Palaeomagnetism of the Silurian Lipeón formation, NW Argentina, and the Gondwana apparent polar wander path

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Accepted 1994 December 12. Received 1994 December 12: in original form 1993 September 21

SUMMARY
A palaeomagnetic study was carried out on ferriferous beds of the Early Silurian Lipeón Formation in NW Argentina (24.5°S, 69.9°W). Samples were collected at 19 sites in four different localities. Detailed thermal demagnetization has permitted the identification of three different magnetic components. All components are carried by haematite, as deduced from IRM curves and microscope analyses. Component A is interpreted to be of Recent origin, due to its coincidence with the geomagnetic dipole direction and its association with post-diagenetic platy haematite. Component B, with exclusive positive inclinations, was found in two out of four sampling localities. Its possible significance is discussed on the basis of an indeterminate result of the fold test and its correlation with the degree of deformation in the samples. The third isolated component (C) was present in the other two localities. It passed both fold and reversal tests and is clearly associated with oolitic haematite of early diagenetic origin. A palaeomagnetic pole of possible Early Silurian age was computed on the basis of mean site directions of component C: 74.9°S, 213.9°E, A95 = 9.9°, K = 47, N = 6. This new pole implies lower latitudes for Gondwana in the Silurian than were previously proposed and suggests a modification of the Gondwana APWP. A reversed polarity option for the Early–Middle Palaeozoic path is suggested as a possible alternative.

Key words: Argentina, Gondwana, palaeomagnetism, Silurian.

INTRODUCTION
Several different Palaeozoic apparent polar wander paths (APWPs) have been proposed for Gondwana in the last two decades (McElhinny & Embleton 1974; Schmidt & Morris 1977; Morel & Irving 1978; Goleby 1980; Van der Voo 1988; Bachtadse & Briden 1990, 1991; Li et al. 1990). Some causes of this uncertainty are (i) the low number of reliable mid-Palaeozoic palaeomagnetic poles (PP); (ii) the uncertainty in the age of magnetization of many of the studied rocks (Embleton 1972; Kent, Dia & Sougy 1984); (iii) the ambiguity in the polarity of pre-Devonian poles (Schmidt & Morris 1977); and (iv) a possible allochthonous origin of the Tasman fold belt (Embleton et al. 1974) from which most Silurian–Devonian poles for Gondwana come.

Three substantially different paths recently proposed are shown in Fig. 1. Path B (Van der Voo 1988; Schmidt et al. 1990), which resembles the ‘Y’ path of Morel & Irving (1978), is based mainly on the Nigerian AIR ring complex pole (Van Houten & Hargraves 1987) and a few high-quality Devonian poles from south-eastern Australia. Path A (Li et al. 1990) is mainly suggested by a disputable Silurian pole from the Mereenie Sandstones from Cratonic Australia and defines an extraordinary long Palaeozoic path. Path C (Bachtadse & Briden 1991) resembles Morel & Irving’s ‘X’ path and is mainly based on a recent high-quality mid-Devonian pole from the Sahara Craton that falls in northern Africa. This path assumes a remagnetization of the Silurian AIR pole in the Carboniferous and implies that all south-eastern Australia data are not representative of Gondwana.

Solving these uncertainties in the Middle Palaeozoic Gondwanan APWP will have important consequences for its palaeogeographic and geodynamic evolution and the tectonic relations with other major continental blocks. It is also essential for the definition of the tectonic origin of possible allochthonous terranes in South America (Arequipa, Patagonia, Chilenia, Precordillera; see Ramos 1988).
In order to provide urgently required palaeomagnetic information for Gondwana in the critical Mid-Ordovician–Devonian interval, a palaeomagnetic study was carried out in the ferriferous horizons of the Early Silurian Lipeñón Formation, exposed at 24.5°S, 65.6°W in NW Argentina.

**GEOLOGY AND PALAEOMAGNETIC SAMPLING**

The Sierras Subandinas ('Sub-Andean Hills') constitute a 50 to 100 km wide north–south trending belt extending from Bolivia southwards to the boundary between the Argentine provinces of Salta and Catamarca (26°S, Fig. 2). It is the easternmost fold and thrust belt of NW Argentina and Bolivia produced by the Late Tertiary Andean deformation and uplift. The main geologic and stratigraphic features of the region outlined here were obtained from numerous local geologic and stratigraphic contributions (e.g. Salfity et al. 1975; Mingramm et al. 1979; Botcher et al. 1984; Acefiolaza, Durand & Sosa Gómez 1989; Vistalli 1989, and references therein).

The oldest rocks reported are a sequence of marine sediments, volcanics and intrusive bodies with ages ranging between Late Precambrian and Ordovician. In Late Ordovician times a tectonic event, the 'Ocloyic' phase, generated an area of positive relief that subdivided the Early Palaeozoic basin into a western and an eastern subbasin that occupied not only NW Argentina but also parts of Bolivia.
Peru, Paraguay and Brazil. Sedimentation developed in a shallow marine environment until the Late Devonian, when another tectonic event, the ‘Chañic’ phase, interrupted it. The pericratonic nature of this basin in the Lower and Middle Palaeozoic rules out any possibility of relative displacement with respect to the South American cratonic areas since those times. Two sedimentary cycles developed in the Late Palaeozoic and Cretaceous Tertiary, the latter interrupted by the Andean Orogeny in the Late Tertiary. This produced most of the structural features of the region. From a structural point of view the Sierras Subandinas are made up of a series of asymmetric anticlines, generally trending N to NE with vergence to the east.

The sequence exposed at the sampling localities starts with Arenigian to Llanvirnian clastic sediments (Monaldi, Bosso & Fernandez 1986), separated by an erosional unconformity from the diamictites of the Zapla Formation (Schlagintweit 1943). The origin of this unit is controversial, as some authors have assigned it to a glacimarine origin (Schlagintweit 1943; Turner 1960), while others attribute it to a sudden subsidence of the basin (Cuerda & Antelo 1973; Antelo 1978). This is conformably overlain by the claystones and sandstones of the Lipeon Formation (Turner 1960), which contains some ferriferous horizons near its basis. Several authors have assigned this unit to the Llandovery–Ludlow on the basis of fossils found in the middle of the sequence, and correlation with similar formations of this age in NW Argentina (Niewniewsky & Wielinsky 1950; Cuerda & Baldis 1971; Cuerda & Antelo 1973; Baldis et al. 1976; Antelo 1978; Mingramm et al. 1979; Andreis et al. 1982). Graptolites found in the basal levels of the formation (Monteros, Moya & Cuerda 1993; Bosso, Monaldi & Salily 1983) indicate a Llandovery age for the ferriferous beds. The Lipeon Formation is conformably overlain by Lower Devonian sandstones which, in turn, are unconformably overlain by Cretaceous and Tertiary continental deposits.

The ferriferous levels of the Lipeon Formation consist of two widely distributed main horizons, the ‘Upper’ and ‘Lower’ horizons, with variable thickness (0.7 to 15 m) and stratigraphic separation (about 30 m at Sierra de Zapla).

The palaeomagnetic sampling was carried out at four localities (Fig. 2), restricted to the Upper and Lower horizons:

- SG1: Sierra del Gallo (24.7°S 64.8°W), sites 1 to 6;
- SG2: Sierra del Gallo (24.7°S 64.8°W), sites 7 to 9;
- SZ: Sierra de Zapla (24.2°S 65.1°W), sites 10 to 13;
- SPV: Sierra de Puesto Viejo (24.5°S 64.9°W), sites 17 to 22.

At each sampling locality both horizons comprise several beds. Each independent bed was considered as a sampling site. Generally, five oriented cores (2.54 cm diameter) were obtained from each site. Sampling was carried out with a portable drill and samples were oriented with both magnetic and sun compasses, where possible. A total of 83 cores, from 19 sites, were collected.

PALAEOMAGNETIC STUDY

The natural remanent magnetization (NRM) and bulk susceptibility of all specimens were initially measured. In order to determine the different magnetic components that integrate to form the NRM and to analyse their magnetic stability, pilot samples were submitted to stepwise AF demagnetization, thermal demagnetization or chemical leaching. Owing to the high coercivities and low porosity of the samples, both AF and chemical treatment proved ineffective for demagnetization. Thus, all samples were submitted to stepwise thermal demagnetization up to 700°C, or until the NRM was virtually destroyed or the samples showed important chemical changes due to heating. To check this, bulk susceptibility values were obtained from each specimen after each demagnetization step.

The magnetometer used was a Digico spinner controlled by a PC; the thermal demagnetization was done with a Schonstedt TSD-1, and bulk susceptibility values were measured using a RMS-III susceptibility meter. All data were processed with the MAG88 palaeomagnetic analysis program (Oviedo 1989).

In general, the Lipeon Formation showed the presence of two magnetic components: a pre-tectonic, probably primary, characteristic remanence was defined at localities SG2 and SZ, while a post-tectonic secondary component was dominant at localities SG1 and SPV. The magnetic components defined at each locality are presented in Table 1.

**Locality SG1**

Nine out of 31 samples from this locality suffered chemical changes due to experimental heating around 550°C and were not analysed further. 16 of the remaining samples showed only one magnetic component with discrete unblocking temperatures at about 675°C (Fig. 3a). Despite similar behaviour, directions with negative and positive inclinations are not antipodal (Fig. 3d), suggesting two different components, denoted A and B. Component A is coincident with the present geomagnetic axial dipole field direction, which suggests that this is a secondary, probably recent, magnetization (Table 1). This is confirmed by six samples that carried both magnetic components (Fig. 3b). In these samples, component A is defined by vectrorial subtraction up to 675°C (Figs 3b and d). The component remaining, although not precisely defined, as no stable endpoints were reached, is directed southwards and of positive inclination, consistent with component B (Table 1). The B component is of higher unblocking temperatures in multicomponent samples, as confirmed by the analysis of remagnetization circles. The common mean direction as shown by the intersection of the circles (Fig. 4a) is coincident with isolated component B directions.

Discrete unblocking temperatures around 675°C in all monocomponent samples indicate that haematite is the magnetic carrier of both A and B components. Partial deletion of component A in the multicomponent samples at low temperatures (<300°C) suggests that goethite is sometimes also a carrier of this component.

**Locality SPV**

All samples analysed from this locality (25) showed two magnetic components. Their magnetic behaviour was very similar to those multicomponent samples from SG1. In most
cases (Fig. 3c) they showed a northward-directed component with negative inclinations, coincident with the present dipole, which was deleted at 650–670°C, while a southward-directed component with positive inclination was clearly defined between 650 and 690°C. These components are interpreted as components A and B found at locality SG1 (Table 1). The high temperature at which component B was isolated explains why it could be properly defined in only nine samples. In situ directions for these components are shown in Fig. 3(d). They are not antipodal as they failed a reversal test (McFadden & McElhinny 1990), although they appear to be very nearly so from the figure. Remagnetization circle analysis defined a common mean direction that is not coincident with the averaged B component direction (difference: 11°, Fig. 4b). This suggests that overprinting by component A may not have been completely erased when defining the higher temperature magnetization.

The unblocking temperatures defined for both components indicate that haematite is the main magnetic carrier
Figure 3. (a) and (b) Characteristic magnetic behaviour of specimens from locality SG1. (c) Multicomponent specimen from locality SPV. (d) In situ directions of components A and B (localities SG1 and SPV). Open (closed) symbols indicate negative (positive) inclinations.
Silurian palaeomagnetism of NW Argentina

Presented antipodal directions inconsistent with components A and B as previously defined. These were assigned to a different magnetic component, called C (Table 1). Unblocking temperatures around 675°C indicate that haematite is the magnetic carrier. Drops in intensity with no changes in direction around 450°C may be associated with ilmeno-haematite. Bossi & Viramonte (1975) reported an interstratification of genetically related haematite and ilmenite in the matrix of the ferriferous beds at this locality.

**Locality SZ**

13 out of 16 samples analysed from this locality were univectorial (Fig. 5b) with unblocking temperatures around 675°C, and were very similar to those from SG2. As shown in Fig. 5(c), those negative directions not coincident with the dipole field (Table 1) were antipodal to those of positive inclinations. Their similarity to those from SG2 suggest that these samples also carry magnetic component C (Table 1). The magnetic carrier is again inferred to be haematite, due to the high unblocking temperatures.

**ROCK MAGNETIC AND PETROGRAPHIC STUDIES**

Samples from several sites at the four localities were submitted to isothermal remanent magnetization (IRM) acquisition experiments. Typical IRM acquisition curves are shown in Fig. 6. All are similar, regardless of whether the samples carried components A, B or C. The curves show very high coercive forces, with saturation reached at applied field $>2.5$ T, which is indicative of fine-grained haematite. The flat section of the curves at low applied fields indicates the lack of any low coercivity mineral (magnetite, maghaemite, pyrrhotite). Remanent acquisition coercive forces (applied field necessary to acquire 50 per cent of the saturation remanence) between 450 and 600 mT suggest very fine grain ($<5\mu$), single-domain haematite (Dankers 1981).

Many thin and polished sections of the palaeomagnetic specimens were analysed using transmitted and reflected light under the microscope. This confirmed that haematite is almost exclusively the only magnetic mineral in these rocks. A diagenetic origin has been postulated for the haematite in these ferriferous beds (Angelelli 1946; Bossi & Viramonte 1975). The petrographic study, however, permitted the determination of two different origins for the haematite (Conti & Castro 1992), one related to an early diagenesis of the sediments and another due to a post-diagenetic migration. These two different origins are represented by two different textural types of haematite. The early diagenetic type is represented by a microgranular-oolitic haematite (H, Fig. 7), which is the product of alteration of the original precipitates (iron silicates: chamosite, thuringite), which are still visible as relicts in some oolites (CH, Fig. 7a). This haematite is sometimes altered to limonite (L, Figs 7b–d). The post-diagenetic textural type consists of iso-oriented platy haematite, with a characteristic limpid aspect, occupying intergranular spaces or filling microfractures that sometimes affect the oolites (PH, Figs 7b–d). A systematic correlation was found between magnetic behaviour and haematite textural type in the samples analysed. Oolitic (diagenetic) haematite was found in those
samples carrying component C, while post-diagenetic platy haematite was present in those with component A. In the latter samples, the diagenetic haematite was found to be partially to completely converted into goethite. Multivectorial samples generally showed both mineral textures. Even though no single mineral texture could be directly associated with component B, samples from the locality SPV showed a high degree of deformation and high percentages of platy haematite.

**ANALYSIS OF RESULTS**

**Component A**

Component A was the dominant magnetization at localities SG1 and SPV. This is a post-tectonic secondary magnetization associated with a post-diagenetic growth of platy haematite. This is indicated by (i) the correlation of the presence of this component with that textural type, as observed in the thin and polished sections (Conti & Castro 1992); (ii) in situ remanence directions coincident with the present dipole field (Table 1, Fig. 3); (iii) IRM acquisition curves indicating that the magnetic carrier is haematite; and (iv) unblocking temperatures above 650°C, ruling out a thermoviscous origin for this component (Pullaiah et al. 1975; Kent 1985). On the basis of the age of the last phase of deformation in the Sierras Subandinas (Gebhard, Giudici & Oliver Gascón 1974; Mingramm et al. 1979; Moya & Salfity 1982; Mpodozis & Ramos 1989), a Pliocene–Pleistocene age for the post-diagenetic formation of the platy haematite is suggested.
Figure 7. Microscopic views of samples from the ferriferous beds of the Lipecón Formation (a) Transmitted light, showing chamosite (CH)-haematite (H) oolite. (b), (c) and (d) Reflected light, showing limpid iso-oriented platy haematite (PH), granular-oolitic haematite (H) and limonite (L).
Figure 6. IRM acquisition curves of samples from the four sampling localities. References are in the text.

Component C
This magnetic component was the dominant, and generally the only, one present at localities SG2 and SZ (Table I). Its association with early diagenetic oolitic haematite, as observed in thin and polished sections, suggests that it corresponds to the formation of haematite as an alteration product of the original silicates during diagenesis. This is confirmed by IRM acquisition curves indicating that very fine-grain (probably SD) haematite is the magnetic carrier, with very high unblocking temperatures around 675 °C. This is also supported by a positive fold test (McFadden 1990; in situ $k = 4.4$, unfolded $k = 53.5$), as shown in Fig. 8(a). In situ mean directions of component C from localities SG2 and SZ are clearly different, while they become coincident after bedding correction. This indicates that C is pre-tectonic, which is consistent with its postulated origin. Component C directions also passed a reversal test (Fig. 8b). Application of the reversal test (McFadden & McElhinny 1990) gives a positive result—class B (angle between normal and reverse mean directions = 2.2°, with a critical angle of 9.3°)—for component C at localities SG2 and SZ. On this basis a palaeomagnetic pole was computed from tilt-corrected site mean directions of component C (Table I).

Component B: a real magnetic component?
No single mineral texture could be directly associated with this component, although several samples from locality SPV showed high degrees of deformation associated with high percentages of platy haematite. In those samples where it was present together with component A (e.g. locality SPV; Table I), both oolitic and platy haematite were found. This may suggest that component B is carried by the diagenetic oolitic haematite. However, the mean directions of this component from localities SG1 and SPV do not agree before or after tectonic correction, although they become closer when restored to the palaeohorizontal. The use of the common mean direction obtained from great circle analyses yields a better agreement between directions from both localities after tectonic correction, although the result of the fold test is statistically inconclusive. The locality mean directions of component B do not agree with those of component C.
Despite the fact that several samples at SG1 were carriers of component B as the only magnetization, it is likely that this is not a real magnetic component but a product of partial overprinting of component C by component A. This is suggested by the following: (i) B was only present at those localities (SG1 and SPV) where A was also found; (ii) in most cases B could not be properly defined due to overprinting by A; (iii) at SPV, the common mean direction of remagnetization circles does not coincide with the mean direction of component B, suggesting that overprinting by A was not completely erased; (iv) the diagenetic microgranular-oolitic haematite carrier of C seems also to be carrying B; (v) very similar unblocking temperatures and coercive forces (IRM curves) for components A and C indicate the difficulty in defining the latter if overprinted by A; and (vi) in situ B mean directions at SG1 and SPV lie on the great circle defined by the present dipole field (component A) and the expected in situ directions of component C at each locality. For these reasons component B is considered to be a combination of A and C components and is not considered further.

**DISCUSSION AND INTERPRETATION**

The palaeomagnetic pole (PP) of the Lipeón Formation fulfils most present reliability criteria (Van der Voo 1990) for palaeogeographic reconstructions. In particular: (i) the age of the formation is well constrained and there is no doubt about its tectonic coherence with the South American Craton; (ii) it was obtained from a sufficient number of sites and with acceptable statistical parameters (Table 1); (iii) the different magnetic components were clearly distinguished and isolated by thorough and complete demagnetization (data from those sites and localities where doubts remained of possible contamination with secondary components were excluded); (iv) remanence directions showed a positive fold test; (v) they also passed a reversal test; and (vi) IRM and petrographic studies revealed that early diagenetic fine-grain (SD?) haematite is the carrier of the component C. Considering the continuing subsidence and sedimentation in the basin after these deposits were formed, the formation of haematite by early diagenetic processes seems likely to have occurred not much later than the latest Lower Silurian.

Despite this, LP falls relatively near to, although not over, Permian to Jurassic South American mean poles. As shown in Fig. 9 its 95 per cent confidence circle partially overlaps those from the Upper Permian–Lower Triassic, Middle to Upper Triassic and Jurassic mean poles for South America as recently computed by Rapalini, Abdeldayem & Tarling (1993a). Older poles (see the mean Upper Carboniferous–Lower Permian) as well as younger ones (Cretaceous poles) do not coincide with LP. Although LP is not strictly coincident with the Permian to Jurassic poles, its location near these younger poles may be taken as evidence of a remagnetization of that age (i.e. Permian to Jurassic). As both polarities were recorded in the Lipeón Formation rocks, the magnetization could not correspond to the
reversed Kiaman Superchron, which ended about 251 Ma (Molina Garza, Geissman & Van der Voo 1989). This would constrain the possible remagnetization age to the Triassic or Jurassic. In the absence of a pre-Triassic positive fold test, the suspicion of an Early Mesozoic remagnetization cannot be ruled out but is considered unlikely. The IRM results and petrographic analyses indicate that component C is a chemical remanent magnetization carried by fine-grain (SD?) haematite in the oolites of the ferriferous beds. In most ferriferous beds, haematite is an early diagenetic product of dehydration of the original precipitates (hydroxides or hydrosilicates) not far from the sediment–water interface at pressures of less than a few hundred bars and temperatures less than 100–150°C (French 1973). This also seems to be the case in the Lipe6n Formation, as preliminary studies on the rest of the Silurian and Devonian rocks of the same sequence (work in progress) indicate that haematite is restricted to the ferriferous beds. This confirms that the origin of this mineral occurred near the water–sediment interface and was associated with the depositional process. Therefore, we speculate that LP as a possible Lower Silurian palaeomagnetic pole for South America and therefore for Gondwanaland.

**GEO_DYNAMIC SPECULATIONS**

Pole LP meets six out of seven of Van der Voo’s (1990) reliability parameters. This and all other reliable Silurian to Carboniferous poles from Gondwanaland (Table 2) are depicted in Fig. 10. All poles have been rotated to South Africa’s coordinates following Lottes & Rowley’s (1990)

**Table 2.** Selected Cambrian to Late Carboniferous–Early Permian palaeomagnetic poles for Gondwana. PP: Palaeomagnetic pole; PP(rot): PP rotated to South Africa coordinates according to Lottes & Rowley (1990). Only Iran has been reconstructed following Scotese & McKerrow (1990). Positive (negative) values indicate north (south) latitudes; longitudes are always E.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Age</th>
<th>PP Lat (°)</th>
<th>A95 (deg/Sm)</th>
<th>PP Long (°)</th>
<th>Q</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2, Upper Nama Gr., S Afr.</td>
<td>Pr-f</td>
<td>5.0</td>
<td>271.0</td>
<td>12.5</td>
<td>5.0</td>
<td>271.0</td>
</tr>
<tr>
<td>WM, Holden Gr., S Afr.</td>
<td>Pr-f</td>
<td>3.0</td>
<td>270.0</td>
<td>14.0</td>
<td>13.0</td>
<td>270.0</td>
</tr>
<tr>
<td>TR, Tood, Allua &amp; Eninta Fm., Aust.</td>
<td>e1</td>
<td>-43.2</td>
<td>339.9</td>
<td>7/7/4.5</td>
<td>-15.1</td>
<td>334.9</td>
</tr>
<tr>
<td>AP, Antrim Plateau Basalts, Aust.</td>
<td>e1</td>
<td>-9.0</td>
<td>340.0</td>
<td>13.0</td>
<td>10.2</td>
<td>311.6</td>
</tr>
<tr>
<td>HK2, Hawker Gr., Aust.</td>
<td>e1</td>
<td>-26.7</td>
<td>2.0</td>
<td>38.7/2.1</td>
<td>9.0</td>
<td>329.5</td>
</tr>
<tr>
<td>SBA, Billy Creek Fm., Aust.</td>
<td>&amp;m</td>
<td>-27.4</td>
<td></td>
<td>-14.4/7.2</td>
<td>5.7</td>
<td>357.8</td>
</tr>
<tr>
<td>AS, Arengyona Section, Aust.</td>
<td>&amp;m</td>
<td>-33.0</td>
<td>12.0</td>
<td>5.0</td>
<td>7.3</td>
<td>350.0</td>
</tr>
<tr>
<td>LPG, Lake Frome Gr., Aust.</td>
<td>&amp;m</td>
<td>-31.4</td>
<td>26.9</td>
<td>10.1/5.1</td>
<td>33.1</td>
<td>1.5</td>
</tr>
<tr>
<td>MI, Mirny Station, Ant.</td>
<td>O1</td>
<td>-1.5</td>
<td>28.5</td>
<td>16.0/8.0</td>
<td>39.1</td>
<td>358.5</td>
</tr>
<tr>
<td>TS, Tumbulagoo Sandstone, Aust.</td>
<td>O1</td>
<td>-26.7</td>
<td>33.7</td>
<td>3.0/2.0</td>
<td>19.0</td>
<td>6.5</td>
</tr>
<tr>
<td>JF, Jinduckin Fm., Aust.</td>
<td>O1</td>
<td>-1.0</td>
<td>25.0</td>
<td>11.0/10.0</td>
<td>30.3</td>
<td>354.1</td>
</tr>
<tr>
<td>NP, Nyongana Ring structure, S Afr.</td>
<td>O1</td>
<td>28.0</td>
<td>345.0</td>
<td>5.0</td>
<td>28.0</td>
<td>345.0</td>
</tr>
<tr>
<td>GW, Graafwater Fm., S Afr.</td>
<td>O1</td>
<td>28.0</td>
<td>14.0</td>
<td>8.8</td>
<td>28.0</td>
<td>14.0</td>
</tr>
<tr>
<td>SR, Sor Rondane, Ant.</td>
<td>O1</td>
<td>-27.9</td>
<td>9.5</td>
<td>5.5</td>
<td>7.6</td>
<td>5.1</td>
</tr>
<tr>
<td>TV, Taylor Valley, Ant.</td>
<td>Om</td>
<td>-9.4</td>
<td>27.3</td>
<td>8.5</td>
<td>32.5</td>
<td>4.3</td>
</tr>
<tr>
<td>BI, Blaubeker Fm., S Afr.</td>
<td>Om</td>
<td>53.0</td>
<td>326.0</td>
<td>12.0/1.0</td>
<td>51.0</td>
<td>31.0</td>
</tr>
<tr>
<td>SA, Salala Ring Complex, NE Afr.</td>
<td>Om</td>
<td>39.6</td>
<td>329.5</td>
<td>12.3/8.3</td>
<td>37.7</td>
<td>328.7</td>
</tr>
<tr>
<td>SUR, F. Suri, SAm. (*)</td>
<td>Om</td>
<td>-8.5</td>
<td>5.9</td>
<td>5.9</td>
<td>22.9</td>
<td>45.5</td>
</tr>
<tr>
<td>AIR, Nigerian Ring Complex, NW Afr.</td>
<td>SI</td>
<td>-43.4</td>
<td>8.6</td>
<td>6.2</td>
<td>-42.4</td>
<td>17.4</td>
</tr>
<tr>
<td>LP, Lipe6n, SAm.</td>
<td>SI</td>
<td>-74.8</td>
<td>215.1</td>
<td>10.1</td>
<td>-67.7</td>
<td>82.9</td>
</tr>
<tr>
<td>AV, Almaden Volcanics, Iberia</td>
<td>Sm</td>
<td>7.5</td>
<td>118.3</td>
<td>13.0/9.0</td>
<td>-53.0</td>
<td>65.0</td>
</tr>
<tr>
<td>SKV, Snowy River Volcanics, Aust.</td>
<td>Sm</td>
<td>-74.3</td>
<td>227.2</td>
<td>14.5/10.9</td>
<td>-59.0</td>
<td>21.0</td>
</tr>
<tr>
<td>SG, P. S. Grande (m.sup.), Pat.</td>
<td>D1</td>
<td>-62.0</td>
<td>283.5</td>
<td>20.4/20.2</td>
<td>-44.4</td>
<td>6.4</td>
</tr>
<tr>
<td>IR, Iranian red beds, Iran</td>
<td>D1</td>
<td>-51.0</td>
<td>16.0</td>
<td>10.0</td>
<td>-50.5</td>
<td>4.9</td>
</tr>
<tr>
<td>CV, Comerong Volcanics, Aust.</td>
<td>Dm-u</td>
<td>-76.9</td>
<td>330.7</td>
<td>7.2</td>
<td>-39.3</td>
<td>2.9</td>
</tr>
<tr>
<td>GH, Illilulla Volcanics, NE Afr. (*)</td>
<td>Dm</td>
<td>26.0</td>
<td>12.0</td>
<td>11.0</td>
<td>-6.8</td>
<td>10.3</td>
</tr>
<tr>
<td>WP, Worong Point Fm., Aust.</td>
<td>Dm</td>
<td>-70.8</td>
<td>19.7</td>
<td>-7.1</td>
<td>-25.7</td>
<td>9.3</td>
</tr>
<tr>
<td>HG, Hervey Gr., Aust.</td>
<td>Dc-Cl</td>
<td>-54.4</td>
<td>24.1</td>
<td>16.2/8.4</td>
<td>-9.6</td>
<td>5.7</td>
</tr>
<tr>
<td>CB, Canning Basin Let., Aust.</td>
<td>Dc-Cl</td>
<td>-49.1</td>
<td>38.0</td>
<td>7.8</td>
<td>-2.7</td>
<td>13.1</td>
</tr>
<tr>
<td>GB, Geelong Basalts, Iran</td>
<td>Dc-Cl</td>
<td>-32.0</td>
<td>4.1</td>
<td>6.0</td>
<td>26.3</td>
<td>5 0</td>
</tr>
<tr>
<td>TP, Grupo Tepuel, Pat.</td>
<td>Cm</td>
<td>-31.7</td>
<td>316.1</td>
<td>16.0/15.0</td>
<td>-18.1</td>
<td>6.6</td>
</tr>
<tr>
<td>DV, Dyoyava Varves, S Afr.</td>
<td>Cm</td>
<td>-26.5</td>
<td>26.5</td>
<td>10.5</td>
<td>-26.5</td>
<td>26.5</td>
</tr>
<tr>
<td>C-P, Mean FP, SAm. + Afr.</td>
<td>Cu-F1</td>
<td>-24.5</td>
<td>59.0</td>
<td>3.8</td>
<td>-24.5</td>
<td>59.0</td>
</tr>
</tbody>
</table>
reconstruction. Iran, not considered by these authors, has been placed in Gondwana according to the reconstruction of Scotese & McKerrow (1990).

From Table 2 it is evident that there is no reliable Silurian palaeomagnetic pole for Gondwana, besides AIR (Hargraves, Dawson & Van Houten 1987) and LP. Recent data on the age of the AIR rocks (Van der Voo 1993) indicate that AIR is more likely to be an Early Devonian pole. This is consistent with its position which is coincident with other Early Devonian Gondwana poles (Fig. 10). This would leave LP as the only pole for the Early Silurian of Gondwana. The pole position suggested by LP remains to be confirmed by new palaeomagnetic data; however, some speculations can be made on its geodynamic and palaeogeographic implications.

The location of LP to the south (in present coordinates) of SR (Snowy River Volcanics, Early Devonian; Schmidt, Embleton & Palmer, 1987) and other Early–Middle Devonian poles (CV, Schmidt et al. 1986; SG2, Rapalini & Vilas 1991; IR, Wensink 1983) smoothly extends the Devonian APWP backwards in time, by defining a continuous and simple Lower Silurian–Devonian path (Fig. 10). A recently obtained palaeomagnetic pole for the Early Silurian (Llandovery–Wenlock) Almaden Volcanics of Spain (Perroud, Calza & Khattach 1991; AV, Fig. 10) situated between LP and SR, when reconstructed for Late Palaeozoic and Cretaceous rotations of Iberia (Perroud et al. 1991), supports the modified APWP proposed here. Although structural uncertainties regarding the palaeoposition and tectonic evolution of Iberia do not permit this to be considered a reliable pole for the definition of the Gondwana APWP, the palaeolatitude values deduced from it, unaffected by possible undetected rotations, are concordant with those from LP. However, Pares & van der Voo (1992) have questioned the primary nature of the remanence of the Almaden Volcanics as indicated by Perroud et al. (1991).

If LP is confirmed as an Early Silurian pole for Gondwanaland, the definition of the Gondwana APWP for Ordovician to Early Silurian times becomes problematic, as it implies an even longer mid-Palaeozoic APWP than the one postulated by Van Houten & Hargraves (1987), Van der Voo (1988) and others (see Fig. 1). An Early Palaeozoic path for Gondwana is presented in Fig. 11(a). After an apparent fast displacement during Early Cambrian times, Middle Cambrian to Middle Ordovician poles are located near northern Africa. They do not form a steady group but seems to define a northward movement, with Middle Ordovician poles located north of northern Africa. This would imply an Ordovician loop of the APWP, already noted by Piper (1987). Lack of reliable Late Ordovician poles has been generally solved by a hypothetical Upper
Ordovician fast section of the APWP leading to southern South America. That section is here continued up to the Early Silurian pole position of Gondwana as defined by LP. The path backtracks then to reach the Early Devonian poles. This APWP implies a very fast displacement of Gondwana from Middle Ordovician to Devonian (over 20 cm yr⁻¹), even though the displacements suggested are smaller than those recently proposed by Li et al. (1990) in an alternative Gondwana path (Fig. 1). This APWP polarity option is commonly accepted because it is consistent with the migration of glacial centres over this supercontinent during the Palaeozoic (Caputo & Crowell 1985). One problem with this correlation, however, is the difference between the Devonian segments of the palaeomagnetic and palaeoclimatic paths. The distribution of Devonian PPs over Gondwana (Fig. 10) indicates that this supercontinent was moving over the South Pole at those times. There is no evidence of ice-sheet glaciations of this time in Gondwanaland. Worsley & Kidder (1991) have suggested the possibility of a certain distribution of land masses causing a very warm world without glaciations, even with a large continent over the pole. This emphasizes the care that must be taken when using glacial records alone as palaeolatitudinal indicators.

A simpler geodynamic evolution for Gondwana can be assumed by choosing the reversed (antipodal) polarity for pre-Silurian poles. This was first postulated by Schmidt & Morris (1977) in order to account for older and less reliable PPs from the Lachlan fold belt. This alternative was not taken into account in most palaeogeographic studies mainly because it is apparently incompatible with the migration of glacial centres across Gondwana as deduced from climatologic indicators (Caputo & Crowell 1985). In Fig. 11(b) all reliable Cambrian or Ordovician poles from Gondwanaland have been plotted, reversing their original polarities. All these poles have ages ranging approximately between 560 and 460 Ma. Except for the Suri Formation pole (Valencio, Vilas & Mendia 1980), all other Middle Cambrian to Middle Ordovician poles form an elongated group towards LP, and the Ordovician loop (Fig. 11a) disappears. Note that BL and SA, whose ages are Mid-Ordovician (470 - 460 Ma), are those located closer to LP. This revised reversed path implies a continuous southward movement of Gondwanaland from high latitudes in the northern hemisphere (North Pole over northern Africa) in the Ordovician to reach the South Pole in the Early Devonian. The speed implied is about half of that obtained from the 'normal' polarity option. The displace-
Figure 11. (Continued.)

ament continued in the same direction throughout the Devonian until Central Gondwana (Central Africa) was located over the South Pole.

CONCLUSIONS

A palaeomagnetic study carried out at four different localities on ferriferous beds from the Early Silurian Lipeón Formation in NW Argentina has yielded a palaeomagnetic pole located at 214.8°E, 74.9°S ($N = 6, K = 46.7, A95 = 9.9^\circ$). The characteristic magnetization was defined as a chemical remanence carried by fine-grain (SD?) oolitic haematite formed by alteration of the original hydrosilicates during diagenesis. Despite some proximity of the palaeomagnetic pole to Permian to Jurassic South American poles, geologic evolution of the region and other evidence suggest a Lower Silurian age for the remanence. Assuming this, two possible Gondwana APWPs are proposed. One is a modification of currently widely accepted paths and implies a fast and complex apparent displacement of Gondwana during the Early and Middle Palaeozoic. Despite the geodynamic implications and assuming a Lower Silurian age for LP, this path is partially compatible with palaeoclimatic indicators. An alternative path is proposed assuming a reversed polarity for all Cambrian and Ordovician poles. This implies a much simpler and slower displacement for Gondwana, but conflicts with the palaeoclimatic evidence.

ACKNOWLEDGMENTS

The authors were grateful for financial support from the Consejo Nacional de Investigaciones Científicas y Técnicas (Argentina), the Universidad de Buenos Aires, and a grant from the Argentine Fundación Antorchas to AER. Fabricaciones Militares (FM) permitted the access to the exposures and provided facilities during the field work. Servicio Geológico Nacional facilitated the use of the microscope. V. Mendez (FM) provided us with unpublished information of the study area. C. Laj (CNRS, France) kindly facilitated the use of the pulse magnetizer. Critical review of an early version of the manuscript by M. J. Orgeira is acknowledged. Critical comments from anonymous reviewers greatly improved the manuscript. Some of the figures were done with Smethurst and Torsvik’s GMAP program.

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