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Syntectonic magnetization of the mid-Palaeozoic Sierra Grande Formation: further constraints on the tectonic evolution of Patagonia

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Abstract: A palaeomagnetic study was carried out in the Silurian–Devonian clastic sedimentary rocks of the Sierra Grande Formation, exposed in northeastern Patagonia (41.6°S, 65.3°W). Thirteen sites ($n=88$) were located on opposite limbs of a syncline–anticline structure. Stepwise thermal demagnetization permitted the identification of a very stable magnetic component of reversed polarity carried by hematite. Stepwise performance of the fold test yielded negative results both *in situ* and after 100% bedding correction, but positive after partial unfolding (19%). This indicates a syntectonic origin for the isolated magnetization. A pole position was computed for the partially (19%) corrected remanence: SG3: 77.3°S, 310.7°E, $\delta p=7.7°$, $\delta m=6.6°$, $N=13$. Its position is coincident with late Early to Late Permian palaeomagnetic poles from South America, suggesting that age for the previously undated folding of the Sierra Grande sequence and therefore for the main tectonic event that affected the northern boundary of Patagonia. Palaeozoic palaeomagnetic poles from Patagonia obtained to date agree with those from Gondwana of Devonian or younger age, suggesting that Patagonia did not undergo important displacements relative to South America since those times. This and the Permian age of deformation determined in this study invalidates tectonic models involving collision of a far-travelled Patagonia with Gondwana in the mid- or Late Palaeozoic.

Keywords: Patagonia, Palaeozoic, Gondwana, palaeomagnetism.

Patagonia is the extreme southern part of South America. Its peculiar geological features have attracted the attention of many geologists since the first decades of this century. In particular, Keidel (1925) and Windhausen (1931) suggested that Patagonia may have evolved apart from the rest of the South American continent during part of the Phanerozoic. In plate-tectonic terms this is to say that Patagonia may be considered as a suspect terrane. In the last two decades several hypotheses were proposed suggesting an allochthonous nature of the Patagonian block (Dalmayrac *et al.* 1980; Martinez 1980; Ramos 1984, 1988; Selles Martinez 1988). These were mainly based on considerations of several geological and tectonic features around the northern boundary of this terrane. However, some of these models cannot sustain thorough scrutiny (see Ramos 1984 for a discussion of different models). More recently, Dalla Salda *et al.* (1992) presented a radically different hypothesis, proposing that the western areas of Patagonia and most of western Argentina were part of an allochthonous terrane with Laurentian affinities ('Occidentalia'), that was accreted to South America in Ordovician times. According to this hypothesis, eastern areas of Patagonia would be part of the older cratonic nuclei of South America. The older ages of accretion of 'western Patagonia' proposed in this model imply an essentially autochthonous character for the whole of Patagonia in mid- and Late Palaeozoic times.

The most consistent and favoured of the 'allochthonous' models that consider Patagonia as a single block is that proposed by Ramos (1984), which suggests that this terrane underwent a frontal collision with the southern margin of Gondwana during the Late Palaeozoic. It has also been speculated that Patagonia was part of a ring of accreted terranes that collided with southern Gondwana in the Late Palaeozoic (Kay *et al.* 1989; Kay 1993). According to Ramos's (1984) model (Fig. 1), an ocean was consumed between the northern boundary of Patagonia and the southern Gondwana margin by subduction beneath Patagonia, until collision between both continental blocks in the mid- or Late Palaeozoic. Several geological features around the northern boundary of Patagonia can be explained by this model (Fig. 1): (i) the Ventana (or Sierras Australes) fold belt, located north of the Patagonian boundary, where Palaeozoic platform sediments were highly deformed with NE vergence during the Permian; (ii) mid- and Late Palaeozoic calcalkaline magmatism on the northern Patagonian margin, interpreted as the magmatic arc developed prior to the collision; (iii) tectonic deformation of mid-Palaeozoic sediments in NE Patagonia, assumed to have happened in the Late Devonian–Early Carboniferous; (iv) a PermoTriassic rhyolitic plateau on La Pampa province, just north of Patagonia, interpreted as post-collisional volcanics.

Despite this, the model has remained controversial for several reasons: (i) lack of a suture with obducted ocean floor between both lithospheric blocks; (ii) no biostratigraphic or palaeoclimatic evidence suggesting different palaeogeographies for Patagonia and South America in the Late Palaeozoic; (iii) comparable Late Proterozoic to Early Palaeozoic basement rocks in northern Patagonia and the Pampean Ranges in central Argentina (e.g. Varela *et al.* 1991), suggesting crustal continuity between both; (iv) unclear location of the hypothetical boundary in western Argentina and Chile.

It is clear that high quality palaeomagnetic data from Palaeozoic rocks in Patagonia could solve the controversy surrounding its tectonic history. However, suitable Palaeozoic sedimentary or volcanic exposures are scarce in Patagonia,

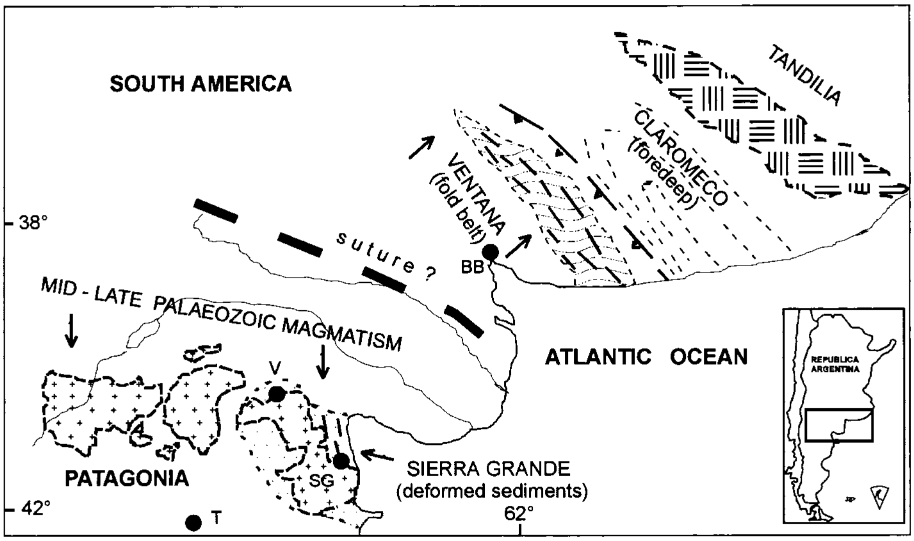

Fig. 1. Main Palaeozoic geologic and tectonic features around the northeastern boundary of Patagonia (simplified from Ramos 1984). BB, Bahia Blanca, V, Valcheta, SG, Sierra Grande, T, Telsen.

most rocks of this age being intrusive or metamorphic basement. This is probably a reason why there was no Palaeozoic pole available for this block until few years ago. Recent work has started to fill this gap (Beck *et al.* 1991; Rapalini *et al.* 1989, 1994; Rapalini & Vilas 1991*a*). The Silurian–Early Devonian clastic sedimentary rocks of the Sierra Grande Fm, exposed in NE Patagonia (Fig. 1) are of particular palaeomagnetic interest as they are the oldest unmetamorphosed sediments recognized in this region. A preliminary study of this unit was recently reported by Rapalini & Vilas (1991*a*) yielding valuable information but indicating the need for a more systematic palaeomagnetic study of these rocks. This was recently carried out and some of the results will be presented here as well as their implications regarding the tectonic history of the Patagonian terrane.

Geology and sampling

The Sierra Grande Formation is exposed in northeastern Patagonia (Fig. 1). Some details on the geology of the area were described in Rapalini & Vilas (1991*a*) and references therein, and will not be repeated here. Briefly, this formation is composed of over 1500 m of clastic marine sediments divided into two members (the San Carlos and Herrada members), each containing an interbedded ferriferous horizon. Fossil assemblages indicate an age spanning from the Wenlock to the Early Devonian for the whole Sierra Grande Formation. The exposed sequence is deformed in N- to NNW-trending and S-plunging folds of few kilometres wavelength. These rocks are also affected by N–S and NW–SE subvertical faults with strike-slip (Japas 1997) and vertical (Ramos & Cortés 1984) displacements. It can be inferred that faulting produced little if any tilting of the Sierra Grande sediments. Japas (1997) has recently shown that faulting and folding were part of a single deformational event. This is consistent with evidence from the southern exposures (south of the Sierra Grande town, Avila 1980). The age of deformation is constrained stratigraphically between the Early Devonian and the Triassic *s.l.* (Nuñez *et al.* 1975; Zanettini 1981). Ramos (1984) and Ramos & Cortés (1984) proposed a Late Devonian age for the tectonism. On the other hand, Cobbold *et al.* (1986) suggested a Permian to Triassic age for the deformation coeval with that in the Ventana fold belt, north of the Sierra Grande area.

As part of a broader palaeomagnetic sampling in the region oriented block samples were collected at 12 sites from medium- to fine-grained sandstones of the San Carlos member situated stratigraphically close to the Rosales Ferriferous horizon. Sites were located on both limbs of a syncline (Fig. 2), seven on the eastern limb (SG1-SG7, Locality A) and five on the western one (SG16-SG17, Locality C; SG18-SG20, Locality D). Three block samples, from which two to four cores were subsequently drilled, were collected at each site. Orientation was performed with sun and magnetic compasses. Figure 2 also shows location of sampling localities (X, Y and Z) for the preliminary study reported by Rapalini & Vilas (1991*a*).

Palaeomagnetic study

Generally, two 2.2 cm high specimens were sliced from each core. Measurements of natural remanence magnetization (NRM) were made in a Digico spinner magnetometer and alternating field (AF) and thermal demagnetization performed in a Molyneux AF demagnetizer and a shielded oven at the Palaeomagnetic Laboratory of the University of Plymouth, United Kingdom. Measurements of bulk susceptibility and anisotropy of magnetic susceptibility were made with a Minisep. One specimen per site was submitted to stepwise AF demagnetization in stages of 3, 5, 7.5, 10, 15, 20, 25, 30, 40, 50, 60 and 80 mT. This method proved ineffective for demagnetization due to the high coercivities of the remanence carrying minerals. Therefore, thermal treatment was selected as the demagnetization procedure, and applied in 14 steps of 150°, 200°, 250°, 300°, 350°, 400°, 450°, 500°, 540°, 580°, 610°, 630°, 660° and 690°C to all remaining specimens. Bulk susceptibility was measured after each step in order to monitor possible chemical changes due to the heating.

Typical magnetic behaviour of representative samples from the San Carlos member submitted to stepwise thermal demagnetization are shown in Fig. 3. Besides the ocurrence of a low-temperature component with no consistent orientation in some samples, most samples showed a single magnetic component with moderate to high positive (downwards) inclinations. This component showed high stability up to 690°C and clear unblocking temperatures between 630°C and 690°C, with linear decay towards the origin. This permitted the isolation of this single magnetic component in virtually all specimens processed. These directions were averaged

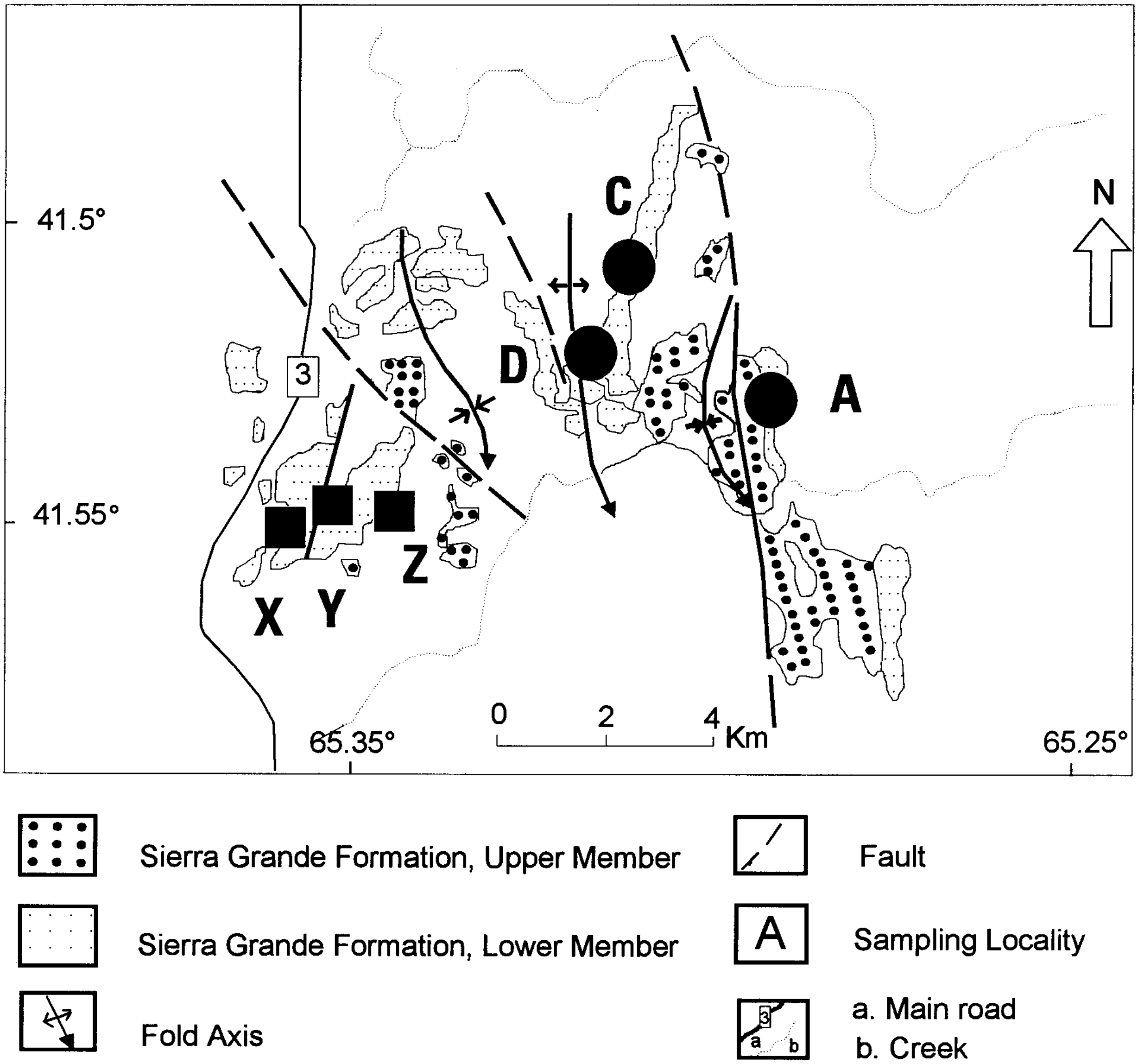

Fig. 2. Simplified geologic map of the Northern exposures of the Sierra Grande Formation and sampling localities (from Zanettini 1981; Ramos & Cortés 1984).

per site, showing a reasonably good withinsite consistency (Table 1).

The high unblocking temperatures suggest hematite as the main magnetic carrier. Lack of low coercivity minerals was confirmed by isothermal remanent magnetization (IRM) acquisition experiments performed on one specimen per site with applied fields up to 0.8 T (Fig. 4). Thin and polished sections showed that the samples analysed consisted of well-sorted fine to medium quartzose sandstones mainly composed of relatively well-rounded quartz grains. Opaque minerals, mostly iron oxides, are present as secondary minerals in the cement of the sandstones. Reflected-light microscopy showed hematite and subordinate limonites as the cementing iron oxides, which is consistent with the magnetic properties. The low-temperature magnetic component with no consistent orientation found in several samples may be speculatively associated with the limonites (goethite).

Figure 5 shows the direction of the averaged characteristic remanence per site. They are shown with different symbols according to the limb in which the site was located. In the preliminary study (Rapalini & Vilas 1991*a*) of these rocks, characteristic remanence directions from two sites on the San Carlos member showed magnetic properties similar to those reported here (sites F1 and F2, locality Y, Fig. 2). Mean direction from site F1 has also been included in Table 1 and Fig. 5 (square). Site F2 was not considered due to its poor within-site consistency. Structural corrections of the remanence directions were made in a two-step process, involving unplunging of the fold axes plunging 35° southward followed by rotation around the strike of the 'unplunged' limbs. Visual inspection of the distribution of the mean site directions before and after structural corrections clearly indicates that the magnetization is not pre-tectonic (Fig. 5). Application of stepwise structural correction shows a clear improvement of grouping of directions around 20% of bedding correction (Fig. 6). Application of McElhinny's (1964) fold test indicates a late syntectonic magnetization at 90% confidence level. This test does not permit to distinguish between a syntectonic

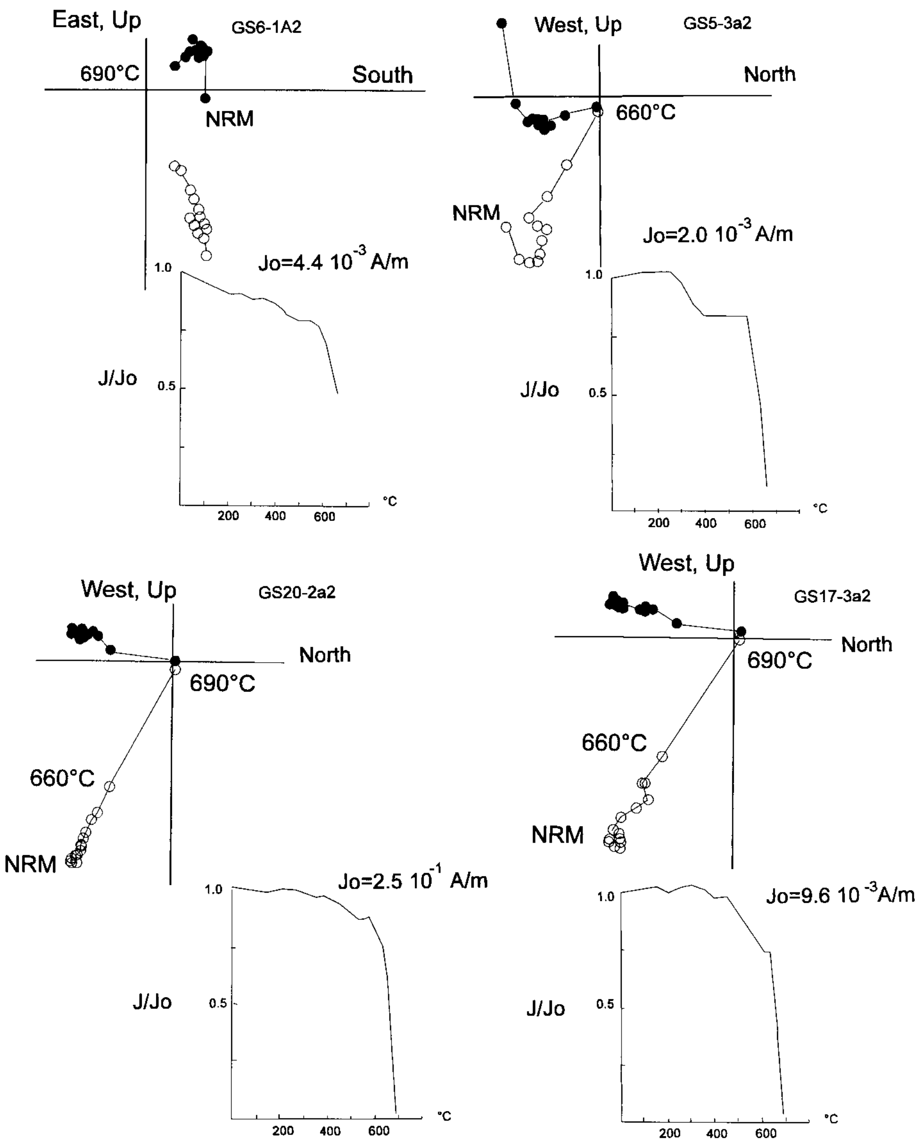

Fig. 3. Representative magnetic behaviour of samples from the San Carlos member of the Sierra Grande Formation shown in normalized demagnetization curves and Zijderveld diagrams (in geographical coordinates). Full (open) circles indicate representation in the horizontal (vertical) plane.

or post-tectonic remanence at a higher confidence level (i.e. 95%, Fig. 6). However, McFadden & Jones (1981) already demonstrated that McElhinny's test is too stringent. Therefore, two other tests were applied in order to determine if magnetization was acquired during or after folding. Application of McFadden's (1990) fold test indicates that there is correlation between the remanence directions and bedding attitudes, both *in situ* and after 100% tectonic correction at a 99% confidence level ($\varepsilon_{99\%}=5.860$, $\varepsilon_{in\ situ}=7.682$, $\varepsilon_{corrected}=12.628$). This suggests that magnetization was acquired neither before nor after complete folding. In turn, a positive result was obtained for partial correction (minimum ε at 18%, Fig. 6). Highest statistical parameter *k* was obtained for 19% of bedding correction (Fig. 6, Table 1). Figure 5c shows that mean site directions cluster after partial tectonic correction (19%). This was performed in a single composite rotation around an inclined axis that is the product of the two successive corrections for axis plunging and bedding attitude as previously mentioned. To definitely rule out the possibility of a post-tectonic remanence, *in situ* average of site-mean remanence directions from the eastern (A) and western limbs (C, D and Y) were statistically compared (McFadden & Lowes 1981). Both mean directions showed an angular separation of 15.0°, exceeding the critical angle of 9.8° and indicating that both directions can be distinguished at 95% confidence level. All these results strongly argue for the magnetization being acquired during folding of the sequence.

Age of magnetization and tectonic implications

The characteristic remanence of the sandstones of the San Carlos Member was acquired during folding of the Sierra Grande Formation. Figure 7 shows the position of its computed palaeomagnetic pole (SG3) on the basis of the partially corrected (19%) mean site directions, together with mid-Carboniferous to Late Triassic–Early Jurassic palaeomagnetic poles from South America. Late Palaeozoic poles from the Andean zone with no suspicion of *in situ* rotation have also been included. The position of SG3 is coincident with most Late Permian poles. In particular, with the late Early to Late Permian Tambillos Formation (Rapalini & Vilas 1991*b*), the Late Permian (268 ± 5 Ma) Cerro Carrizalito Group (Valencio & Mitchell 1972) and the Amaná Formation (Valencio *et al.*

Table 1. *Palaeomagnetic data of the San Carlos member*

Site	Remanence direction (*in situ*) Dec (°)	Inc (°)	*n*	*k*	α95 (°)	Bedding attitude Strike (°)	Dip (°)	Rem. dir. (100%) Dec (°)	Inc (°)	Rem. dir. (19%) Dec (°)	Inc (°)
GS-1	158.7	77.6	7	13.7	16.9	189	37	246.4	57.7	196.7	78.4
GS-2	170.5	67.7	7	128.8	5.3	191	55	235.2	39.9	197.6	67.3
GS-3	168.5	59.3	8	31.5	10.0	191	55	224.2	41.0	186.5	60.4
GS-4	142.9	67.1	9	234.7	3.4	191	55	239.1	50.1	170.8	72.8
GS-5	153.3	62.6	8	187.9	4.1	191	55	230.1	47.9	175.0	66.6
GS-6	136.7	62.7	7	198.2	4.3	191	55	235.5	54.7	156.7	70.3
GS-7	169.7	55.4	5	118.1	7.1	204	61	233.1	42.3	186.8	59.1
GS-16	158.0	74.6	6	91.6	7.0	11	38	130.2	41.7	142.4	68.1
GS-17	190.6	63.0	7	150.5	5.0	1	54	142.4	35.8	171.0	61.0
GS-18	227.3	80.9	2	—	—	9	50	125.4	45.7	158.7	79.9
GS-19	175.0	83.8	7	131.5	5.3	31	35	138.0	51.1	148.3	77.1
GS-20	193.1	68.1	8	220.6	3.7	31	35	159.6	44.1	179.2	64.1
F1	213.8	76.2	7	36.1	10.2	48	52	164.7	33.5	183.9	69.1
Mean direction (*in situ*)											
	169.2	70.6	13	46.4	6.1						
Mean direction (100% correction)											
	191.4	55.3	13	6.3	17.9						
Mean direction (19% correction)											
	174.1	69.8	13	84.3	4.5						

Data from site F1 from a previous study by Rapalini & Vilas (1991*a*).

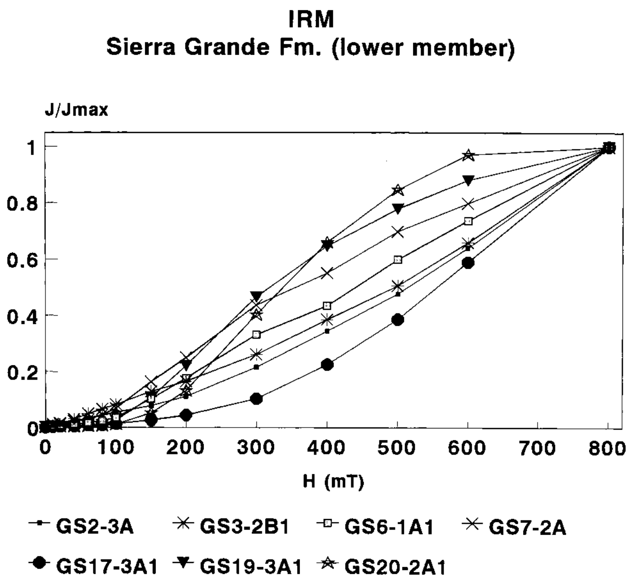

Fig. 4. Normalized isothermal remanent magnetization acquisition curves for representative samples of the San Carlos member.

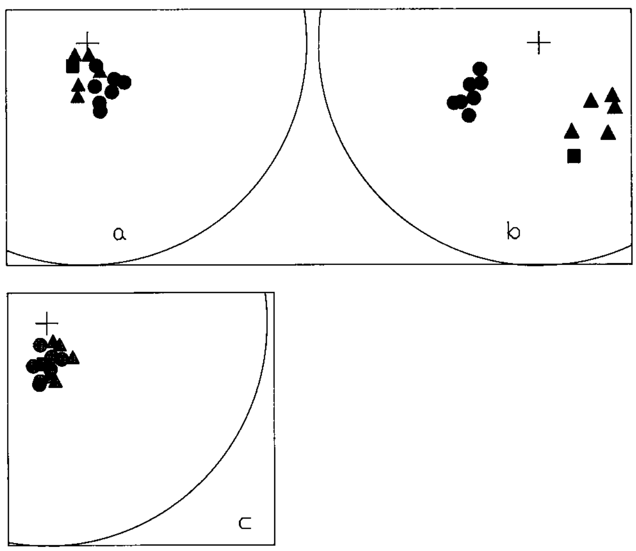

Fig. 5. (**a**) *In situ*, (**b**) fully (100%) and (**c**) partially (19%) corrected mean site characteristic directions of magnetization for the San Carlos member. Circles: mean site directions from locality A. Triangles: mean site directions for localities C and D. Square: mean site directions from locality Y from a previous study by Rapalini & Vilas (1991*a*).

1977) poles. The latter was originally assigned to the Early Triassic on the basis of the apparent recording of the beginning of the Illawarra mixed magnetic zone. However, the end of the Kiaman superchrone has been recently determined to occur in the Late Permian (Molina Garza *et al.* 1989; Haag & Heller 1991; Menning 1995), suggesting that the Amaná pole is most probably of this age. The position of SG3 is far from the Late Carboniferous and Early Permian poles from South America, which indicates an age younger than mid-Early Permian (280–275 Ma). This suggests a late Early or Late Permian age for the magnetization and therefore for the deformation of the Sierra Grande sedimentary rocks. The exclusive reversed polarity found is consistent with this age, suggesting a magnetization occurring during the Kiaman interval, and therefore before the end of the Permian.

Ramos & Cortés (1984) suggested a Late Devonian to Early Carboniferous age for the deformation of the Sierra Grande sediments, based on the fact that magmatic rocks exposed in northern Patagonia considered as mid-Carboniferous in age (Llambías *et al.* 1984; Caminos *et al.* 1988) are not disturbed by the orogeny. However, recently obtained radiometric dates on these rocks suggest that previous mid-Carboniferous ages

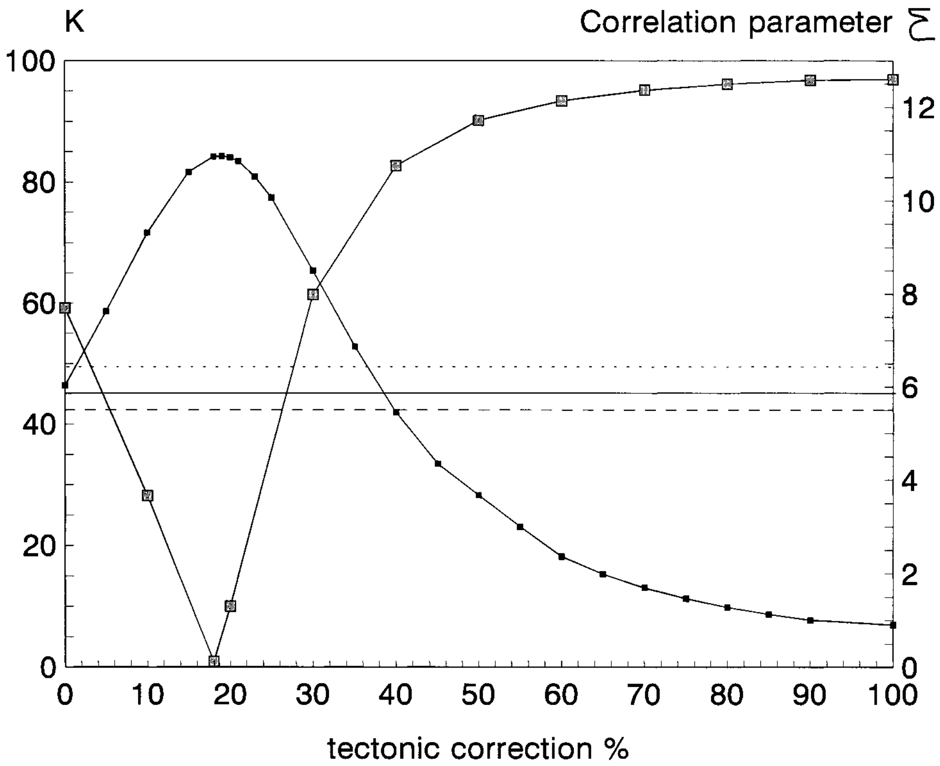

Fig. 6. Plot of *k* (Fisher's precision parameter, dots) and ε (correlation parameter, McFadden 1990, squares) v. percentage of tectonic correction for the whole population of site mean directions from localities A, C, D and Y. Continuous line: ε of 99% significance (McFadden 1990); dashed and dotted lines: *k* of 95% and 90% significance, respectively, according to McElhinny's (1964) fold test.

are not valid (Pankhurst *et al.* 1992, 1993). These new datings yielded Rb/Sr ages ranging from Late Permian to Jurassic for the same units previously dated as mid-Carboniferous. Ramos & Cortés (1984) assigned the tectonism to the collision of Patagonia, considered as a separate terrane, against the Gondwana margin. On the other hand, Cobbold *et al.* (1986) correlated the deformation of the Sierra Grande sequence to that of the Sierras Australes (or Sierra de la Ventana) in southwestern Buenos Aires province, which most likely occurred as a single phase during the Permian (Japas 1987; Von Gosen *et al.* 1990; Cobbold *et al.* 1991; Tomezzoli & Vilas 1996). The palaeomagnetic data obtained strongly argue in favour of the latter hypothesis indicating a Permian age for the deformation. Taking into account the complexity of the deformation in some exposures of the Sierra Grande area, the possibility of a deformational event occuring in a two-stage process cannot be definitely ruled out. However, structural studies of the southern exposures (Avila 1980) and preliminary structural information from the sampling area suggest that deformation occurred in a single but composite phase of deformation (Japas pers. comm.). Deformation could also be contemporaneous with the intrusion of a granodioritic body in the southern exposures of the area, which was dated as 251 ± 5 Ma (Halpern *et al.* 1970), although radimetric ages up to 270 ± 10 Ma have been reported (Nuñez *et al.* 1975). Recent structural surveys in the area suggest that the intrusion of the Permian granodiorite in the southern exposures was associated with tectonic deformation (E. Rossello, pers. comm.).

The implications of a Permian age of deformation in the Sierra Grande area for the tectonic relations between the Patagonian block and the Rio de la Plata (Gondwana) Craton cannot be fully assessed if the available Palaeozoic palaeomagnetic data from Patagonia are not taken into account. These will be briefly reviewed in the following section.

Palaeozoic palaeomagnetic poles from Patagonia and the Gondwana APWP

Only recently have palaeomagnetic poles become available from Palaeozoic rocks in Patagonia (Table 2). On the basis of a simple, albeit somewhat subjective, reliability index of three levels (A, high; B, moderate; C, low reliability) each of them was qualified according to: (i) fully published demagnetization procedures, including accurate components definition, (ii) number of samples and sites greater than 20 and 4 respectively, (iii) positive field tests (fold, reversal, conglomerate tests) or other evidence constraining the age of magnetization. If a pole fulfills the three criteria it is qualified as A, while one criterion not met indicates a B qualification. Failure of two or more of these items qualifies a pole as C.

The Palaeozoic palaeomagnetic poles from Patagonia have been plotted in Fig. 8 together with the Mid-Palaeozoic to Early Mesozoic path for Gondwana. Individual poles, as selected by Schmidt *et al.* (1990) and Chen *et al.* (1994), have been plotted for the Silurian–mid-Carboniferous interval. Mean Western Gondwana Late Carboniferous to Late Triassic palaeomagnetic poles were taken from Van der Voo's (1993) compilation (poles selected are presented in Table 3).

SG2, TP, CI and SG3 poles fall on the Gondwana path, the first three being also consistent with their expected position on the path according to the assumed age of magnetization. As previously shown, the age of SG3 was determined on the basis of its position on the path. CH, is a high-quality pole from Permian volcanic rocks from NW Patagonia. Its position is not consistent with the Gondwana path, but this is due to a large clockwise rotation of the sampling area, presumably related to Mesozoic dextral movements along a main transcurrent fault on the northern boundary of Patagonia (Rapalini 1989). A counterclockwise rotation of about 80° around the sampling locality restores CH to a position consistent with the Late

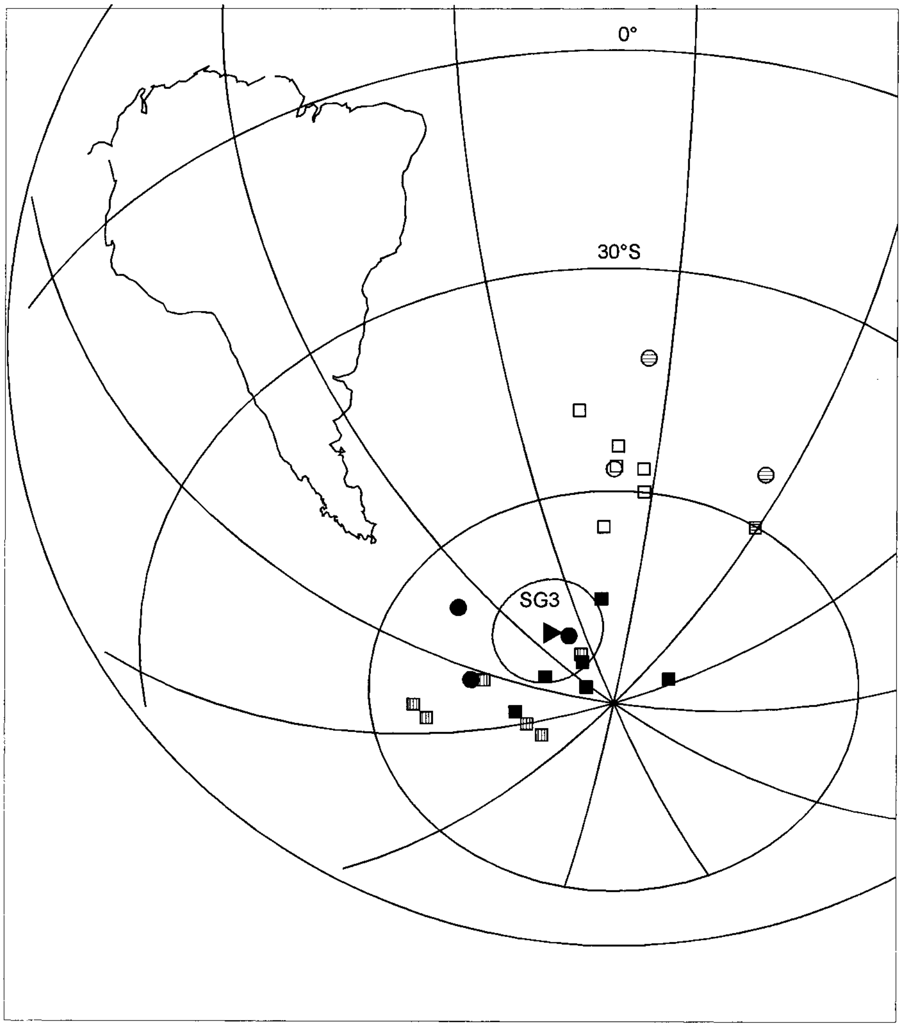

Fig. 7. Position of SG3 (triangle), palaeomagnetic pole computed for the syntectonic magnetization of the San Carlos member, and its 95% confidence oval. Late Palaeozoic and Early Mesozoic South American poles from the cratonic areas (squares) and the Andean region (circles) are also shown. Late Carboniferous, open symbols; Early Permian, horizontal lines; Late Permian, full symbols; Triassic, vertical lines. Cratonic poles as selected by Rapalini *et al.* (1993) plus poles obtained by Ernesto *et al.* (1991) and Montes Lauar *et al.* (1994). Andean poles from Jesinkey *et al.* (1987), Rapalini & Vilas (1991*b*) and Truco & Rapalini (1996).

Table 2. *Abbreviated characteristics of Palaeozoic palaeomagnetic poles from Patagonia and their qualification according to the reliability criteria set in the text*

	Palaeomagnetic pole						
Formation	Lat.	Long.	α95 (dp/dm)	Palaeomagnetic results	Age of PP	Class.	References
SG1 Sierra Grande Fm. (Lower member)	3.4	238.0	8/14	AF and Th. demag.; both polarities; apparent recording of reversal; no FT; $n=14$ ($N=4$)	Silurian?	C	Rapalini & Vilas (1991)
SG2 Sierra Grande Fm. (Upper member)	−42.0	283.5	20	Th and Ch demag.; FT; second. comp. removed; $n=10$ ($N=2$)	Early Devonian	B	Rapalini & Vilas (1991)
TP Tepuel Group	−31.7	316.1	15/16	AF and Th demag.; FT; second. comp. removed; IRM; magnetiz. carried by detrital magnetite; $N=16$ ($n=62$)	Mid-Carboniferous.	A	Rapalini *et al.* (1994)
CI Chilean Intrusives	−57.4	323.5	19	AF and Th demag.; both polarities; no tectonic control; $N=7$ ($n=58$)	Late Carboniferous: 285–307 Ma	B	Beck *et al.* (1991)
SG3 Sierra Grande Fm.	−77.3	310.7	8/7	AF and Th demag; IRM; FT: syntectonic magnetization (19%); $N=13$ ($n=88$)	Late Permian?	B	This paper
CH Choiyoi Fm.	−21.0	232.3	8	AF and Th demag; FT; second. comp. removed; $N=33$ ($n=85$)	Late Permian	A	Rapalini *et al.* (1989)

Pole classification: A, high quality; B, medium quality; C, low quality.
AF: alternating field, Th: thermal, Ch: chemical.
FT: positive fold or tilt test
RT: positive reversal test

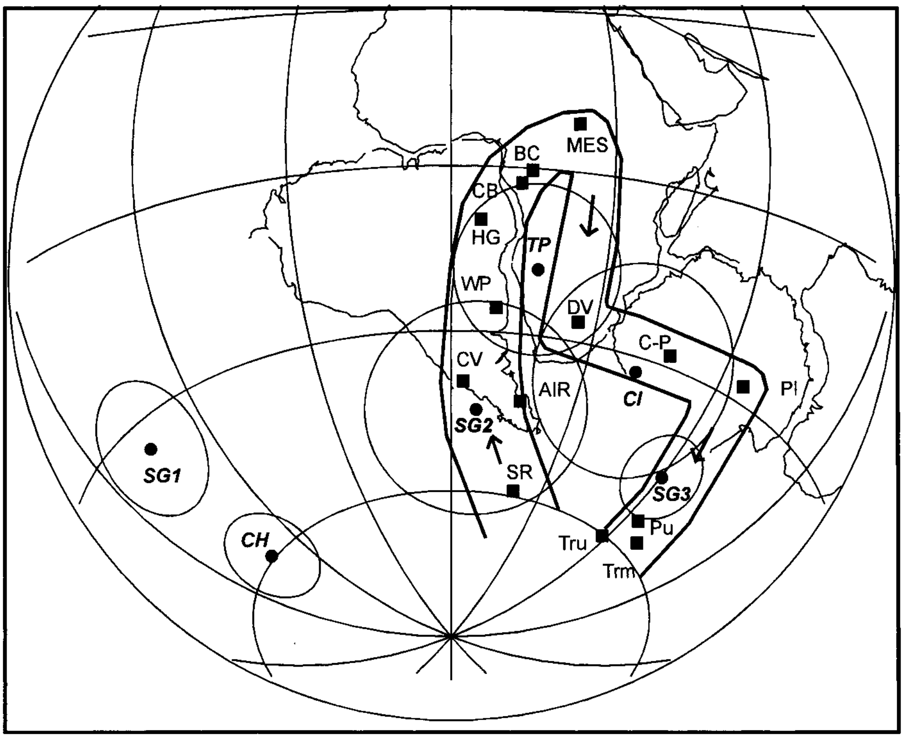

Fig. 8. Comparison of Patagonian Palaeozoic palaeomagnetic poles (circles, Table 2) with the Silurian to Jurassic APWP for Gondwana. The Gondwana path is based on individual high quality poles from Early Devonian to Late Carboniferous and mean Western Gondwana poles from Late Carboniferous to Triassic–Jurassic boundary (squares, Table 3).

Table 3. *Selected Early Devonian to Triassic palaeomagnetic poles for Gondwana and their position after rotation to southern Africa coordinates following reconstruction by Lottes & Rowley (1990)*

		PP			PP (rot.)			
Geological unit	Age	Lat (°)	Long (°)	α95 (°)	Lat (°)	Long (°)	*Q*	Ref.
AIR, Nigerian Ring Complex, NWAfr.	Dl	− 43.4	8.6	6.2	− 42.4	17.0	6	1
SR, Snowy River Volcanics, Aust.	Dl	− 74.3	222.7	10.9/14.5	− 59.0	21.0	7	1
CV, Comerong Volcanics, Aust.	Dm-u	− 76.9	330.7	7.2	− 39.3	2.9	6	1
GH, Gilif Hills volc., NEAfr. (*)	Dm	26.0	12.0	11.0	24.8	10.3	6	2
WP, Worange Point Fm., Aust.	Du	− 70.8	19.7	7.1	− 25.7	9.3	6	1
BC, Brewer Conglomerate, Aust.	Du	− 47.1	41.0	6.4	− 0.4	14.9	7	4
HG, Hervey Gr., Aust.	Du-Cl	− 54.4	24.1	16.2/8.4	− 9.6	5.7	5	1
CB, Canning Basin Lst., Aust.	Du-Cl	− 49.1	38.0	7.8	− 2.7	13.1	6	1
MES, Mount Eclipse Sandst., Aust.	Cl	− 37.6	52.6	8.7	8.9	23.5	7	5
DV, Dwyka Varves, SAfr.	Cm	− 26.5	26.5	10.5	− 26.5	26.5	5	1
C-P, Mean PP, Western Gondwana	Cu-Pl	− 33.0*	43.0†	8.0	− 28.1	47.8	—	3
Pl, Mean PP, Western Gondana	Pl	− 34.0*	62.0†	7.0	− 27.5	65.7	—	3
Pu, Mean PP, Western Gondwana	Pu	− 61.0*	56.0†	9.0	− 54.7	64.4	—	3
Trm, Mean PP, Western Gondwana	Trm-Tru	− 64.0*	62.0†	8.0	− 57.3	70.1	—	3
Tru, Mean PP, Western Gondwana	Tru-Jl	− 66.0*	47.0†	13.0	− 60.3	58.6	—	3

*Pole not considered for definition of the APWP.
†Pole positions in NW African coordinates.
References: 1, selection by Schmidt *et al.* (1990); 2, Bachtadse & Briden (1991); 3, selection by Van der Voo (1993); 4, Chen *et al.* (1993); 5, Chen *et al.* (1994).

Permian mean pole for Gondwana. This is also shown in the customary palaeolatitude v. geological time diagram of Fig. 9. Palaeolatitudes have been computed for the Sierra Grande outcrops in northeastern Patagonia on the basis of palaeomagnetic poles from Gondwana and Patagonia for Silurian to Triassic times. The Patagonian poles are consistent within the error margins with the palaeolatitudes expected from the Gondwana poles, showing that Patagonia moved from polar latitudes in the Devonian to mid southern latitudes in Permian times. This confirms that no significant latitudinal displacements can be postulated between Patagonia and Gondwana since Devonian times.

Therefore, from all palaeomagnetic poles, SG1 is the only showing discordant declination and inclination values. The fact that it belongs to the oldest (Silurian) rocks, might suggest an accretional origin for Patagonia, as originally suggested by Rapalini & Vilas (1991*a*). However, SG1 has a low reliability index due to the low number of samples and lack of a field test

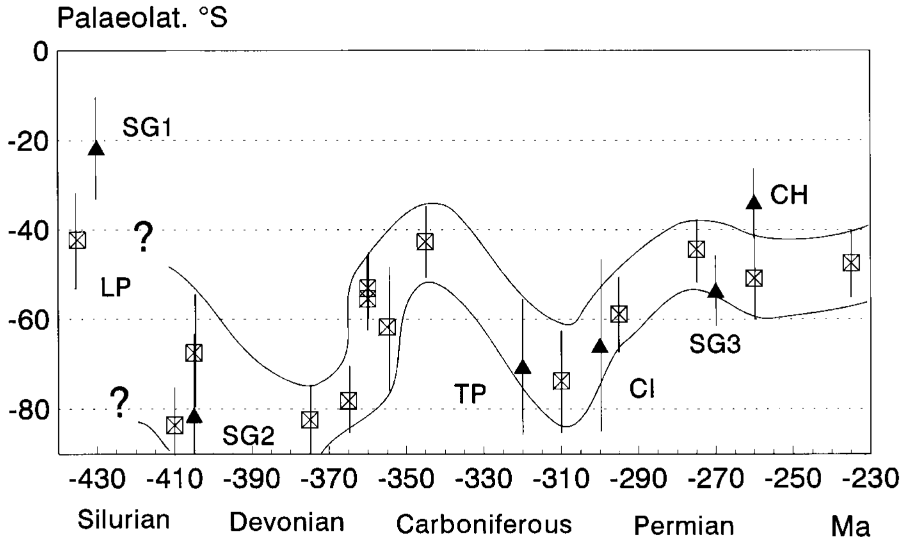

Fig. 9. Palaeolatitude v. geological time plot for the Sierra Grande outcrops according to Gondwana poles from Table 3 (squares) and the Patagonian poles (triangles, Table 2). Bars indicate 95% confidence margins of palaeolatitude determinations. Note the consistency of Patagonian and Gondwana poles since the Devonian. LP is a recently obtained pole for South America (Conti *et al.* 1995), which suggests low latitudes for Gondwana in the Early Silurian. Question marks indicate uncertainty in actual Gondwana pole path for the Silurian. More references and discussion in the text.

constraining the age of magnetization. The low reliability of SG1 prevents, then, from assesing the pre-Devonian palaeogeographic relations between both crustal masses. Furthermore, the palaeogeographic evolution of Gondwana in the Silurian is not well established, since the AIR pole (see Table 3) has been re-dated as Early Devonian (Moreau *et al.* 1994; Van der Voo 1994) leaving the controversial pole from the Lipeón Formation (Conti *et al.* 1995) as the only Gondwanan pole for this period.

The palaeomagnetic data summarized above suggests that if Patagonia is an accreted terrane, its collision with Gondwana occurred before Devonian times. However, syntectonic magnetization of the Sierra Grande sediments permits to establish that the main deformational event in northern Patagonia occurred during Permian times, more or less at the same time as in the Ventana Fold Belt, north of the Patagonian boundary. This renders unlikely any tectonic model involving a continent–continent collision to account for the deformational event around the northern boundary of Patagonia, unless deformation can be explained occurring well over 100 Ma after collision started. Tectonic models that propose that Patagonia was part of Gondwana since the Early Palaeozoic (e.g. Varela *et al.* 1991; Dalla Salda *et al.* 1992) seem to be more consistent with the palaeomagnetic data obtained so far. However, determination of pre-Devonian palaeogeographic evolution of Patagonia will require acquisition of new palaeomagnetic poles.

Conclusions

A palaeomagnetic study on the Silurian–Early Devonian sediments of the Sierra Grande Formation, exposed in NE Patagonia, indicated that these rocks are carriers of a syntectonic magnetization acquired during the late stages of folding of the sequence. Unblocking temperatures, some rock magnetic experiments and optical microscopy indicated that fine grain hematite residing in the cement of the sandstones is the only magnetic carrier. The position of the palaeomagnetic pole suggests that magnetization and therefore folding occurred during late Early to Late Permian times. Previously obtained Palaeozoic palaeomagnetic poles from Patagonia agree with those from Gondwana since Devonian times, suggesting that if Patagonia is a far-travelled terrane accretion must have occurred before Devonian. Therefore, any tectonic model explaining deformation around the northern boundary of Patagonia as a product of continent–continent collision must account for deformation occurring more than 100 Ma after begining of collision. Models that propose that Patagonia was part of Gondwana since the Early Palaeozoic are more consistent with the palaeomagnetic data.

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