thus, on the basis of palaeomagnetic data, it is interpreted that the boundary between the El Cholo and China Muerta Formations in Arroyo Blanco falls within the normal polarity zone JN_{11}, between Z14 and Z15. Therefore, Arroyo Blanco would comprise the polarity zones from Z13 (JN_8) to Z18 (JN_{12}) (Fig. 9) although the best fit is achieved in the Lower Toarcian rather than in the Upper Toarcian due to the scarce number of samples.

PALAEOGEOGRAPHY

The two Jurassic palaeomagnetic poles were combined with others from the literature to construct South America's apparent polar wander (APW) path (Tabl. 1, Fig. 8). APW paths depict (Creer *et al.,* 1954) the ancient positions of the Earth's spin axis (= averaged palaeomagnetic pole) with respect to a certain lithospheric plate, hence the name "apparent". The path is constructed as a sequence of palaeomagnetic poles tracking away from the geographic pole with increasing age. Tracks represent rotations about Euler poles whereas cusps symbolise times of reorganization of the lithospheric plate boundaries and resulting driving forces (Cox & Hart, 1986). In other words, a cusp establishes the precise time when the motion of plates changed relative to the spin axis.
The resultant APW path shows two different pole positions, i.e. Hettangian-Sinemurian (197 Ma) and Pliensbachian-Toarcian (185 Ma), which determines the occurrence of a cusp during the Lower Jurassic (Tabl. 1, Fig. 8). This change in the pole positions has been previously suggested in Iglesia Llanos (1997) and Vizán (1998). The 197-185 Ma track reveals a c. 50° shift in the pole positions during this time, and a minimum angular change of poles of approximately 4° Myr^{-1}, which is rather fast.
A key question is whether the same polar shift could be observed in other continents from Pangea. Therefore, we chose the continent bearing the most reliable Jurassic data, both palaeomagnetic and biostratigraphic, i.e. Eurasia (Tabl. 1, Fig. 8). This continent's APW path was derived using the global palaeomagnetic database (Tabl. 1) (http://www.tsrc.uwa.edu.au/data_bases), and pole ages were recalculated according to Ogg (2004). Palaeopoles were translated to South American present-day geographic coordinates using the kinematic models that provided the best fit between poles. For Eurasia,

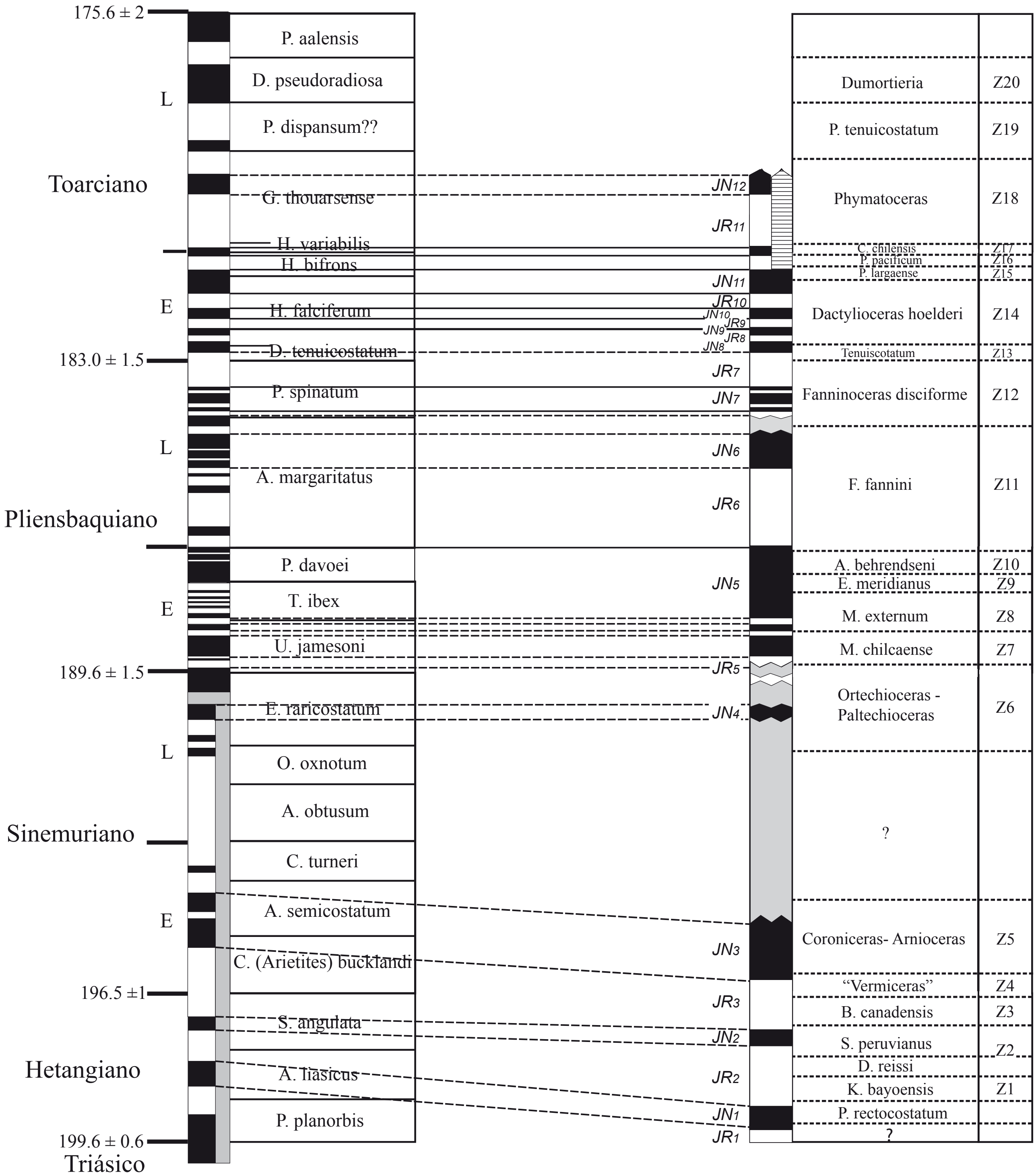


Fig. 9: Bio-magnetostratigraphic correlation between (right) the local scale and (left) the international geomagnetic time scale (Ogg, 2004). Biostratigraphic scheme follows Riccardi (2008). In order to achieve a good fit in the Hettangian and Lower Sinemurian, polarities in the international scale should be displaced downward, whereas the reverse polarity JR_5 does not show in the international scale. In the Pliensbachian on the other hand, there is a good fit between polarity zones although their frequency is somewhat higher. In the Toarcian we found the greatest frequency of reversals, the best fit between scales and precise dating of sampling levels in Rapalo and Arroyo Blanco. From the correlation between scales, it was possible to date barren intervals in the studied sections.

Frei & Cox (1987) were used to move the continent to North America, Lawver & Scotese (1987) to move North America to Africa and to South America. The resultant path became very similar to the one obtained for South America in terms of shape and chronology (Fig. 8). This constitutes one of the first evidences regarding the occurrence of (true) polar wander, which is the drift of the whole rigid Earth with respect to the rotation (= palaeomagnetic) axis.

From the two new palaeopoles, palaeolatitudes of Chos Malal (37.3°S, 70.5°W) in the centre of the Neuquén basin were computed (Fig. 10). Thus, during the Upper Triassic and Lower Jurassic, the locality was positioned in its southernmost palaeolatitudes, i.e. 50°S. By the end of the Lower Jurassic, the continent moved at around 20 cm yr^{-1} to the north, until in the Pliensbachian-Toarcian Chos Malal was located at 25°S.

“Absolute” palaeogeographical reconstructions of South America

Palaeomagnetism provides palaeolatitudes and orientations of the continents to perform palaeogeographical reconstructions. Yet, the methodology alone cannot estimate palaeolongitudes due to the symmetry of the time-averaged geomagnetic field about the rotation axis. In order to carry out palaeolatitudinally and palaeolongitudinally - controlled or “absolute” palaeoreconstructions, Morgan’s (1983) grid hot spots (HS) have been used. HS are considered to remain more or less fixed to the mantle, although this is still matter of hot debate. Thus, if the motion of South America can be determined with respect to the grid of HS and is combined with the palaeomagnetic data that are indicative of the ancient position of the geomagnetic pole (palaeopole) for a specific locality and time, an absolute palaeogeographic reconstruction for the continent is achieved.

Accordingly, to achieve an absolute palaeoreconstruction, South America has been translated to the palaeolatitudinal position that occupied from 215 to 160 Ma using the palaeopoles from the apparent polar wander path (Fig. 8), and then rotated once again to compensate for the motion of South America in relation with the Atlantic Ocean hotspots (Fig. 9). For rotations, we used the GMAP software (Torsvik & Smethurst, 1999).

Results show that, during the Late Triassic until the Sinemurian (~ 210 to 200 Ma), South America would have been located at its southernmost position and rotated counter clockwise (CCW) with respect to present-day orientation (Fig. 9). Subsequently, the continent moved northward while rotated approximately 50° CW at higher speeds (c. 4° Myr^{-1}). By the Pliensbachian (~ 185 Ma, Fig. 6), South America reached its northernmost latitudes whereas by the end of the Early Jurassic, the continent moved back to the south until in the Middle Jurassic occupied similar present-day latitudes.

We know that latitude is one of the important variables that affects climate. This leads to the question whether the changes in palaeolatitudinal positions were supported by palaeoclimatic proxies. We thus analysed data derived from geological and palaeobiogeographic records, with the intention of throwing light on the palaeoclimate that has been inferred for the Jurassic.

Marine invertebrates

Bivalves are considered to be sensitive to water temperatures. In the Southern Hemisphere during the Hettangian-Sinemurian (~ 200 Ma), the boundary between the South Pacific – high latitudes – and Tethyan – low latitudes – Realms was located (Fig. 10) in northern Chile (Damborenea, 2001, 2002), at the time that the supercontinent was located at its southernmost position. By the end of the Sinemurian and throughout the Early Jurassic, the same boundary shifted to the south until by the Toarcian, high-latitudes bivalves became restricted to southernmost South America (Damborenea, 2001, 2002). At this time, the continent was located at low palaeolatitudes (Fig. 10). Likewise, the Pliensbachian marked the first expansion of colonial corals (warm water temperatures) in west-central Argentina (Fig. 10).

Palaeoflora

Volkheimer *et al.* (2008) record that the content of the warm temperatures pollen *Classopollis* in the Neuquén Basin in west-central Argentina, was not greater than 60% during the Sinemurian-Early Pliensbachian, when the Neuquén basin, presently at c. 37°S, was located at c. 50°S (Fig. 10). However, during the Late Pliensbachian-Early Toarcian, pollen *Classopollis* increased to 91-99%. By this time, also the first appearance of a new group of Araucariaceae (*Callialasporites* spp.) indicates a climatic amelioration (Volkheimer & Quattrocchio, 1981). This time coincides with the interpretation that during this time the Neuquén basin was at its northernmost position – c. 25°S – (Fig. 10).

Vertebrates

In the central southern Andes in Argentina, abundant marine crocodiles, turtles and frogs have been reported. Although the interpretation of vertebrates as reliable palaeoclimatic proxies should be handled with some caution, they seem to indicate rather warm waters during the Middle and Late Jurassic (Volkeimer *et al.,* 2008 and references therein).

Geology

During the lowermost Jurassic in the Southern Hemisphere, cool conditions prevailed. This primary interpretation is based on the fact that carbonates were absent, whereas siliciclastic deposits prevailed (e.g. Spalletti *et al.,* 1999; Gómez-Pérez, 2003). During this time, it is interpreted that the continent was located at its southernmost position (Fig. 10). Subsequently, by the Late Early to Middle Jurassic, climate became humid, as indicated by the frequent occurrence of coal and well preserved flora (Volkheimer *et al*., 2008).

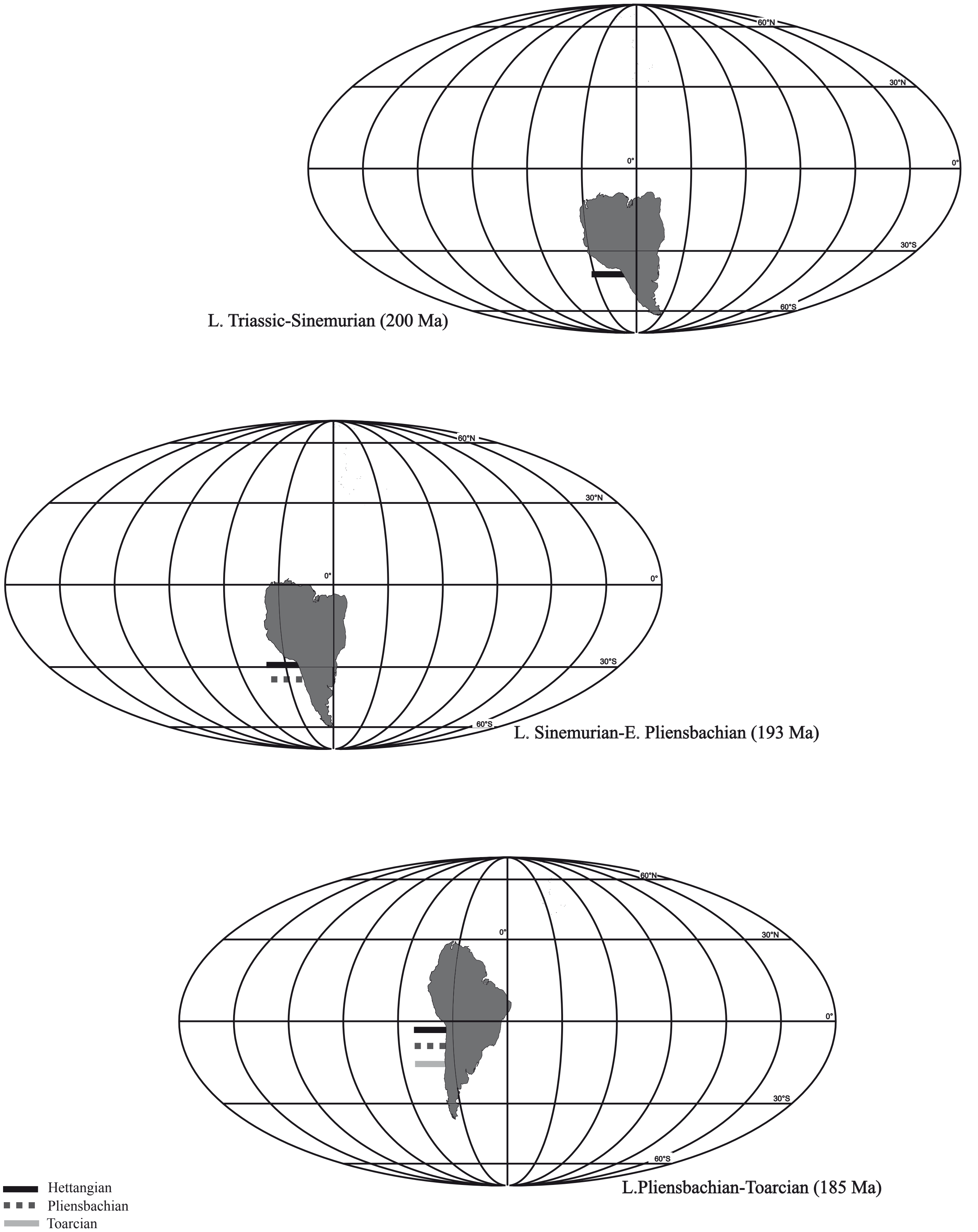


Fig. 10: "Absolute" palaeogeographical reconstructions of crude Pangea for the Early Jurassic. During the Late Triassic-Early Sinemurian, Pangea was placed at its southernmost position. At this time, the boundary – solid thick line – between the South Pacific (high latitudes) and Tethyan (low latitudes) Realms of bivalves was located in northern Chile (Damborenea, 2001, 2002). Subsequently and throughout the Early Jurassic, Pangea moved northward and rotated CW, until the Late Pliensbachian-Early Toarcian when it reached the northernmost position. During this time, the boundary kept shifting toward the south until in the Early Toarcian, high-latitudes bivalves became restricted to the southern extreme of the continent.

Thus we can conclude that, in general terms, palaeoecological data support the palaeolatidudinal changes observed in this study.

CONCLUSIONS

Five ammonite-bearing sections located to the north and centre of the Neuquén basin have been sampled for palaeomagnetic purposes. These sections are made up of sedimentary and subordinately, volcanic rocks of Lower Jurassic age.

The palaeomagnetic study showed that there are two magnetic components, one soft that coincides with the dipolar field of the region, and another harder that is dissimilar from any younger magnetisation. According to the field tests for palaeomagnetic stability and petrographical studies, the latter component has been acquired during or shortly after the deposition (cooling) of sedimentary (volcanic) rocks. Thus, the hard component is interpreted as the original Jurassic.

With polarities isolated in all five sections, the first Lower Jurassic magnetostratigraphic scale of the southern hemisphere has been constructed. To anchor the polarities to the international geomagnetic scale we used ammonites (Riccardi, 2008), which in turn were correlated with the Tethyan biozones. Thus, the regional scale is made up of 11 dominant reverse (JR_1 to JR_{11}) and 12 dominantly normal (JN_1 to JN_{12}) polarities, included in 19 ammonite Zones. A good correlation was achieved with the international scale that helped to constrain some issues that were still at loose ends. In the first place, in the Hettangian-Sinemurian interval, polarities comprised within the international Liasicus and Semicostatum biozones should be displaced down until the dominant normal polarity coincides with the regional JN_3. In the second place, during the Pliensbachian and Toarcian, the frequency of reversals increases and yet, correlations between the scales are more solid. Results allowed assigning precise ages to those levels devoid of diagnostic fossils. This is the case of the Sinemurian-Pliensbachian boundary in Puesto Araya, the Pliensbachian-Toarcian boundary in Rajapalo, or the Toarcian in Arroyo Blanco. In addition, two PP have been computed, one for the Hettangian-Sinemurian interval (223°E, 51°S, A_{95}=6°, N=25), and the other for the Pliensbachian-Toarcian (67°E, 74°S, A_{95}= 5°, N=52). These palaeopoles were combined with others from South America in order to obtain the continent's APW path for the Jurassic. The resultant path turned out dissimilar to those proposed in the literature, showing a cusp at 197 Ma that indicates that, particularly during the Early Jurassic, South America was subjected to notable changes both in orientation and palaeolatitudes. This model is in opposition with the common interpretation that the continent had remained in a fixed position throughout most of the Mesozoic. According to our interpretation, during the Late Triassic–Sinemurian, South America was rotated counterclockwise with respect to the present-day and at its southernmost position with Chos Malal in the centre of the Neuquén basin, located at 50°S. In the Pliensbachian-Toarcian, the continent rotated clockwise and displaced to the north until in it reached its northernmost location, with Chos Malal placed at 25°S. By the end of the Early Jurassic, South America moved back to the south until the Middle and Late Jurassic, when the continent was positioned at similar present-day latitudes.

Results suggest that South America's displacements were the result of true polar wander, which is the shift of the whole rigid Earth with respect to the rotation (= palaeomagnetic) axis.

The palaeolatitudinal changes observed in the Jurassic are fully supported by palaeocological data, derived from marine invertebrates, vertebrates, palaeoflora and geological data.

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