Palaeomagnetism: Applications to Palaeogeography and Plate Tectonics

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Introduction

The ability of certain rocks to become magnetised parallel to the earth's magnetic field has been recognised since the mid 19th century. It was not until the latter half of last century, however, that palaeomagnetism came into its own and was accepted by the scientific community as a whole. Indeed, early palaeogeographic applications of fundamental palaeomagnetic properties played a pivotal role in the development and acceptance of plate tectonic theory. Over the last 40 years, our understanding of all aspects of palaeo- and rock magnetism have improved dramatically, and palaeomagnetism is now one of the most important techniques available within the Earth Sciences to determine the changing geographical distribution of the continents over geological time (palaeogeography). For post Jurassic times, the presence of marine magnetic anomalies provide determination of relative plate motions, and, at least for the Cenozoic, accurate palaeogeographic reconstruction's can be made using these anomalies. For pre Late Jurassic times, however, reconstructing the relative positions of the continents is more complicated. The ability of rocks to record the ambient magnetic field during their deposition and formation, however, and the ability of many rocks to retain this record over geological time provides the basis for palaeomagnetic research and enables the palaeomagnetist to track the movement of the different continents with respect to the magnetic and geographic poles through time. After a brief description of some of the fundamental aspects of palaeomagnetism, an example of recent advances made in the field of Palaeozoic geography using palaeomagnetic techniques will be given.

Palaeomagnetism and palaeogeography

The fundamental hypothesis underlying palaeomagnetism is that the time averaged geomagnetic field is that of a geocentric axial dipole (GAD), i.e. the field resembles that produced by a giant bar-magnet in the Earth's core. For the present days magnetic field, however, only approximately 90% of the field can be accounted for by a geocentric dipole - the remaining 10% being non-dipolar in origin. Whilst the non-dipolar element is in itself important, it is subject to rapid (secular) variations, such that when the field is averaged over 100´s of years the variations average out to zero. Thus, on the geological time scale secular variations are insignificant. Similarly, the dipole field itself is also subject to temporal variations but of slightly longer periodicity. Magnetic records obtained for the last 2000yrs show that the dipole field meanders randomly around the north geographic pole. The average position of the geomagnetic pole is indistinguishable from the earth's rotation axis, this indicating that the GAD model describes the time averaged geomagnetic field. The GAD hypothesis is firmly established, and from various lines of evidence has been sufficiently demonstrated to hold for at least the last 600 My. For palaeomagnetic studies, it is necessary simply to collect samples covering several thousands of years in order to average out any effects of dipolar and non-dipolar variations. One of the most important properties of the GAD for palaeogeography is that the inclination value of the magnetic field is a direct function of the latitude. That means, that if rocks acquire a remanent magnetisation during formation, and this is retained over geological time, we can obtain direct information about the palaeolatitude at which the rocks were formed from the inclination value recorded within the rocks. Given high quality palaeomagnetic data, the orientation and palaeolatitude of a continent can be established to within 10° at the 95% level of confidence. Such precision is not possible using other commonly used palaeogeographic techniques, such as biogeography (latitudinal and/or provincial controls on the distribution of certain faunas) and lithostratigraphy (distribution of latitude-dependant sedimentary facies) which may also be influenced by a number of `external` factors such as global climate variations and eustatic oscillations which can influence faunal distributions and interchange. Also, the dispersal of larvae in the marine realm is directly related to the duration of larval development and the ocean-current velocity and palaeo-circulation patterns, all of which are extremely hard to quantify for geological time periods. These other methods, therefore, can only provide qualitative information about ancient continental margins and palaeolatitudes.

Palaeomagnetism, however, does have certain limitations. One major problem is that it depends upon the preservation of the ancient magnetic field within the rocks, i.e. that the ambient field during deposition/lithification of the sequences has been `locked-in´ and preserved over geological time. This factor is a major problem in palaeomagnetic studies, particularly those conducted in orogenic systems such as the Variscan fold belt (both in Europe and North America) where widespread remagnetisation (i.e. destruction and overprinting of the original magnetisation) is common (Elmore and McCabe, 1991). Secondly, palaeomagnetic data can only provide information on the larger scale latitudinal and rotational motion of the plates. For example, the resolution of palaeomagnetic data is such that separations to the order of up to ±500km cannot be recognised. Thus, the actual timing of the collision and amalgamation of continents cannot be accurately determined, and (relatively) small scale rifting and intraplate deformation (where no rotations are involved) remain unobserved by the palaeomagnetist. Another important point to remember is that palaeomagnetism in general provides no information regarding the palaeo-longitude at which the rocks formed. Such information can often be inferred from faunal and geological evidence. Thus, properly viewed, palaeomagnetism can be an extremely powerful tool for palaeogeographic research which should be used in conjunction with other palaeogeographic techniques and geological indicators.

Palaeozoic Geography of the Variscan Fold Belt of Europe

The major continental plates controlling Palaeozoic palaeogeography and development of the Caledonian and Variscan orogenic belts (Fig. 1) are Baltica (Scandinavia and the East European Platform), Laurentia (North America, Greenland and Scotland) and Gondwana (South America, Africa, Madagascar, Antarctica, Australia and India). With the exception of Gondwana, most palaeogeographic models are in general good agreement regarding the Palaeozoic drift history of these landmasses. The palaeogeography of Gondwana remains equivocal and a number of different models have been proposed. Nevertheless, what is clear is that in Cambro-Ordovician times the south pole was situated in north Africa, but by Late Carboniferous times Gondwana had drifted northwards and the ocean separating it from the northern continents had closed, resulting in formation of the supercontinent Pangaea. Incorporated within this Gondwana/Laurentia/Baltica system are a number of pre-Variscan terranes, or microplates. Most of these have demonstrably Cadomian basement, indicating Late Precambrian/Cambrian affinity with the northern margin of Gondwana which was at high southerly palaeolatitudes in the Early Palaeozoic. These terranes are generally grouped into two microplates termed Avalonia and Armorica (Fig. 1).

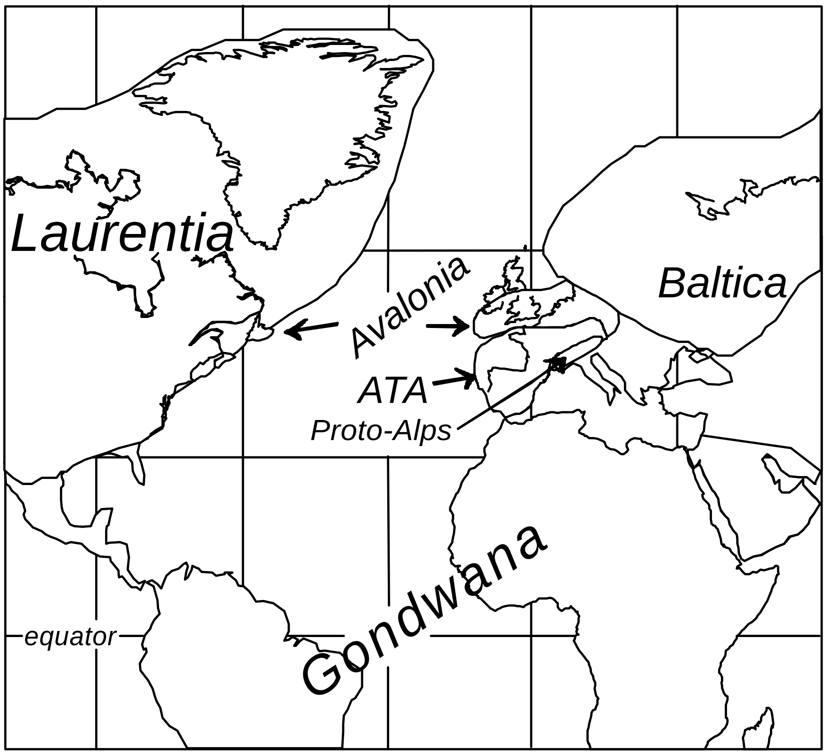

Figure 1: Sketch map of the present day boundaries of the Early Palaeozoic plates and microplates.

Whilst the hypothesis of the Avalonian microplate is now well accepted, the concept of the Armorican Microplate is more enigmatic. Armorica is generally considered to comprise the southern European massifs of Armorica, Iberia and Bohemia. However, the palaeogeographic affinities of these blocks in the Palaeozoic remains unclear, and whether they remained adjacent to Gondwana, or formed an independent microplate (or microplates) during closure of the Tornquist, Iapetus and Rheic Oceans remains unresolved from palaeomagnetic, geological and faunal evidence. Similarly, the Palaeozoic tectonic affinities of the pre-Variscan terranes now situated within the Alpine fold belt (the Proto-Alps) are also poorly constrained. No reliable palaeomagnetic data are as yet available, and faunal and geological evidence are sparse. Basement rocks in the Alpine realm show clear Gondwana affinities, but the subsequent drift history and the tectonic affinity of these blocks remains unclear due to strong Alpine overprinting and deformation.

In order to resolve some of these problems, the palaeomagnetic working group of Munich have carried out a number of studies in various Palaeozoic units of central and southern Europe (Fig. 2). The principal regions of study have are the Bohemian Massif, the Armorican Massif of northern France, the eastern Pyrenees and Catalan Coastal Ranges of north eastern Spain, and the Greywacke Zone and Carnic Alps of Austria. In all of these regions, samples were collected from well-dated sequences (usually biostratigraphically dated), and from rocks ranging from the Early Ordovician (~480Ma) to the Late Devonian (~360Ma). The results of these studies have important implications for Palaeozoic palaeogeography. They demonstrate that the so-called "Armorican microplate" comprises an assemblage of terranes or microblocks, with a major tectonic discontinuity between Bohemia and

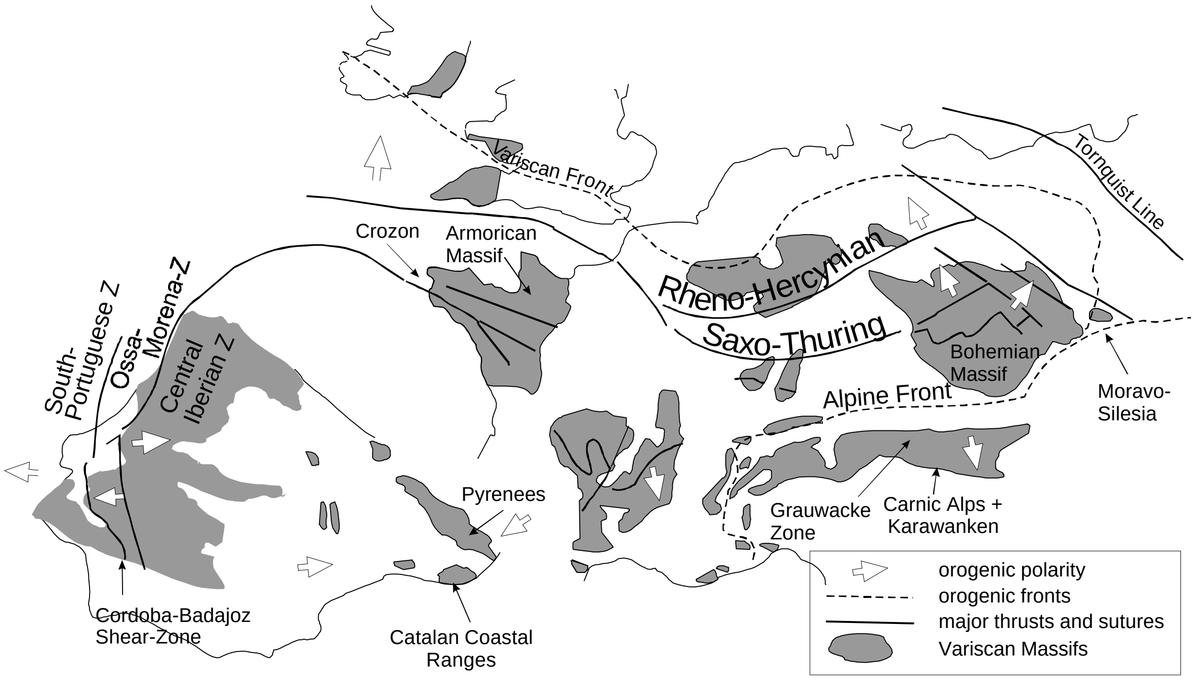

Figure 2: Main structural elements of the European Variscan fold belt.

the more westerly units. The term `Armorican Terrane Assemblage´ (ATA) is now used to refer to these Palaeozoic elements. The new palaeomagnetic data also indicate that these terranes rifted from the northern margin of Gondwana in (mid) Ordovician times, and subsequently all had similar northward drift histories. The Rheic Ocean separating, Avalonia from the ATA, closed in Early to mid Devonian times.   With regards the results obtained from the Eastern Alps (i.e. the Proto-Alpine units), the palaeomagnetic data show that they formed a separate microplate, independent of both the ATA and Gondwana, which drifted northwards away from the African margin sometime during the Ordovician. This is in good agreement with the available lithological and faunal evidence which place the timing of final suturing of the Proto-Alps with the southern margin of Laurasia in the Late Carboniferous (Stampfli, 1996). Collating all the available palaeomagnetic and geological data, it is now possible to create fairly accurate palaeogeographies for the continents and microplates bordering the Iapetus, Tornquist, and Rheic oceanic basins for key periods in the Lower Palaeozoic. These reconstructions are summarised below.

Early Ordovician

From palaeomagetnic, lithological and biogeographic evidence, the palaeogeographic scenario for Early Ordovician times is now well-constrained (Fig. 3). The south pole was situated in northern Africa, Laurentia was straddling the equator where it remained for most of the Palaeozoic, and Baltica was at intermediated palaeolatitudes and rotated with respect to its present day orientation (Torsvik et al., 1992). It is also well accepted that Avalonia, the various elements of the ATA and the Proto-Alpine terranes were all adjacent to the northern margin of Gondwana and thus situated at high southerly palaeolatitudes. This is based on faunal and palaeomagnetic evidence and the fact that all the terranes have either Cadomian basement, or Gondwana derived detrital material. By the Llanvirn

Figure 3: Early Ordovician (Llanvirn) palaeogeography using palaeomagnetic data of Tait et al., 1994a (Bohemian Massif); McCabe and Channell, 1990 (Avalonia); Van der Voo, 1993 (Gondwana); MacNiocall and Smethurst; 1994 (Laurentia); Torsvik et al., 1992 (Baltica); Smethurst et al., 1998 (Siberia).

Avalonia had rifted from the Gondwana margin as indicated by palaeomagnetic data, the development of an endemic faunal assemblage (Torsvik et al. 1993, Cocks et al., 1997). The onset of Avalonias northward translation and the change from a passive to active margin is marked y the occurrence of calc-alkaline volcanics and subduction related magmatism in northern England which continued until the Late Ordovician (Pharaoh et al., 1993). Thus the Rheic Ocean opened up between Avalonia and the ATA. The ATA and Proto-Alpine terranes remained adjacent to Gondwana (Dallmeyer & Neubauer 1994, Handler et al. 1997) probably until Mid-Ordovician times, when they too started to move northwards in combination with beginning volcanic activity (Tait et al. 1995, Schönlaub 1992).

Late Ordovician

By Late Ordovician time, the position of Laurentia had not changed significantly, and Gondwana had moved only slightly towards the north. Baltica also drifted northwards and rotated anticlockwise during the Ordovician. By the Late Ordovician its (present day) northern margin was close to the equator and the Iapetus Ocean between Baltic and Laurentia was narrowing (Fig. 4). Avalonia also continued its northward movement, and collided with Baltica in the Late Ordovician thus closing the Tornquist Sea. This is evidenced both in the palaeomagnetic and geological records (Torsvik et al. 1993, Berdan 1990). The Bohemian Massif

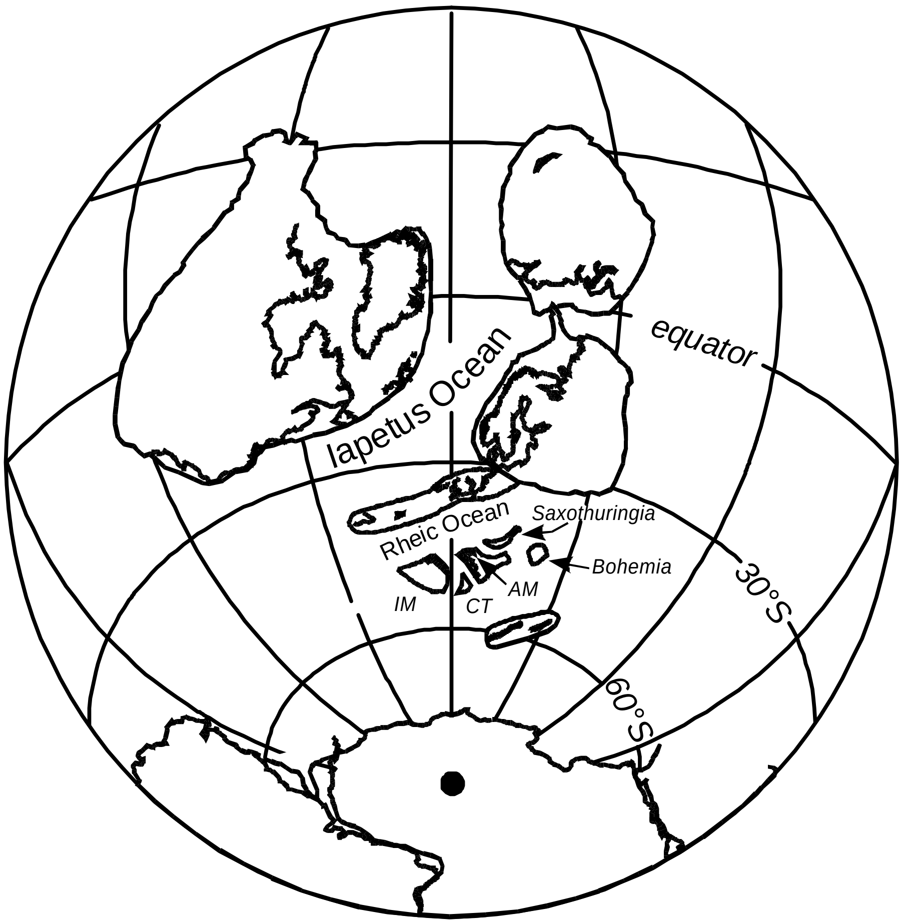

Figure 4: Late Ordovician palaeogeography, based primarily on palaeomagnetic data from Tait et al., 1995 (Bohemian Massif); Torsvik et al., 1993 (Avalonia); (Laurentia); Torsvik et al., 1992 (Baltica); Smethurst et al., 1998 (Siberia); Schönlaub 1992 (Proto-Alps). CT=Catalan Terrane, IM=Iberian Massif, AM=Armorican Massif.

Bachtadse and Briden, 1990, Gondwana; MacNiocall and Smethurst, 1994 separated from northern Gondwana in the Mid Ordovician and drifted northwards, gradually closing the Rheic Ocean. Although the position of the other elements of the ATA are not well constrained by palaeomagnetic data, faunal and lithological evidence would tend to argue against any major separation of the various terranes and they are thus placed at similar latitudes to the Bohemian Massif in the Late Ordovician (Fig. 4). The palaeomagnetic data, however, indicate a major tectonic discontinuity in form of major rotations between Bohemian Massif (Tait et al. 1995) and Saxothuringia (Kössler et al., 1996), thus demonstrating that they did not form part of a coherent microplate. No palaeomagnetic data are as yet available from the Proto-Alpine terranes, lithological, palaeoclimatic and faunal indicators, however, suggest separation of this block from the northern margin of Gondwana, and palaolatitudes of 50°-60°S as shown in figure 4.

Late Silurian

The Late Silurian is now one of the best constrained time periods with regards the palaeogeography of the European blocks. Palaeomagnetic data show that by Siluro-Devonian boundary times the Bohemian Massif and Saxothuringia were at palaeolatitudes of some 30°S (Fig. 5) i.e. approaching the southern margin of Avalonia which had already collided with Baltica (Kössler et al. 1996, Tait et al. 1994, Torsvik et al., 1993). The Armorican Massif was also at similar palaeolatitudes in the Early Devonian (Tait 1999). No reliable palaeomagnetic data are as yet available for the Iberian Massif, but new results from the Catalan Terrane (Catalan Coastal Ranges and Eastern Pyrenees, NE-Spain) show that this block was also at 30°S in the latest Silurian(Tait et al., 2000). This suggests, therefore, that the various pre-Variscan blocks of the Variscan fold belt had similar drift histories throughout the Palaeozoic. Palaeomagnetic data from the Proto-Alpine terranes (Schätz et al.

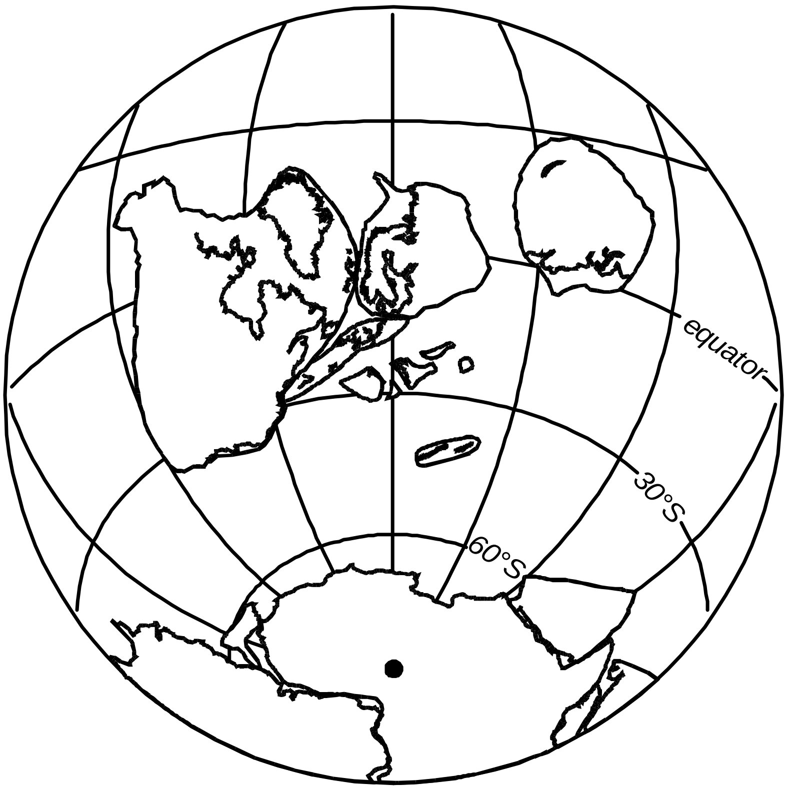

Figure 5: Late Silurian palaeogeograpic reconstruction based primarily on palaeomagnetic data from Tait et al., 1994 (Bohemian Massif); Tait et al., 2000 (Catalan Terrane; Torsvik et al., 1993 (Avalonia); Van der Voo, 1993 (Gondwana); MacNiocall and Smethurst, 1994 (Laurentia); Douglass, 1988 (Baltica); Smethurst et al., 1998 (Siberia); Schätz et al., 2000 (Proto-Alps).

2000) indicate that, whilst they also had drifted away from the Gondwana margin and moved northwards, they remained distinct from the ATA and formed an independent microplate (Fig. 5). The palaolatitude obtained from the palaeomagnetic data is supported by faunal data, which indicate a change to warmer water conditions (Schönlaub 1992).

This time remains rather controversial with regards to the palaeoposition of Gondwana due to the lack of high quality, unambiguous palaeomagnetic data. From palaeomagnetism essentially two different models have been proposed for this time period. Details of the argumentation behind the different models are out of the scope of this contribution. Suffice to say that we have opted for the simpler of the two paths which involves gradual northward drift of Gondwana throughout the Palaoeozoic and places the northern margin of Gondwana at some 65°S in the Late Silurian. Palaeobiogeographic models, however, tend to place northern Gondwana at slightly lower latitudes. This problem regarding Gondwana cannot be resolved until more reliable palaeomagnetic data become available.

Figure 6: Mid Devonian palaeogeographic reconstruction based on palaeomagnetic given in Tait et al., 1997 (ATA); Torsvik et al., 1993 (Avalonia); Torsvik et al., 1992 (Baltica), MacNiocall and Smethurst 1994 (Laurentia); Bachtadse and Briden 1991 (Gondwana); Schätz et al., 2000, (Proto-Alps).

Mid Devonian

By the Mid Devonian, the Iapetus Ocean had finally closed and subduction related magmatism ceased. Progressive collision of the ATA with the southern margin of the Avalonia/Baltica/Laurentia amalgam (Laurussia) continued during the Mid-Devonian. Available palaeomagnetic data (Tait 1999; Bachtadse et al. 1983; Zwing and Bachtadse 2000), show that, within the resolution of palaeomagnetic data, the various elements of the ATA were adjacent to the southern margin of Laurussia. Final closure of the Rheic Ocean occurred in Mid Devonian times as indicated by both vertebrate and invertebrate faunas of the various blocks which remained distinct until the Givetian. Palaeomagnetic data demonstrate that final consolidation of the ATA with Laurussia, however, did not occur until the Late Devonian (Tait et al. 1997). For the Proto-Alpine terranes, recent palaeomagnetic data now demonstrate that this

Figure 7: Palaeogeographic reconstruction for the Late Carboniferous using palaeomagnetic data listed in Van der Voo (1993).

microplate was still located significantly further south than the ATA and was distinct from Gondwana (Schätz et al. 2000). This is supported by faunal and floral evidence, in particular from the Carnic Alps, which show strong affinities to Variscan and Bohemian provinces. The position of Gondwana in the Mid Devonian is again not generally agreed upon. Palaeobiogeographic models question the presence of an ocean between northern Africa and southern Laurussia. However, from the geological record, there is no evidence for any pre-Carboniferous orogenic events in the Eastern Alps, rather there was continuous sedimentation from Ordovician to Late Carboniferous times in a passive margin-type environment (Frey et al., 1999, Neubauer et al., 1999, Stampfli, 1996, Schönlaub, 1992). This argues strongly against any Devonian collision of Gondwana with Laurussia (see Tait et al., 2000 for discussion)

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Carboniferous

The Carboniferous period witnessed the final approach of Gondwana and collision with Laurussia and formation of Pangaea. This resulted in significant internal (intra-continental) deformation of the Variscan foldbelt. This is evidenced by oroclinal bending around the Bay of Biscay (Pares et al. 1994, and references therein), and in eastern parts of the Variscan fold belt with bending of the Moravo Silesian zone around the Bohemian Massif (Tait et al., 1996). Although the mechanisms for these processes are still unknown, it may be speculated that they were caused by indentation of an irregularly shaped northern margin of Gondwana into Palaeozoic Europe (Tait et al. 1997 and references therein).

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