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The Late Carboniferous to Late Triassic segment of the apparent polar wander path of Iberia

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Abstract

A palaeomagnetic study has been carried out at 16 well-dated sites from four areas in central Spain (southeastern Iberian Massif and western Iberian Ranges) in order to constrain the Late Carboniferous to Late Triassic segment of the apparent polar wander path (APWP) of Iberia. 322 samples (218 with useful results) were collected from andesitic rocks at Atienza (287 ± 12 Ma) and from Triassic continental red beds at Molina de Aragón (Anisian-Ladinian), Alcaraz (Ladinian-Carnian), Alcázar de San Juan (Ladinian-Carnian) and Cuevas de Ayllón (Carnian-Norian). Comparison of the palaeomagnetic results from the western Iberian Ranges and from the Iberian Massif indicates that the investigated area of the Iberian Ranges forms part of Stable Iberia. The palaeomagnetic poles obtained in this study and a revision of previous palaeomagnetic data, discarding poles obtained from areas of doubtful stability, show together a gradual and consistent change in latitude and longitude resulting in a coherent segment of the APWP for the Late Carboniferous to Late Triassic time span.

Introduction

During the Mesozoic opening of the Central Atlantic, the Iberian microplate occupied a key tectonic position between the European, African, and North American plates. The pattern of magnetic anomalies in the Bay of Biscay (Srivastava et al. 1990), and available palaeomagnetic data from Iberia, reviewed by Van der Voo (1993), document its 35 to 40° anticlockwise rotation associated with the opening of the Bay of Biscay. However, the exact plate motion of Iberia during the Mesozoic is still poorly understood, and several proposals for its apparent polar wander path (APWP) are under discussion.

The Iberian plate can be defined as a lithospheric unit consisting of a central continental domain that is bordered by a domain of thinned or thickened continental crust, and an oceanic domain. The western part of continental Iberia is dominated by the large Iberian Massif of Hercynian age. It also comprises the Central System, an Alpine-deformed mountain chain of nearly E-W orientation (Figure 1). The rest of the geotectonic features of Iberia can be described in terms of the deformed Mesozoic basins that constitute the main morphostructural reliefs (Pyrenees, Betics and the Iberian and Catalonian Ranges), and the lightly deformed Cenozoic Basins (Tajo, Duero, Ebro and Guadalquivir basins) located between them. Most of these features were established by Early Miocene times, during the last important tectonic event that affected the western Mediterranean, when Iberia was moving as part of Eurasia. The pre-Miocene evolution of the plate is not so straightforward. It is related to the Triassic-Liassic rifting and subsequent sea-floor spreading of the Atlantic Ridge and opening of the Bay of Biscay during Cretaceous times (Galdeano et al. 1989, Srivastava et al. 1990).

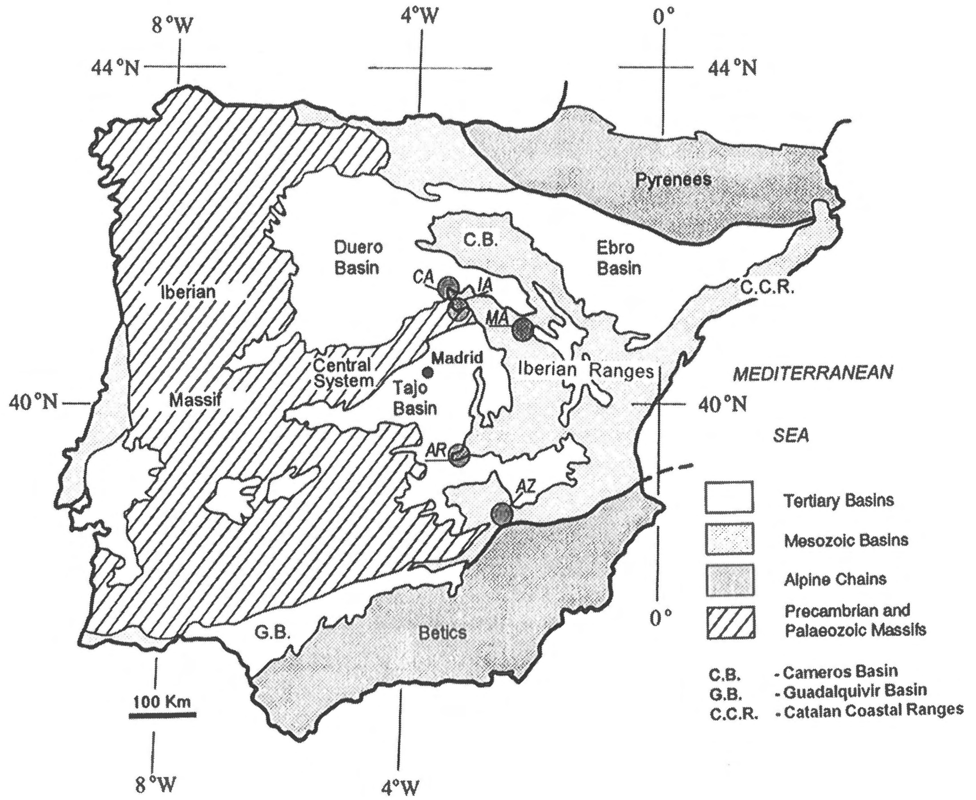

Figure 1. Main morphostructural units of the Iberian Peninsula and general distribution of the sampled regions. IA = Atienza (Upper Carboniferous-Lower Permian); MA = Molina de Aragón (Anisian-Ladinian); AZ = Alcaraz (Ladinian-Carnian); AR = Alcázar de San Juan (Ladinian-Carnian); CA = Cuevas de Ayllón (Carnian-Norian).

Stable Iberia and the reliability of its palaeopoles

In the last 40 years numerous palaeomagnetic studies have been carried out on Permian and younger rocks from the Iberian Peninsula (e.g. Clegg et al. 1957, Schwarz 1963, Van der Voo 1967, 1969, Stauffer & Tarling 1971, Van der Voo & Zijderveld 1971, Vandenberg 1980, Schott & Peres 1987a, b, 1988, Galdeano et al. 1989). The first systematic study which covered a significant time span (Ordovician to Eocene) was carried out by Van der Voo (1969). This work constitutes the first well-documented palaeomagnetic evidence for the 35° anti-clockwise rotation of Iberia. Despite the numerous palaeomagnetic data the APWP of Iberia is still poorly defined. This is mainly because the published palaeopole positions for Iberia do not follow a clear trend, and thus the selection of data for any APWP construction is dependent on the criteria used by the different authors. The observed scatter of the published palaeopoles may be due to the complications discussed below.

Stable Iberia

Recent structural and palaeomagnetic studies of the Iberian plate borders reveal local tectonic deformations that raise questions about the directional stability of the data used for the calculation of palaeopoles. Palaeomagnetic data obtained in the Betic Cordilleras, for example, show important clockwise rotations (Osete et al. 1989, Platzman & Lowrie 1992, Villalaín et al. 1994, Allerton et al. 1993). Data from the Pyrenees reveal a pattern of contrasting tectonic rotations (Schott & Peres 1988; Dinarès et al. 1992, Keller et al. 1994). Clockwise rotations have also been described from the Catalan Coastal Ranges (Parés et al. 1988). The Iberian Ranges have been traditionally considered as part of Stable Iberia. However, Van der Voo (1993) questioned their stability on the basis of recent geological interpretations of this chain that suggest the existence of deep detachment surfaces related to important thrusting (Guimerá & Alvaro 1990). On the other side, very recent palaeomagnetic studies of Oxfordian limestones covering a large area of the Iberian Ranges have not only demonstrated that there is directional consistency in most of the chain but also that significant rotations may occur locally (Juárez et al. 1996). Finally, Vegas et al. (1990) consider that part of the deformation due to the collision of Africa and Eurasia has been partially accommodated in the Central System by small-scale block rotations. Accounting for these observations, only data from undeformed areas, or from rocks younger than the particular deformation, should be used to construct the APWP of Iberia. If that is so, can only the Meseta be considered as Stable Iberia? As will be discussed later, it is likely that a large part of the Iberian Ranges can also be considered stable.

Magnetization overprint

Some of the magnetization directions which were used for palaeopole calculations were later recognized as remagnetizations. In fact, the first palaeomagnetic study carried out on the Iberian plate (Clegg et al. 1957) was thought to provide the first evidence for its anticlockwise rotation, but it was later recognized as being based on an erroneous interpretation of the magnetization age (Van der Voo 1993). Schott et al. (1987a, b) have shown the existence of important Tertiary overprints in Triassic rocks of the Cantabrian Cordillera and Lower Cretaceous rocks of the Iberian Ranges. Juárez et al. (1994, 1996) have demonstrated the existence of pervasive overprints in Jurassic limestones of the Iberian Ranges, suggesting that most of the Jurassic data previously obtained in this region (Stauffer & Tarling 1971, Vandenberg 1980), and used to calculate palaeopoles, are remagnetized. Moreau et al. (1992) have also shown a widespread remagnetization of Lower Cretaceous limestones from the Maestrazgo in the southern Iberian Ranges. Turner et al. (1989) argued the existence of pervasive overprints affecting a large part of Triassic Buntsandstein rocks in the Iberian Ranges, although Rey et at. (1996) later showed that some Triassic red-bed outcrops from this area yield reliable palaeomagnetic results.

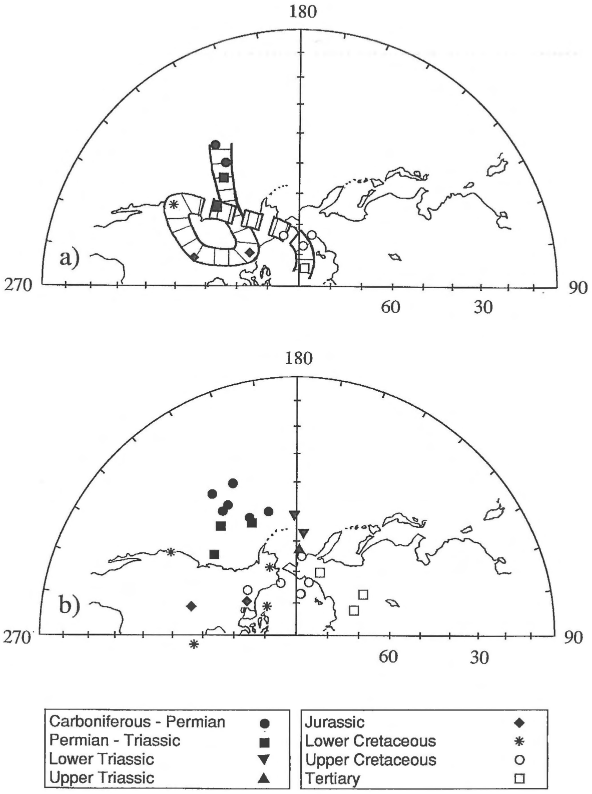

Figure 2. a) Apparent polar wander path for Iberia proposed by Schott (1988). b) Iberian palaeopoles with a quality factor Q $\geq$ 3 selected from Van der Voo (1993).

Age determination

The originally inferred ages of the units studied during the early palaeomagnetic research on Iberia, have often been modified on the basis of newer geological evidence. In fact, some of the discrepancies between the APWPs of Schott (1988) and Van der Voo (1993) can be attributed to this problem (Figures 2a, b). The Late Triassic pole obtained by Van der Voo (1967) in red beds from Alcázar de San Juan (southern Meseta) was initially dated as Early Triassic. The position of this pole falls far away from the Permo-Triassic poles for the Cantabrian Ranges considered as representative of Stable Iberia by Schott (1988).

In addition, ages of several volcanic units have been revised by radiometric methods over the last ten years. The Lisbon basalts, originally studied by Van der Voo & Zijderveld (1971) and attributed to the Eocene by stratigraphical methods, now have a radiometric age of about 70 Ma (Late Cretaceous). K-Ar dating performed on the Atienza andesites, investigated by Van der Voo

(1967), gives an age of about 290 Ma in contrast to their previously assigned Silurian age.

Scarcity of data

The number of palaeomagnetic studies of the Iberian Peninsula has greatly increased over the last ten years. Unfortunately this increasing activity has not resulted in a substantial increase of the number and reliability of palaeomagnetic poles from which the APWP of Iberia can be adequately constrained. This is mainly due to the fact that most of these studies have concentrated on magnetostratigraphic problems, and have been carried out in areas which cannot be considered as Stable Iberia (i.e. Ogg et al. 1984, 1988, Steiner et al. 1987, Mazaud et al. 1986). On the other hand, a considerable amount of work has been concerned with the study of deformed chains like the Betics and the Pyrenees, which cannot be used for the purpose of constructing an APWP for Iberia. Furthermore, many of the Cretaceous and Jurassic rocks sampled with the aim of defining this sector of the Iberian APWP, display pervasive overprints that severely limit the number of poles that can be reasonably expected for this period (Galdeano et al. 1989, Moreau et al. 1992). After more than 40 years of palaeomagnetic research in Iberia, the number of available palaeomagnetic data is still too small to construct a detailed APWP.

Previous APWPs for Iberia

Schott (1988) proposed a Late Carboniferous to Miocene APWP for Iberia based on his own work plus a selection of previously published data (Figure 2a). He considers eleven poles, including two from the Cantabrian Ranges (Vandenberg 1980, Schott & Peres 1987b) and two of Jurassic (Steiner et al. 1985) and Early Cretaceous (Schott and Peres, 1987a) age from the Iberian Ranges. The Late Triassic pole (originally dated as Early Triassic) obtained by Van der Voo (1967) from red beds in the southern Meseta was discarded by Schott owing to its deviation from the other contemporary poles. Its proximity to the Tertiary poles made him suspect that it was remagnetized.

Van der Voo (1993) published a review of previously published palaeomagnetic poles and assigned a quality factor to them. Figure 2b shows a projection of poles from Iberia with a quality factor Q ≥ 3. This figure includes the Permo-Triassic and Early Triassic poles from the Catalan Coastal Ranges, although Van der Voo advises that, following the opinion of the authors (Parés et al. 1988), they may be affected by local rotations. Finally, Van der Voo (1993) considers that the Late Triassic departure from the trend of the APWP proposed by Schott (1988), is related to the Late Triassic cusp observed in the North American APWP (Gordon et al. 1984, Ekstrand & Butler 1989).

These two versions show important differences for the Permian to Late Triassic time span.

In a more recent study Parés & Dinarès (1994) investigated Triassic red beds from the Algarve (southern Portugal) and southeastern Iberian Meseta. They selected these areas as representative of the southeast and southwest margin of Stable Iberia. They did not establish a precise chronology but considered that the ages of the studied rocks span the Late Triassic. Their results from the southern Meseta confirm the pole obtained by Van der Voo (1967). In contrast, directions from southern Portugal lie 15° westward of the directions obtained from the southern Iberian Massif. This discrepancy can be due to the fact that both poles are not representative of the same Triassic palaeofield, or to the existence of intraplate rotations, or to a combination of both phenomena. After discussing these possibilities, the authors conclude that Alpine intraplate deformation has produced the observed discrepancy. And, therefore, the Algarve palaeopole reflects a rotation associated with the Alpine evolution of the Iberian Atlantic margin.

The present study intends to improve the resolution of the Late Carboniferous to Late Triassic segment of the APWP. In order to achieve this we have sampled 16 sites from 4 localities of Late Carboniferous to Late Triassic age. We have been careful in selecting the sampling sites so that the ages of the rocks, the presence of overprints and their tectonic context are adequately constrained.

Sampling strategy and palaeomagnetic methods

This study is based on 218 useful (out of 322) oriented samples collected from andesitic rocks at Atienza (locations IA1–4; 287 ± 12 Ma, Carboniferous-Permian), and from Triassic continental red beds at Molina de Aragón (MA1–3, Anisian–Ladinian), Alcaraz (AZ1–6, Ladinian-Carnian), Alcázar de San Juan (AR1 and 2, Ladinian-Carnian), and Cuevas de Ayllón (CA1, Carnian-Norian). The investigated regions are located in the intersection of the Central System and the Iberian Ranges (IA and CA, Figures

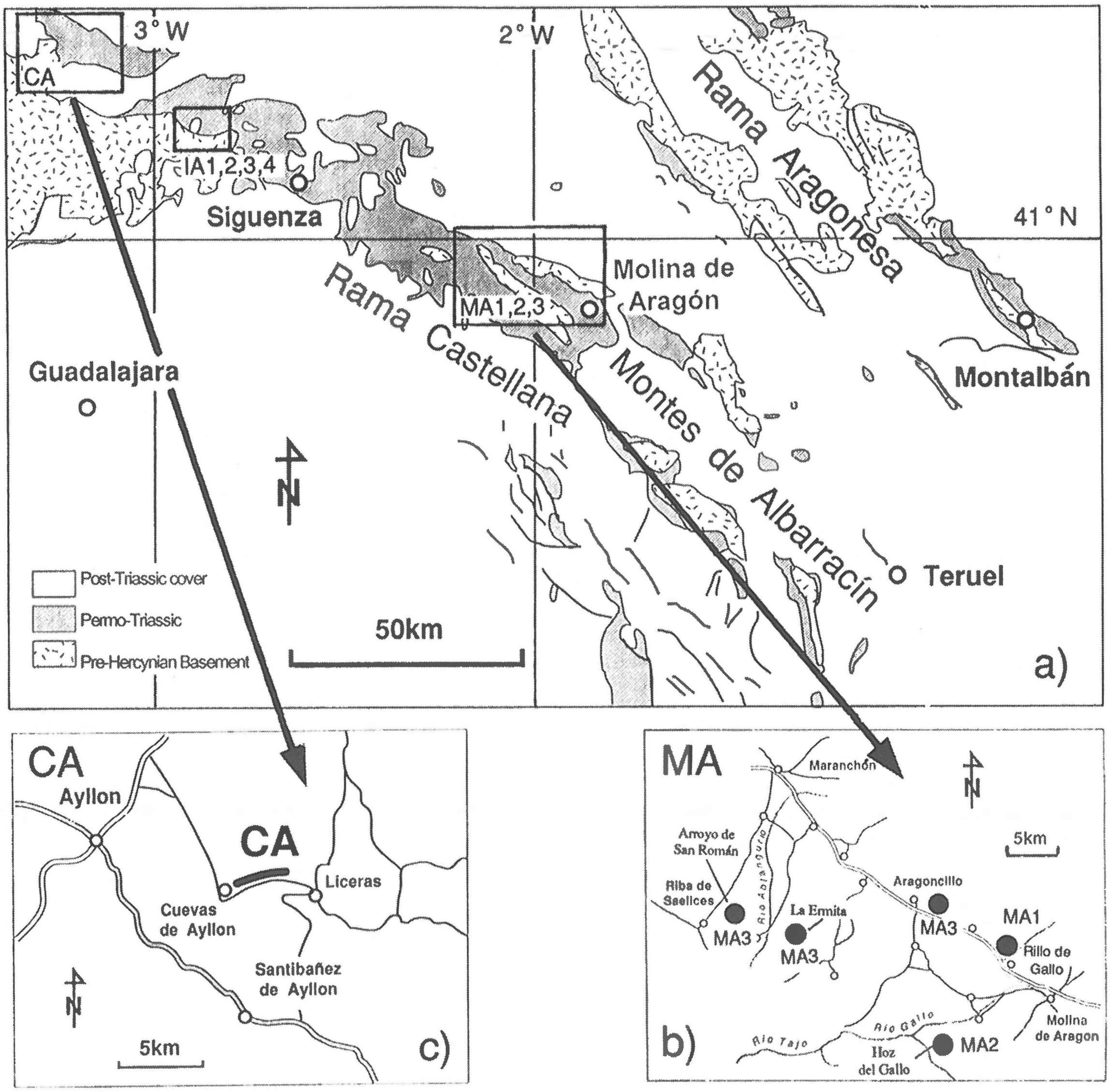

Figure 3. a) Geological sketch map showing the main structural units (after Sopeña et al. 1988) and the locations of the Molina de Aragón (MA), the Cuevas de Ayllón (CA) and the Atienza (IA) sites. b) Location map of the MA sites. c) Location map of the CA site.

1, 3a), in the western part of the Iberian Ranges (MA, Figures 1, 3a), and in the eastern part of the Iberian Massif, in the southern Meseta (AR and AZ, Figures 1, 4a). All sampling locations are in presumed Stable Iberia except Molina de Aragón which is situated in the western part of the Iberian Ranges. The stability of this region will be discussed later in this paper.

Two of the investigated localities, Atienza and Alcazar de San Juan, have been studied by Van der Voo (1967) using the alternating-field (AF) demagnetization techniques that were available 30 years ago. We intend to improve the quality and test the reliability of these key localities by using thermal demagnetization and by constraining their ages on newer stratigraphical and structural evidence.

Turner et al. (1989) investigated the Buntsandstein facies in the Molina de Aragón area. They found that much of the Buntsandstein outcrops were completely remagnetized in a direction similar to the present local geomagnetic field. However, they were able to produce a preliminary magnetostratigraphical column based on the primary remanence preserved in some

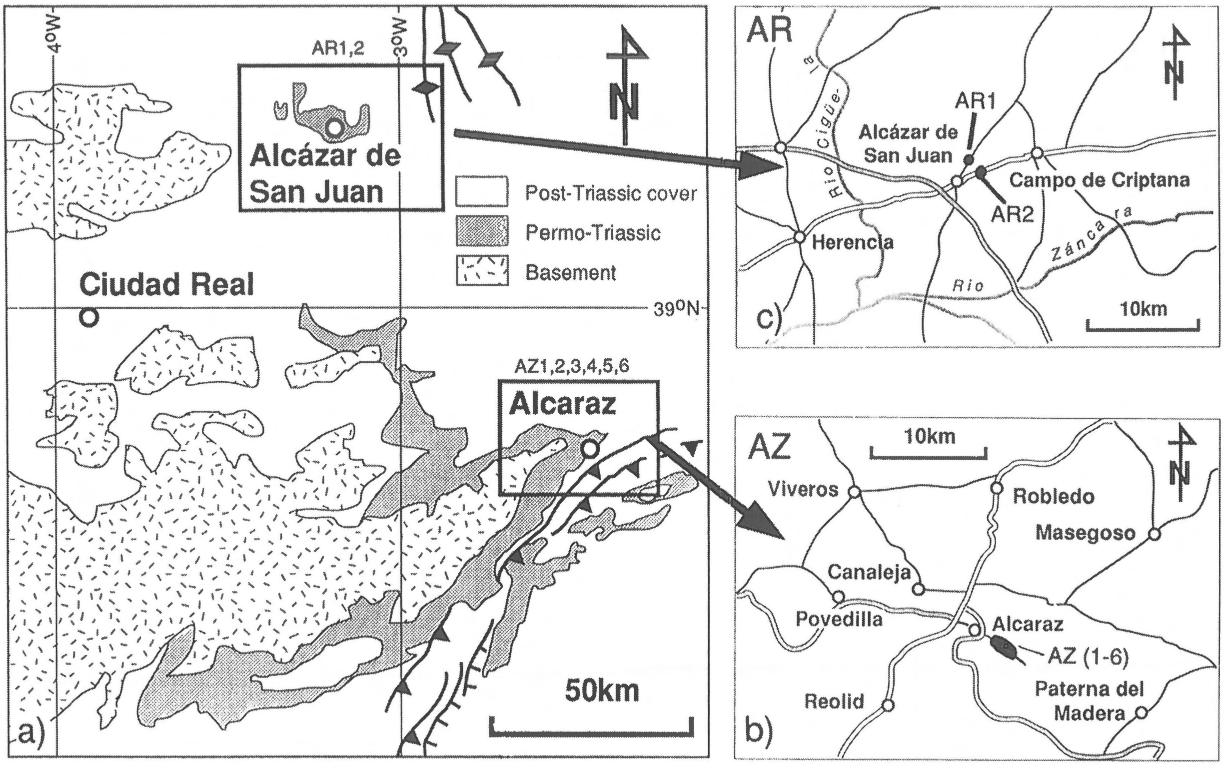

Figure 4. a) Geological sketch map showing the locations of the Alcaraz (AZ) and Alcázar de San Juan (AR) sites. b) Location map of the AZ sites. c) Location map of the AR sites.

fine-grained lithologies. The low intensity shown by the primary remanence made it difficult to calculate a mean direction for this component. Consequently, Turner et al. (1989) do not give a palaeomagnetic pole for the Molina de Aragón Buntsandstein facies. Following the path-breaking work of these authors, Rey et al. (1996) have later shown a more refined Upper Triassic magnetostratigraphy for this area that correlates well with magnetostratigraphical sequences in North America and Asia.

Most palaeomagnetic samples were drilled in the field, where cores of 2.5 cm diameter were oriented using a magnetic compass and an inclinometer. However, the oriented hand samples collected at Molina de Aragón were drilled and prepared into standard palaeomagnetic specimens in the laboratory. Magnetic measurements were carried out at the palaeomagnetic laboratories of the Madrid, Birmingham and Newcastle Universities. The natural remanent magnetization (NRM) was generally measured with spinner magnetometers (Minispin). A cryogenic magnetometer was occasionally used for specimens with initial intensities < 1 mA/m. Progressive thermal demagnetization was performed using Schonstedt TSD-1 and MMTD furnaces. In addition some volcanic samples from Atienza were AF-demagnetized with GSD-5 Schonstedt equipment. The susceptibility was measured after each thermal demagnetization step using a Minisep instrument. The characteristic NRM components were evaluated by least-squares fitting of linear segments to orthogonal vector plots during progressive demagnetization (Zijderveld 1967), and by principal-component analysis (Kirschvink 1980). Isothermal remanent magnetization (IRM) in fields up to 1T, was used to identify magnetic minerals in the samples by means of their coercivity (Lowrie & Heller 1982).

Palaeomagnetic and rock-magnetic results

Atienza (Carboniferous-Permian boundary)

The Atienza area is located at the eastern border of the Central System close to the Iberian Ranges (Figure 3a). The studied rocks are from the Atienza volcanics, a sequence of two andesitic units interbedded

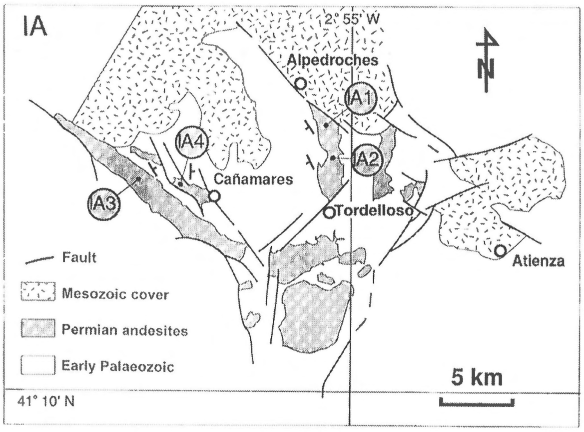

Figure 5. Geological sketch map showing the locations of the sites IA1 to 4 in rocks dated at the Carboniferous-Permian boundary at Atienza. Samples were collected in both limbs of a syncline to perform a fold test. The general location of the IA sites is shown in Figure 3a.

with detrital sediments. The volcanics crop out west of Atienza in a NW-SE striking syncline (Figure 5). The sequence consists of volcanic rocks with subvolcanic associated intrusions (Muñoz et al. 1985). The age of the andesites was originally established as Silurian (Schröder 1930). Later, Virgili et al. (1973) and Hernando (1977) considered a Permian age for them due to their stratigraphical position. Hernando et al. (1980) dated them radiometrically as 287 ± 12 Ma (Carboniferous-Permian boundary). The andesitic rocks lie unconformably on an older Palaeozoic basement, are interbedded with Permian sediments, and are overlain by the Buntsandstein (Hernando et al. 1980).

The Atienza andesites have been the subject of two previous palaeomagnetic studies. Van der Voo (1967) carried out a detailed study in four localities. Hernando et al. (1980) performed the radiometic datating of the rocks, reinterpreted the site tectonics as a syncline, and collected seven more cores for palaeomagnetism. These authors recalculated the Atienza palaeopole by combining their results with Van der Voo's (1967), applying a new bedding correction based on their tectonic interpretation. They also performed a fold test with an inconclusive result, concluding that the tectonic setting may be more complex than they originally thought.

Considering the above, we have chosen four sites at this location with the simplest possible tectonic setting, and located in both limbs of the Atienza syncline in order to perform a fold test. The bedding corrections were taken from the overlying Permian detrital beds at each site (IA1: Dip dir = 240° / Dip = 42°, IA2: 250°/38°, IA3: 56°/40° and IA4: 93°/24°).

Our results are based on 12 fully demagnetized specimens for each site. Thermal and AF-demagnetization showed the presence of two stable components of magnetization in sites IA1, 2 and 4 (Figure 6b), whilst in IA3 samples only one single stable direction was found (Figure 6a). All samples showed the presence of a component with a low coercivity and with maximum unblocking temperatures of 575–580°C. We interpret this component to be carried by titanomagnetite (of low Ti content). This component has been considered as the characteristic remanent magnetization (ChRM) of these rocks. Samples from sites IA1, 2 and 4, also showed the presence of a higher-coercivity component with maximum unblocking temperatures of 675°C (Figure 6b). Haematite is likely to be the carrier of this second component. Both components show reversed polarities and declinations directed to the southeast. The inclinations of the higher-temperature component are slightly steeper than those of the lower-temperature component (Figure 6b).

Comparison of the statistical parameters of McFadden & Jones (1981) before ($f_{before} = 0.3406$) and after tectonic correction ($f_{after} = 0.0097$) with the 95%-significance-level value ($F_{95\%} = 0.0679$) indicates a 95%-significance positive fold test suggesting a pre-folding acquisition of the ChRM during a reverse palaeomagnetic field (the Kiaman Superchron). Moreover, the ChRM direction resembles that of other Late Carboniferous to Early Permian directions. Consequently, it is very likely that this component represents the original magnetization of these rocks. An inconclusive result of the fold test performed for the high-temperature component indicates a secondary origin for this component. Directions of the high unblocking temperature before (Dec = 161.8°, Inc = −13.8°) and after (Dec = 156.5°, Inc = −19.0°) bedding correction are close to Middle Triassic data presented in this study. Therefore we have interpreted this component as a Permo-Triassic remagnetization. Geological evidence indicates that these rocks have not only been affected by the Alpine orogeny, but possibly also by Tardihercynian movements (Hernando et al. 1980).

Molina de Aragón (Anisian-Ladinian)

The Molina de Aragón area is located in the western part of the Iberian Ranges (Figure 3a). In this area, we have investigated two stratigraphical units, the Rillo Mudstones and Sandstones Formation and the Torete

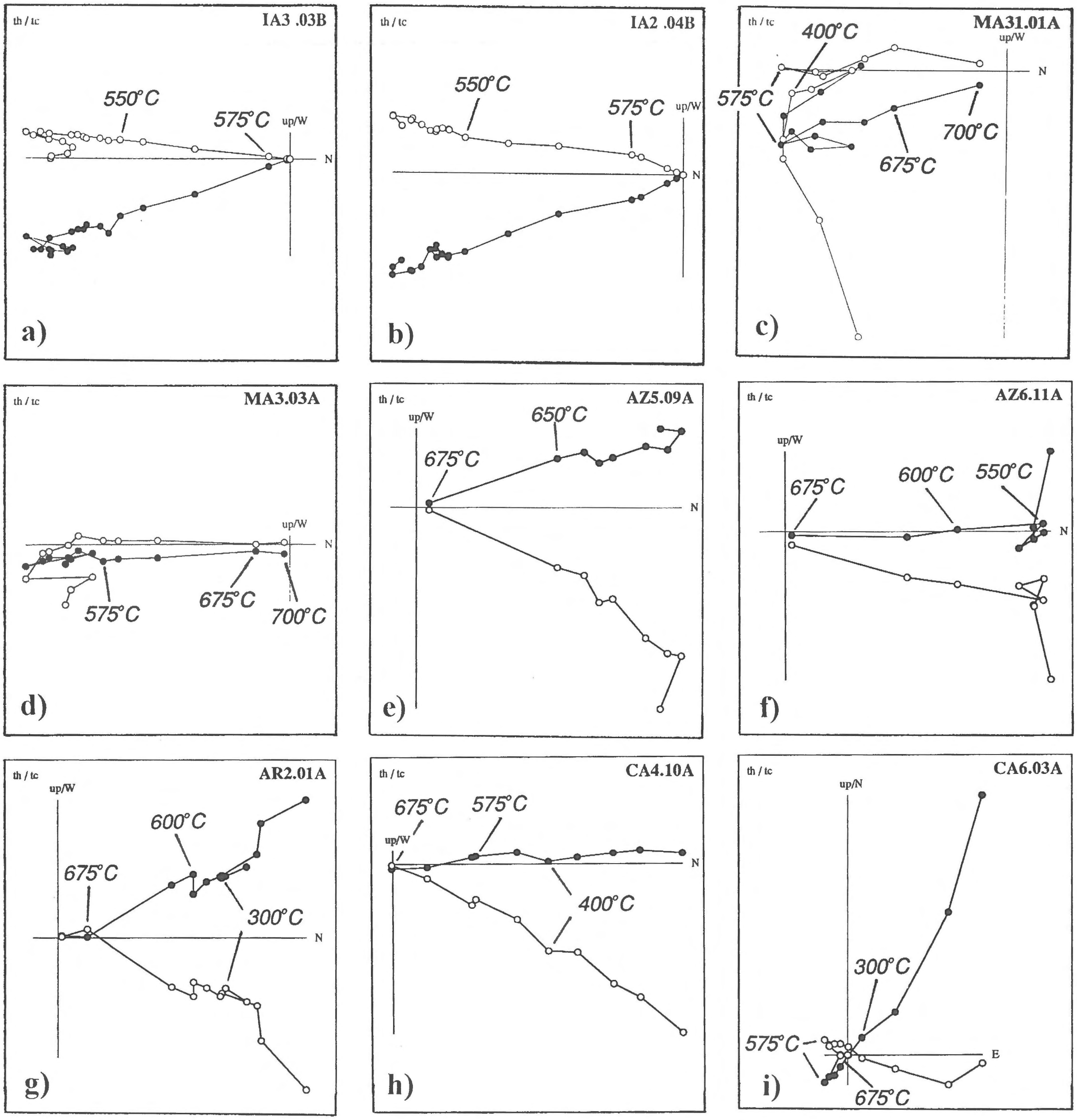

Figure 6. Representative Zijderveld diagrams after tilt correction (tc) from the studied sites. a) Sample IA3.03B, Atienza, Iberian Ranges, Carboniferous-Permian. b) Sample IA2.04B, Atienza, Carboniferous-Permian. c) Sample MA31.01A, Molina de Aragón, Iberian Ranges, Anisian-Ladinian. d) Sample MA3.03A, Molina de Aragón, Anisian-Ladinian. e) Sample AZ5.09A, Alcaraz, southern Meseta, Ladinian-Carnian. f) Sample AZ6.11A, Alcaraz, Ladinian-Carnian. g) Sample AR2.01A, Alcázar de San Juan, southern Meseta, Ladinian-Carnian. h) Sample CA4.10A, Cuevas de Ayllón, Iberian Ranges, Carnian-Norian. i) Sample CA6.03A, Cuevas de Ayllón, Carnian-Norian. Solid circles are projections on the horizontal plane and open circles those on the vertical plane.

Multicoloured Mudstones and Sandstones Formation, at five sections stratigraphically grouped in three localities (Figure 3b). These are: the Rillo de Gallo section (MA1 locality), the Hoz del Gallo section (MA2) and the Ermita, the Arroyo de San Román and Aragoncillo sections (MA3). The investigated beds dip lightly (10–15°) to the southwest.

The Rillo Fm consists of a 120-m-thick sequence of interbedded red mudstones and sandstones with a basal conglomerate (Ramos 1979). The top half of this unit was sampled at 1 to 2-m intervals in the Rillo de Gallo section (MA1), yielding 40 hand samples from which an average of two specimens per stratigraphic level were used for the palaeomagnetic study. The age of this formation has been established as Anisian (Middle Triassic) on the basis of the palynological assemblage found in the upper part of the unit at this particular site (Ramos 1979).

The overlying Torete Fm comprises up to 40 m of thin-bedded red, green and violet mudstones and sandstones with finely laminated dolomitic horizons towards the top (Ramos 1979). The whole formation was sampled at four different sections. In the La Hoz del Gallo section (MA2) 24 hand samples were collected. In addition 16 hand samples were collected at the La Ermita, Arroyo de San Roman and Aragoncillo sections (MA3). The age of this formation has been established as Ladinian (Middle Triassic) by Ramos (1979) on the basis of several palynological assemblages found in these sections.

The initial NRM intensities range from 0.05 to 2 mA/m. Thermal demagnetization showed a progressive removal of the magnetic remanence up to 700°C. The NRM showed multicomponent magnetizations. Most samples showed, after removing a viscous magnetization, two stable NRM components with maximum unblocking temperatures between 100–400°C and 575–700°C, respectively (Figure 6c). The low-temperature component always shows the normal polarity and steep inclinations that characterize directions close to the present-day field. The maximum unblocking temperature of this component is quite variable, but generally below 400°C. The other component is characterized by high unblocking temperatures, and directions with low inclinations of both polarities, and anti-parallel NNW or SSE declinations. The proportion in which these two components are present in individual samples is variable, and the NRM of the samples is often dominated by only one of the two components. Sample MA3.03A (Figure 6d), for example, shows a remanence completely dominated by the high-temperature component. At intermediate unblocking temperatures (400–575°C) there is a complex demagnetization behaviour resulting from overlap of normal and reverse components. This behaviour is evident in samples in which the characteristic component presents reversed polarity.

IRM-acquisition curves show that both components are carried by high-coercivity minerals only. These magnetic phases were identified in a detailed petrographical study as haematite, ilmeno-haematite, goethite and several other oxihydroxides. Goethite and several textural phases of late-authigenic haematite, are therefore likely to be the carrier of the low-temperature component. Both minerals are considered to have acquired a recent CRM (chemical remanent magnetization). Haematite and/or ilmeno-haematite have been identified as the carriers of components isolated in the high-unblocking-temperature spectrum, which in turn is interpreted as the result of a DRM (depositional remanent magnetization) or pDRM (post-depositional remanent magnetization). Samples showing exclusively the low-temperature component were discarded for calculation of the mean palaeomagnetic directions. A total number of 89 specimens were used in the final calculations representing 57 specimens from MA1, 26 from MA2 and 6 from MA3 localities. Directional analysis of these components showed that normal (Dec = 346.4°; Inc = 32.0°; α_{95} = 4.0°) and reversed (Dec = 167.2°; Inc = 2.9°; α_{95} = 5.3°) directions were not antipodal in terms of their inclinations. This can be explained by incomplete removal of the low-unblocking-temperature component during thermal cleaning, as a consequence of the unblocking-temperature overlap between the high-coercivity minerals that carry both components. However, a compensated mean direction (Rey 1992) could be calculated. Rey et al. (1996) have shown several magnetostratigraphical sequences from this area that correlate well with magnetostratigraphical sequences of the same age in North America and Asia.

Alcaraz (Ladinian-Carnian)

Sampling of the Middle and Upper Triassic in the southern Meseta was undertaken in Alcaraz (Figures 4a, b). These rocks constitute the easternmost Triassic outcrops of the so-called Triassic Continental Domain that represents the eastern border deposits of the Iberian Massif. They constitute the unfolded tabular cover of Buntsandstein and Keuper that crops out in this area. The chronostratigraphical data (Besems 1981, Márquez-Aliaga et al. 1982, Pérez-López et al. 1992) enabled to locate the Ladinian at the base of the Alcaraz sequence, and the Norian in the evaporitic rocks that constitute the uppermost part of the sequence. The position of the Carnian can only be inferred from correlation with the better dated Triassic sequences of the pre-Betic (Fernández & Dabrio 1985).

The sequence sampled at Alcaraz comprises up to 160 m of flat-lying continental red beds capped by an evaporitic succession. This sequence has been divided into three depositional sequences by Dabrio & Fernández (1986). The first depositional sequence (Ladinian) comprises the lower 75 m of the succession and is mostly formed by lenticular, channelized sandstone bodies and flood-plain mudstones with interbedded sheets of thin sands and micritic carbonates. It represents the typical Buntsandstein facies of the southern Meseta. The second depositional sequence is about 20 m thick and shows a similar sedimentary succession but with a greater development of ferruginated and bioturbated palaeosols. Its age cannot be established with precision but contains the Ladinian-Carnian boundary (Dabrio & Fernández 1986). The base of the third and uppermost sequence corresponds to a thick (15 m) tabular sandstone body of great lateral continuity that represents the K2 Keuper unit in the area and has an assigned Carnian age (Fernández & Dabrio 1985).

Sixty-six drilled samples and four hand samples were initially collected from six sites corresponding to the two uppermost units. Samples from sites AZ1 and 2 were collected from the thick sandbody located at the base of the K2 unit. Samples from sites AZ3 and 4 are located stratigraphically several metres below K2 whilst AZ5 and 6 are located above. A total number of 35 fully thermally demagnetized samples from sites AZ2, 4, 5 and 6 were used in this study. The rest of the samples either did not survive transport (AZ3 samples were very friable) or showed inconsistent palaeomagnetic results (initial intensities were very low in AZ1).

Initial NRM-intensity values ranged from 0.2 to 8 mA/m. Initial susceptibility values ranged between 1 and 5 × 10^{-5} (SI). Thermal demagnetization of Alcaraz samples showed the existence of a high-unblocking-temperature component responsible for most of the NRM in the sample. Two different behavioural types were observed during thermal demagnetization. In most cases demagnetization is very sudden (Figure 6e, sample AZ5.09a). Thermal demagnetization can also be gradual. In those cases, the high-temperature component starts to unblock between 500 and 550°C (Figure 6f, sample AZ6.11a). The maximum unblocking temperature is 675°C. We interpret this component as mainly carried by haematite, on the basis of its high-unblocking-temperature distribution. We also interpret this component, that dominates the Alcaraz samples, as the characteristic Triassic remanence of the samples.

Alcázar de San Juan (Ladinian-Carnian)

The Alcázar de San Juan rocks constitute the northernmost Triassic outcrops of the Triassic Continental Domain in the southern Meseta (Figure 4a). Here, the Triassic sedimentary sequence also comprises a flat-lying succession of interbedded mudstones and sandstones capped by the typically evaporitic deposits of the uppermost Keuper. The stratigraphy has been studied by Sopeña (1981) who defines a number of units that can be correlated with those of Fernández & Dabrio (1985) on the basis of the easily recognizable K2 unit. Consequently the age of the Alcázar de San Juan sites can be constrained to the Ladinian and Carnian stages.

Two sites have been sampled (Figure 4c). We intended to collect the samples at the same sites as those of Van der Voo's (1967) study in order to verify his data. Our samples have been thermally demagnetized (only AF demagnetization was used in the previous work). Our palaeomagnetic results are based on better constrained stratigraphical positioning so they can be compared with the Alcaraz and Cuevas de Ayllón sequences. The sampling sites (AR1 and 2) are located at the El Doncel windmill and N240 road respectively, probably very close to Van der Voo's (1967) sites. Nine AR1 samples were drilled from the thick sandstone bodies of the K2 unit. The nine samples drilled at the AR2 site were located in a sandy horizon cropping out a few metres above the K2 unit.

The initial intensities ranged from 0.7 to 7 mA/m and initial susceptibilities from 1 to 8 × 10^{-5}(SI). Thermal demagnetization showed a slow but consistent decrease in low-field magnetic susceptibility up to 500°C. AR1 samples undergo an important increase between 500 and 600°C, decreasing rapidly afterwards. The susceptibility decreased constantly for the AR2 samples but drops slightly faster at around 600°C.

Thermal demagnetization of AR1 and 2 samples showed a similar behaviour. Two directionally stable components were identified after removal of a viscous component of magnetization. The first stable component unblocks between 100 and 300°C. Between 300 and 600°C the magnetization does not decrease significantly, with most samples showing a stable cluster of points in this interval. A higher-temperature component suddenly unblocks at 600°C and is completely destroyed above 700°C (Figure 6g). The high-temperature component is interpreted as the character-

Table 1. Summary of palaeomagnetic poles and directions obtained in this study.

				Before tilt correction				After tilt correction				V.G.P.		
Locality	Age	Code	N	Dec (°)	Inc(°)	k	α_{95}(°)	Dec(°)	Inc(°)	k	α_{95}(°)	Lat P(°)	Long P(°)	P Lat(°)
Atienza	**275–299 Ma**	**IA**	**48**	**341.5**	**4.6**	**50.0**	**2.9**	**342.7**	**7.5**	**64.2**	**2.6**	**49.6**	**204.6**	**3.8**
		IA1	12	163.9	0.5	192.0	3.1	160.6	–9.1	192.4	3.1			
		IA2	12	166.0	–0.4	48.9	6.3	164.5	–4.0	48.9	6.3			
		IA3	12	156.7	–13.9	109.0	4.2	163.0	–3.9	109.5	4.2			
		IA4	12	159.3	–4.5	48.5	6.3	162.7	–13.2	48.4	6.3			
Molina	**AN-LAD**	**MA**	**89**	**348.6**	**7.1**	**10.9**	**4.8**	**346.8**	**15.8**	**12.3**	**4.5**	**55.1**	**201.4**	**8.0**
		MA1	57	348.6	0.7	16.8	4.7	347.1	10.0	16.8	4.7			
		MA2	26	348.8	28.8	18.3	6.8	343.6	34.0	18.3	6.8			
		MA3	6	347.8	–26.1	14.2	18.5	351.5	–8.3	13.2	19.2			
Alcaraz	**LAD-CAR**	**AZ**	**35**	**0.7**	**17.0**	**22.9**	**5.2**	**0.7**	**17.0**	**22.9**	**5.2**	**57.9**	**175.6**	**8.7**
		AZ2	5	356.1	29.1	8.0	28.9	356.1	29.1	8.0	28.9			
		AZ4	10	7.0	13.5	38.3	7.9	7.0	13.5	38.3	7.9			
		AZ5	11	357.9	19.1	28.4	8.7	357.9	19.1	28.4	8.7			
		AZ6	9	359.3	11.7	58.3	6.8	359.3	11.7	58.3	6.8			
Alcázar	**LAD-CAR**	**AR**	**16**	**353.9**	**23.3**	**10.7**	**11.8**	**353.9**	**23.3**	**10.7**	**11.8**	**62.1**	**189.8**	**12.5**
		AR1	8	6.6	24.0	9.4	19.0	6.6	24.0	9.4	19.0			
		AR2	8	342.1	21.7	18.8	13.0	342.1	21.7	18.8	13.0			
Ayllón	**CAR-NOR**	**CA**	**30**	**348.9**	**48.1**	**19.5**	**6.1**	**352.0**	**23.4**	**19.5**	**6.1**	**60.1**	**192.3**	**12.2**

AN = Anisian, LAD = Ladinian, CAR = Carnian, NOR = Norian. The age of the Atienza site has been established radiometrically (Hernando et al. 1980). Ages of the other sites have been obtained biostratigraphically. N = number of samples; k, α_{95} = Fisher statistical parameters; VGP = virtual geomagnetic pole; Lat P / Long P = latitude/longitude of palaeomagnetic pole; P lat = palaeo latitude.

istic Triassic magnetization carried by haematite. This component shows positive inclinations and spreads between north and NNW. Occasionally a few specimens may appear completely remagnetized. This distribution is similar to that found by Van der Voo (1967). The mean computed direction of both sites is also comparable to that of Van der Voo (1967).

Cuevas de Ayllón (Carnian-Norian)

Cuevas de Ayllón is located in the westernmost margin of the Iberian Ranges, at the intersection with the Central System (Figure 3a). Sampling was carried out along a large stratigraphical section of Upper Triassic rocks dipping 25° towards the north (Figure 3c). The Keuper section at Cuevas de Ayllón mostly consists of a thick sequence (> 120 m) of interbedded mudstones and sandstones. Thirty samples were drilled from red-coloured fine-grained sandstones of the central 30 m of the section. The age of this formation has been established as Carnian-Norian on the basis of Carnian palynological assemblages found in the underlying Muschelkalk unit in this area (Hernando 1977, Doubinger et al. 1978) and because it is stratigraphically capped by Lower Jurassic dolomites. These samples constitute the youngest material collected in this study.

The initial NRM intensities ranged from 3 to 7 mA/m and initial susceptibilities from 5 to 25 $\times 10^{-5}$(SI).Thermal demagnetization of the samples showed a progressive removal of the NRM intensity up to 675°C. Most samples showed at least two components of magnetization, thermally distributed in the low and high-temperature spectra. The low-temperature component is destroyed between room temperature and 550°C. This component always shows normal polarity and a mean direction close to the present-day field direction before tectonic correction. It is interpreted as an overprint. The high-temperature component unblocks between 575 and 675°C (typical of a haematite carrier), and shows normal and reversed polarity directions that are antipodal in bedding coordinates (Figures 6h, i). Mean directions of normal polarity (N = 14, Dec = 354.0°, Inc = 26.5°, k = 31.5, α_{95} = 7.2°) and reversed polarity (N = 16, Dec = 170.2°, Inc = –20.5°, k = 14.7, α_{95} = 10.0°) coincide for a confidence level of 95%. This component passes a reversal test for a confidence level of 95%. The statistical method to compare the mean direction of the two populations is that proposed by McFadden & Lowes (1981). In this case the statistical parameters are: $f = 0.071 < F = 0.113$. We consider the high-temperature component as the Triassic characteristic magnetization of these rocks.

Discussion of the results

Table 1 summarizes the palaeomagnetic data obtained by this study. Samples from localities AZ1 and 3 were discarded on the basis of the reasons explained in the previous section.

The palaeomagnetic data obtained for Alcaraz and Alcázar de San Juan in the southern Meseta, and for Cuevas de Ayllón in the northwestern margin of the Iberian Ranges are sufficiently close in time to allow some degree of comparison between their poles. Considering this and the fact that these three poles are statistically indistinguishable, we can conclude that the Cuevas de Ayllón area forms part of Stable Iberia. A similar reasoning can be applied to demonstrate the stability of other areas in the Iberian Ranges. Atienza is quite close to Cuevas de Ayllón (Figure 3a), forming part of the same morphostructural unit of this part of the ranges, and displaying a similar deformation style. The pole obtained for Atienza agrees well with Van der Voo's (1969) data from Viar in the southern Meseta (Table 2). This also supports that this area is part of Stable Iberia.

The Molina de Aragón region is located in the Castilian Branch of the Iberian Ranges (Figure 3a) where tectonic stability is questionable. One of the stratigraphical sections we sampled in this region was the Rillo the Gallo section. The lower part of this section consists of organic-rich mudstones, sandstones and limestones interbedded with thick volcanoclastic beds that have been biostratigraphically dated as Autunian (Ramos et al. 1986). The Autunian (Early Permian) palaeomagnetic pole obtained by Turner et al. (1989) from this section is statistically indistinguishable from the andesites pole of Late Carboniferous to Early Permian age of Atienza obtained in this study. Consequently, the Molina de Aragón region can also be considered as Stable Iberia. From what has been discussed above we can also conclude that all the poles obtained in this study are representative of Stable Iberia.

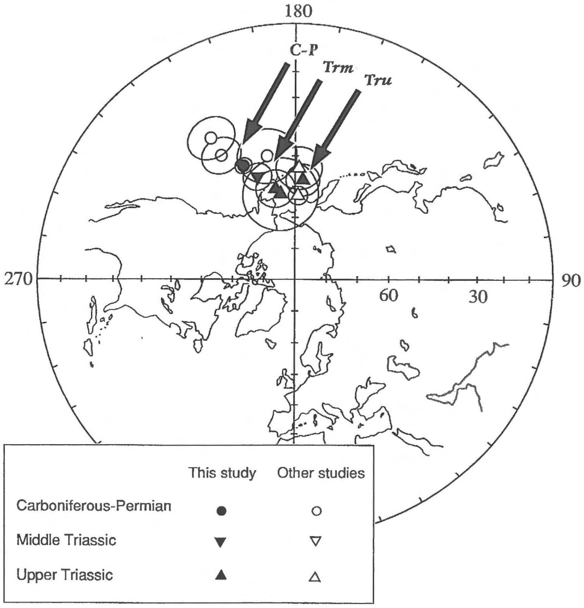

Figure 7. Polar projection showing the proposed Late Carboniferous to Late Triassic segment of the apparent polar wander path of Iberia. Solid symbols indicate the new data presented in this paper and listed in Tables 1 (full statistics) and 2 (summary). Open symbols indicate the data taken from other authors and listed in Table 2.

The palaeomagnetic data taken from other authors and used in this paper to construct the Late Carboniferous to Late Triassic segment of the APWP of Iberia are listed in Table 2. In this table, we have cautiously discarded the Permian and Triassic poles from the Cantabrian Cordillera because its stability has not been adequately demonstrated yet. We have also excluded the Triassic data from the Catalan Coastal Ranges because they have been interpreted as the result of about 20° of clockwise rotation (Parés 1988; Parés et al. 1988). In turn we have included the Late Triassic pole from the southern Meseta (Parés & Dinarès 1994). The palaeomagnetic poles presented in this study also confirm the Late Triassic pole of Van der Voo (1967).

Figure 7 shows the palaeomagnetic poles considered in this study to define the Late Carboniferous to Late Triassic section of the APWP of Iberia. These data show a gradual and consistent change in latitude and longitude and thus present a coherent segment of the APWP of Iberia for this period.

Table 2. Summary of palaeomagnetic poles considered for the Late Carboniferous to Late Triassic segment of the APWP of Iberia shown in Figure 7.

Location	Age	Lat P	Long P	α_{95} (°)	Reference
This study					
Atienza (Iberian Ranges/C. System)	275–299 Ma	49.6	204.6	2.6	
Molina (Iberian Ranges)	Anisian-Ladinian	55.1	201.4	4.5	
Alcaraz (Southern Meseta)	Ladinian-Carnian	57.9	175.6	5.2	
Alcázar (Southern Meseta)	Ladinian-Carnian	62.1	189.8	11.8	
Ayllón (Iberian Ranges)	Carnian-Norian	60.1	192.3	6.1	
Other studies					
Viar Intrusions (Southern Meseta)	Stephano-Autunian	43	211	6	Van der Voo (1969)
Bucaco (Northern Portugal)	Stephano-Autunian	36	211	7	Van der Voo (1969)
Rillo de Gallo (Iberian Ranges)	Autunian	49	193	9	Turner et al. (1989)
Alcázar (Southern Meseta)	Late Triassic	63	178	3	Van der Voo (1969)
Southern Meseta	Late Triassic	54	178	7	Parés & Dinarès (1994)

Conclusions

- The Late Triassic palaeomagnetic poles obtained in this study confirm Van der Voo's (1967) pole for Alcazar the San Juan. Schott (1988) considered this pole as an anomalous direction.
- Comparison of the palaeomagnetic results from the western Iberian Ranges with data of similar age from the Meseta indicates that the areas sampled in the Iberian Ranges form part of Stable Iberia.
- The palaeomagnetic data obtained in this study, combined with a revision of previous palaeomagnetic results, allow to define the Late Carboniferous to Late Triassic segment of the Apparent Polar Wander Path for Iberia.

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