Palaeomagnetism and Palaeozoic palaeogeography of Gondwana and European terranes

JENNY TAIT, MICHAEL SCHÄTZ, VALERIAN BACHTADSE & HEINRICH SOFFEL

Institut für Allgemeine und Angewandte Geophysik, Ludwig-Maximilian-Universität, Theresienstraße 41, D-80333 München, Germany

Abstract: Neoproterozoic to Late Palaeozoic times saw the break-up of the supercontinent Rodinia, and the subsequent construction of Pangaea. The intervening time period involved major redistribution of continents and continental fragments, and various palaeogeographical models have been proposed for this period. The principal differences between these models are with regard to the drift history of Gondwana, the timing of collision between northern Africa and Laurussia, and formation of Pangaea. Palaeomagnetic evidence provides basically two contrasting models for the Ordovician to Late Devonian apparent polar wander (APW) path for Gondwana involving either rapid north and southward movement of this continent, or gradual northward drift throughout Palaeozoic time. In contrast, palaeobiogeographical models suggest contact between Laurussia and Gondwana as early as mid-Devonian time with the continents basically remaining in this configuration until break-up of Pangaea in the Mesozoic era. This is in conflict, however, with most palaeomagnetic data, which demonstrate that in Late Devonian time, north Africa and the European margin of Laurussia were separated by an ocean of at least 3000 km width. This is also in agreement with the geological record of present-day southern Europe, which argues against any collision of northern Africa with Europe in Devonian time. With regard to formation of Laurussia, however, palaeobiogeographical and palaeomagnetic data are in excellent agreement that by mid-Devonian time the oceanic basins separating Baltica, Laurentia, Gondwana-derived Avalonia and the Armorican Terrane Assemblage (ATA) had all closed. Palaeomagnetic and geological data are also in agreement that the Palaeozoic basement rocks of the European Alpine realm formed an independent microplate, which was situated to the south of Laurussia. In Late Silurian times it was separated by an ocean of *c.* 1000 km, and by Late Devonian time was approaching the southern Laurussian margin. According to palaeomagnetic data, the northern margin of Gondwana was still further to the south in Late Devonian time, and according to the geological record in southern Europe, the main continent–continent collision of northern Africa with European Laurussia and closure of the intervening ocean occurred in Late Carboniferous times. Location of this suture is situated to the south of the Palaeozoic alpine units (e.g. the Greywacke zone, Carnic Alps, Sardinia and Sicily), but has been obscured by younger deformational events and cannot be precisely positioned. Assessing available evidence and as discussed in the text, it is proposed that the most likely scenario is that the northern margin of Gondwana drifted gradually northwards from Ordovician to Late Carboniferous times when it collided with Laurussia, resulting in formation of Pangaea.

All reconstructions and models for the drift history of the Palaeozoic plates presented in this paper are based primarily on palaeomagnetic evidence. The advantage of palaeomagnetism over other palaeogeographical methods is that it depends only upon the hypothesis that the time-averaged Earth's magnetic field can be described as a geocentric axial dipole field (i.e. magnetic North corresponds to geographical North). Although recently questioned by some workers (Kent & Smethurst 1998), this hypothesis has been demonstrated to hold for at least the last 800 Ma and one of its most significant features is the direct relationship between magnetic inclination and geographical latitude. Palaeomagnetic data, therefore, can provide quantitative information for the (palaeo-) latitude at which rocks were formed and is independent of any external factors. This is in contrast to the other most commonly used techniques, such as palaeobiogeography, which may be strongly influenced by external factors such as global

From: FRANKE, W., HAAK, V., ONCKEN, O. & TANNER, D. (eds).
Orogenic Processes: Quantification and Modelling in the Variscan Belt.
Geological Society, London, Special Publications, **179**, 21–34. 0305-8719/00/$15.00

climate variations and eustatic oscillations, which can influence faunal distributions and interchange. Also, dispersal of larvae 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 questions regarding faunal distribution patterns have been a matter of debate and discussion for many years. Details of the various aspects are beyond the scope of this paper and the reader is referred to Cloud (1961), Ross (1975), Klapper & Johnson (1980), Schallreuter & Siveter (1985), Fortey & Cocks (1988), Jokiel (1990), Oclzon (1990), Schönlaub (1992), Benedetto (1998) and McKerrow *et al.* (this volume), for further discussion.

The break-up of Rodinia

The main elements controlling and driving Palaeozoic palaeogeography are Laurentia, Baltica, Gondwana and Siberia, which formed as a result of the break-up of the Proterozoic supercontinent Rodinia. This was a fairly long-lived process (Dalziel 1992), and the final break-up of Rodinia is constrained as occurring between 590 and 550 Ma from continental margin subsidence and sedimentation rates (Bond *et al.* 1984; Van Staal *et al.* 1998). Laurentia and Baltica separated from Amazonia and Africa and drifted towards the equator, thus opening the Iapetus Ocean. By Early to mid-Cambrian time, Baltica had a diverse trilobite fauna indicating lower palaeolatitudes and warmer-water environment. Formation of Gondwana into its Palaeozoic configuration occurred during break-up of Rodinia, and consolidation of this large continental mass was completed by latest Cambrian time (see discussion by Van Staal *et al.* (1998). During this time the northern margin of Gondwana was an active margin, resulting in the Cadomian deformation event. Cadomian basement rocks have been identified in the European Palaeozoic blocks of Iberia, Bohemia, the Armorican massif and also within basement rocks of the Alpine realm, thus demonstrating that they were all situated on the northern margin of Gondwana, adjacent to north Africa in Late Cambrian times. Other European and North American Gondwana-derived terranes and microplates, such as Avalonia, the Gander terrane and Florida, were probably adjacent to northern South America (see also Van Staal *et al.* (1998) and references therein for further discussion of Rodinia and its break-up).

Formation of Pangaea

Most palaeogeographical models are in good agreement with regard to the Palaeozoic drift history of Laurentia, Baltica and Gondwana-derived Avalonia and Armorican Terrane Assemblage (ATA). Much discussion and debate surrounds the drift history of Gondwana itself, however. Many recent palaeobiogeographical models (see, e.g. McKerrow *et al.* this volume) tend to favour collision of northern Africa with the European plates in Early or mid-Devonian times, and from the palaeomagnetic data at least two widely contrasting models have been proposed. What is clear is that at least by Late Carboniferous times the ocean between northern Gondwana and the northern continents had closed. Timing of collision, however, is vital for a full understanding of the orogenic processes involved within Variscan Europe.

In the following sections various models for Gondwana will be discussed, together with arguments for and against these models and their implications for Palaeozoic palaeogeography within the overall tectonic framework for the development of the Caledonian and Variscan orogenies. A brief description of the drift histories for Baltica, Laurentia and Avalonia will also be given; for more details regarding these plates the reader is referred to Van der Voo (1993) and various more recent reviews as mentioned in the text. A more in-depth discussion of the Palaeozoic drift histories and palaeogeography of the ATA and Alpine domains leading up to formation of Pangaea is given.

Gondwana

Gondwana, which comprised South America, Africa, Madagascar, Antarctica, Australia and India, dominated Palaeozoic palaeogeography and accounted for more than two-thirds of the entire continental crust. The drift history of this continent in Palaeozoic times, however, remains the least well constrained of all the Palaeozoic plates, and is a matter of much debate within the geoscience community. From the existing palaeomagnetic database alone essentially two contrasting models for the Palaeozoic apparent polar wander (APW) path of Gondwana have been proposed (Fig. 1). They indicate either gradual northward movement of Gondwana from Late Ordovician to Early Carboniferous times, or, alternatively, a much more complex path implying collision of northern Africa with Laurussia in the Late Silurian–Early Devonian time and then again in Carboniferous times.

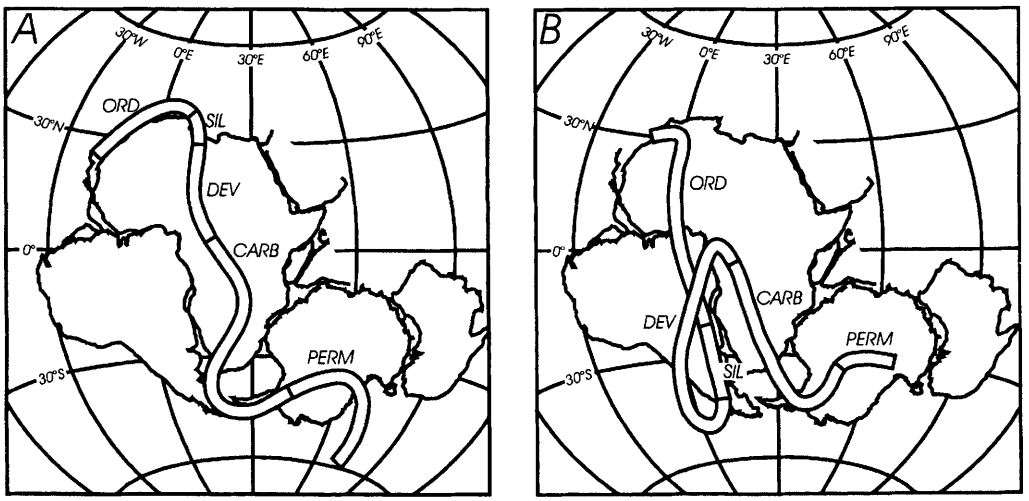

Fig. 1. Alternative APW curves for the Palaeozoic of Gondwana, (**a**) path X after Bachtadse & Briden (1991); (**b**) path Y modified after Schmidt *et al.* (1990), taking into account more recently published radiometric age for the AIR pole as mentioned in the text and listed in Table 1.

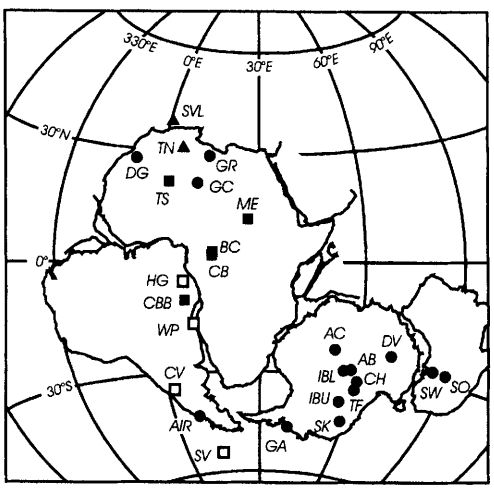

Fig. 2. Selected paleopole positions ($Q > 3/7$) for Ordovician to Permian time from Australia (■), Antarctica (▲) and Africa (●) as listed in Table 1. Pole positions from the Lachlan fold belt (Australia) are shown as open squares. Gondwana is reconstructed using the rotation parameters of Lawver & Scotese (1987). Africa is in present-day co-ordinates.

Obviously, these different models have important implications for the geodynamic evolution of the Caledonian and Variscan orogenic systems in Europe and North America as well as our understanding and interpretation of the geological record in Gondwana itself.

Both models agree that in Early Ordovician times the south pole was situated in northwest Africa, for the Late Devonian both paths are anchored by the small cluster of high-quality palaeopoles in central Africa (poles BC, CB and CBB in Fig. 2 and Table 1), and by Late Carboniferous to Permian times the south pole was clearly located in Antarctica. The differences between the APW paths are how these three groups are connected. The simpler model involves gradual and continuous northward movement of Gondwana, and simply connects these three tie points (Fig. 1a). Such a path was first suggested by McElhinny (1968), subsequently termed path X by Morel & Irving (1978), and more recently was redefined by Bachtadse & Briden (1991) on the basis of new, although poorly constrained, palaeomagnetic data from South Africa (pole GC, Fig. 2). The alternative model, originally termed path Y by Morel & Irving (1978), and subsequently modified by Schmidt *et al.* (1990), is more complex with at least one distinct loop in Silurian times (Fig. 1b), and requires rather high drift rates for Gondwana in the Palaeozoic era. The Silurian and Devonian segments of the original Schmidt *et al.* (1990) APW path were based on palaeomagnetic results from the Aïr complex of Niger (Hargreaves *et al.* 1987), northern Africa, which yield a palaeopole position in south Chile (pole AIR, Fig. 2). At that time, these rocks were thought to have an Early Silurian (*c.* 435 Ma) emplacement age. More recent radiometric ages, however, yield an Early Devonian age (409 Ma, Moreau *et al.* 1994). The Siluro-Devonian sector of the APW path of Schmidt *et al.* therefore, needs to be modified accordingly, as shown in Fig. 1. The Devonian sector of this APW path is

Table 1. *Ordoricean to Permian palaeopoles with quality factors >3/7*

Formation		Symbol	Age	Lat. (°N)	Long. (°E)	α_{95} k	(dp, dm)
Reference							
Africa							
Damara granites*	DG	458 ± 8^2	27	351	–	5	(Corner & Nethorn 1978)
Graafwater Formation	GR	Ol^5	28	14	25	9	(Bachtadse *et al.* 1987)
Aïr intrusive rocks	AIR	409^4	−43	9	50	6	(Hargreaves *et al.* 1987)
Gilif Hills C	GC	377 ± 5^2	26	12		(20, 21)	(Bachtadse & Briden 1991)
Mount Eclipse	ME	Cl^5	12	27		(8.7, 8.7)	(Chen *et al.* 1994)
Ain Ech Chebbi, Algeria*	AC	Cu^5	−25	55		(35, 3.5)	(Daly & Irving 1983)
Illizi Basin (lower formation)	IBL	Cu^5	−29	56	161	3.5	(Henry *et al.* 1992)
Dwyka varves	DV	P-C^5	−25	67	–	12	(Opdyke 1999)
Tiguentourine formation	TF	P-C^5	−34	61	170	4.1	(Derder *et al.* 1994)
Illizi Basin (upper formation)	IBU	P-C^5	−38	57	837	2.8	(Henry *et al.* 1992
Galula red beds, Tanzania	GA	P-C^5	−46	40		(8.4, 8.4)	(Opdyke 1964)
Abadla Red Beds, Algeria	AB	Pl^5	−29	58	–	(2, 2)	(Merabet *et al.* 1998)
Songwe–Ketawaka red beds	SO	Pl^5	−28	90	59.8	12	(Opdyke 1964)
Chougrane red beds	CH	Pl^5	−32	64	20	5	(Daly & Pozzi 1976)
Songwee–Kiwira red beds	SW	Pl-u^5	−27	85	84.2	5.3	(Nyblade *et al.* 1993)
Madagascar							
Sakoa Group glacial deposits	SK	Cu^5	−43	60	50	8	(McElhinny *et al.* 1976)
East Antarctica							
Southern Victoria Land	SVL	475 ± 10^2	37	360		(5.9, 5.9)	(Grunow 1995)
Teall Nunatak	TN	475 ± 4^2	31	5	163	7.2	(Lanza & Tonarini 1998)
Australia							
Tumblagooda Sandstone*	TS	Ou^5	24	7	556	3	(Schmidt & Embleton 1990)
Canning Basin*	CB	Du^5	2	16	62	8	(Hurley & Van der Voo 1987)
Canning Basin	CBB	Du^5	−12	9		(14.6, 14.6)	(Chen *et al.* 1995)
Brewer Conglomerate	BC	Du^5	3	17		(6.4, 6.4)	(Chen *et al.* 1993)
Hervey Group[1]	HG	Du^5	−5	8	–	(8.4, 16.2)	(Li *et al.* 1988)
Snowy River volcanic rocks[1]	SV	Dl^5	−54	15	–	(10.9, 14.5)	(Schmidt *et al.* 1987)
Comerong volcanic rocks[1]	CV	Dm^5	−34	2	–	(7.2, 7.2)	(Schmidt *et al.* 1986)
Worange Point[1]	WP	Du^5	−17	12		(10.9, 10.9)	(Thrupp *et al.* 1991)

Selected palaeopoles (quality factor > 3/7 including good age control, acceptable statistics and adequate demagnetization; see van der Voo (1990) for Ordovician to mid-Permian time for Africa, Madagascar, Australia and Antarctica in African co-ordinates (rotation parameters after Lawver & Scotese (1987)). α_{95}, semi-cone of 95% confidence for the palaeopole; dp, dm, semi-axes of oval of 95% confidence of the palaeopole. Lat., Long., latitude and longitude of the palaeomagnetic palaeopole. k, precision parameter after Fisher (1953). O, Ordovician; S, Silurian; D, Devonian; P-C, Permo-Carboniferous. l, lower; m, middle; u, upper, * Palaeopoles used in the palaeogeographical reconstructions in Fig. 3.

[1]Palaeopoles derived from the Lachlan fold belt (LFB) (allochthonous?).[2] Rb/Sr age.[3] K/Ar age.[4] $^{40}Ar/^{39}Ar$ age. [5]Stratigraphic age.

then based on Latest Silurian to Late Devonian results from the Lachlan fold belt of southeast Australia. These data describe a swathe of pole positions (SV, CV, WP and HG in Fig. 2) from southern Chile in Siluro-Devonian time to the Late Devonian cluster of palaeopoles in central Africa (Schmidt *et al.* 1986, 1987; I *et al.* 1991; Thrupp *et al.* 1991).

In recent years, the more complex APW path for Gondwana has gained significantly in popularity and is generally accepted as the more reliable model. However, many controversies surround the acceptance of this APW path. The main problems are the lack of field tests to unambiguously constrain the age of magnetization of the Aïr complex, and that the model relies heavily on palaeomagnetic data from the Lachlan fold belt (LFB) of southeast Australia. Whether or not Siluro-Devonian data from this region can be used to constrain Gondwana remains highly controversial. The LFB of eastern Australia can be subdivided into a number of different tectono-stratigraphic terranes or zones (Collins & Vernon 1922; Scheibner & Basden 1996; Gray *et al.* 1997). In some models, these different blocks are considered to be

(para)autochthonous to cratonic Australia, with only minimal differential movement of the blocks during Palaeozoic time (Powell 1983, 1984; Coney 1992). According to this hypothesis, any subduction zone must have been outboard of the present-day eastern margin of Australia. Alternatively, the presence of ophiolites along the major fault zones, different Ordovician faunal characteristics, and different Silurian to Early Devonian tectono-metamorphic histories of juxtaposed blocks have led to the interpretation that these faults represent Palaeozoic subduction zones or major tectonic discontinuities, with potentially large-scale differential movement of the individual blocks between at least late Ordovician and Late Devonian–Early Carboniferous time (Collins & Vernon 1992; Glen 1993; Gray *et al.* 1997; Glen *et al.* 1998; B. Webby, pers. comm.)

While reasonable doubt remains as to the tectonic evolution of SE Australia, it is the current authors' opinion that palaeomagnetic data from this region should not be used to defined the APW path of Gondwana. The only palaeopole then supporting the complex APW path is the Aïr pole. The main arguments against using this palaeopole to constrain the Devonian segment of the APW path are: (a) the age of magnetization in these rocks is not well constrained; (b) it would require high drift rates of Gondwana with repeated changes in direction of motion; (c) it implies either Early Devonian collision of Gondwana with the northern continents (for which there is no geological evidence in the alpine domains as discussed below), or it would invoke a complex tectonic regime for the northern Gondwana–southern European realm to avoid collision but allow for the equatorial position of northern Africa. Taking all factors into consideration, the complex APW is not considered reliable. Adopting the more conservative APW path, therefore, palaeomagnetic data indicate that in Early Devonian time, north Africa was still separated from the European sector of Laurussia by an ocean of *c.* 2500 km, but which was considerably narrower at its eastern and western extremities. This APW path is similar to that proposed by Scotese *et al.* (1999), which is based on palaeoclimatic indicators.

For mid-Devonian time, some palaeobiogeographical models support an Emsian–Eifelian connection between the African margin of Gondwana and Laurussia, with continued faunal interchange and proximity until final consolidation of Pangaea in Late Carboniferous time. This model is based on fossil fish similarities in Northern Australia and Laurentia (McKerrow *et al.* this volume), and the similarity of Emsian ostracode faunas in Algeria and Baltica (Berdan 1991). It is in apparent conflict, however, with late Devonian palaeomagnetic data for Gondwana. There are three palaeopoles for the Frasnian–Famennian and one for the Visean of Godwana (Hurley & Van der Voo 1987; Chen *et al.* 1993, 1994, 1995), which are grouped in central Africa (Fig. 2), thus indicating major separation of Gondwana from Laurussia (Fig. 3e). These palaeomagnetic data are all from cratonic Australia, and it is difficult to find grounds for their rejection; either our concept of the configuration of Gondwana itself could be argued, or local rotation of the areas studied could be inferred. Both of these solutions, however, are unlikely. Alternatively, the magnetization identified may represent a younger remagnetization event. Although possible, this would also seem unlikely given the quality of the palaeomagnetic data in question and the implications such an argument would involve (i.e. at some time after the Devonian period the south pole was situated in central Africa). Thus there remains a major discordance between palaeomagnetic and palaeobiogeographical data for this time period. What is clear, however, is that, in southern Europe there is little evidence for a Devonian continental collision between Gondwana and Laurasia as Devonian sequences in the European Alpine realm reflect a period of continuous sedimentation in a passive margin environment until Late Carboniferous times (Stampfli 1996). Devonian faunas of the southern Alps are also significantly different from those of Gondwana (Schönlaub 1992). Early Devonian deformation is seen, however, in the Appalachians and Britain (Acadian Orogeny). The causes of this event remain ambiguous, but are frequently attributed to collision with Gondwana, thus apparently supporting the complex APW path and, specifically, the Aïr palaeopole, which places the northern margin of Africa at the equator in Early Devonian time. Given this scenario, it is difficult to envisage why the effects of collision between Gondwana and Laurasia should be manifest within the Laurentian–Avalonian realm but not in southern Europe.

Formation of Pangaea is constrained by palaeomagnetic data as having occurred in Latest Palaeozoic time. Data from Algeria (AC and IBL, Fig. 2) demonstrate that by Late Carboniferous times the northern margin of Africa was approaching the southern margin of Europe and final collision probably occurred in latest Carboniferous to Early Permian times.

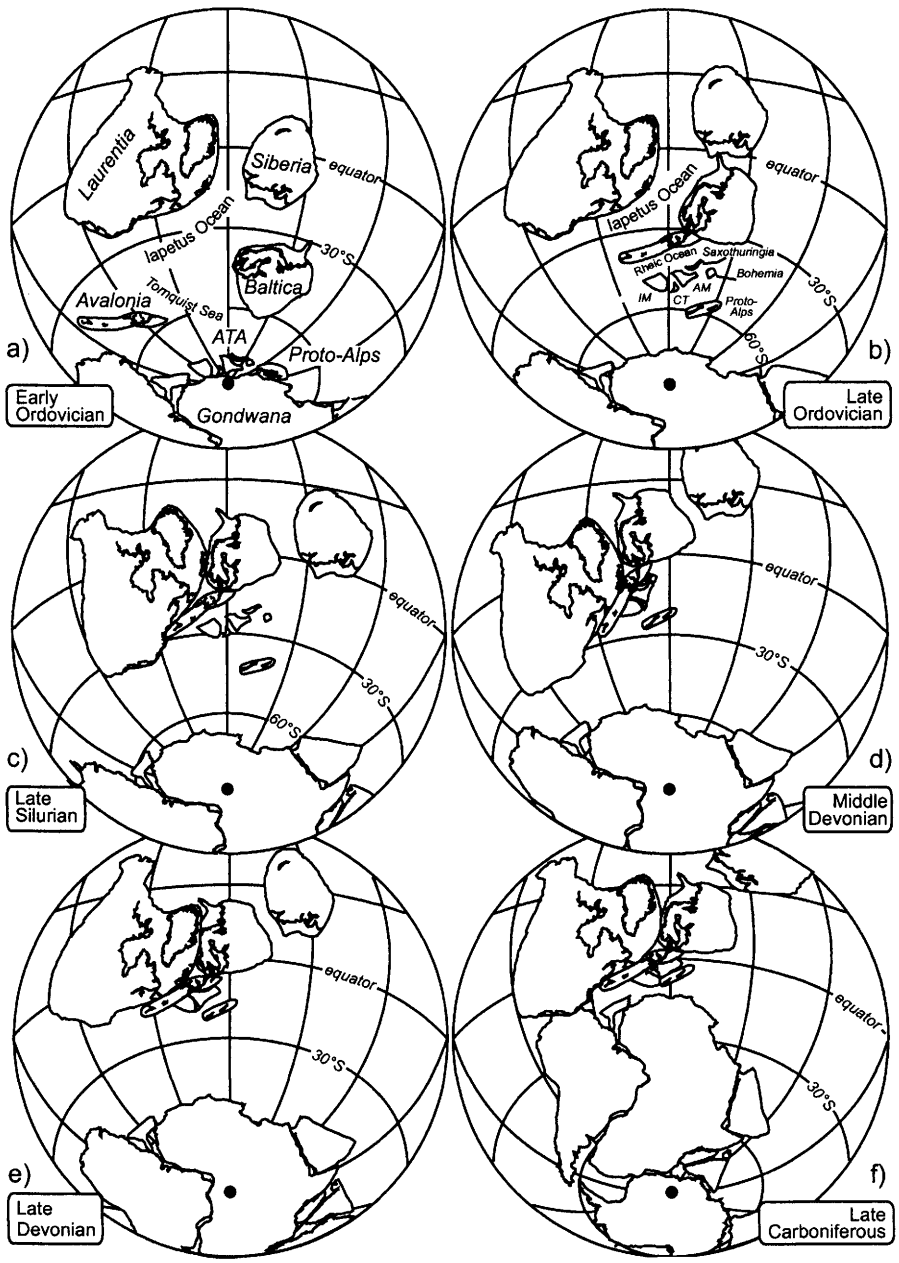

Fig. 3. Palaeogeographical reconstructions based on palaeomagnetic data. Proto-Alps and ATA based on data mentioned in the text (for Avalonia, see data compilation of Torsvik *et al.* 1993); for Baltica, see review by Torsvik *et al.* 1992; for Laurentia, see MacNiocaill & Smethurst (1994); for Siberia, see review by Smethurst *et al.* (1998). The palaeopoles used for Gondwana are indicated (*) in Table 1 (Late Silurian and Mid-Devonian palaeopole are interpolated from the Late Ordovician and Late Devonian palaeopoles). IM, Iberian Massif; AM, Armorican Massif; CT, Catalan terrane.

Laurentia

The APW path for Laurentia (comprising most of present-day North America, Greenland and Scotland), is now well constrained for the whole of the Palaeozoic era. Faunal, lithological and palaeomagnetic data are in good agreement that after the break-up of Rodinia, Laurentia drifted northwards towards the equator thus opening the Iapetus Ocean along its present-day eastern and southern margins. Throughout most of the Palaeozoic era, this continent remained in equatorial latitudes (Fig. 3) with the development of warm-water carbonates, and is characterized by the classic warm-water Edgewood faunas. For further discussion of the Palaeozoic palaeogeography of Laurentia, the reader is referred to MacNiocaill & Smethhurst (1994), for a review and compilation of previously published palaeomagnetic data, and to Witzke (1990) and McKerrow *et al.* (1991).

Baltica

The Palaeozoic APW path for Baltica is also fairly well constrained. In Early Ordovician times, Baltica was rotated with respect to its present-day orientation and was located at intermediate to high palaeolatitudes (Torsvik *et al.* 1990, 1992, 1996; Perroud *et al.* 1992). Ordovician faunas of Baltica are significantly different from those of Gondwana and Laurentia, and the lithological record also demonstrates a gradual northward movement of Baltica throughout Palaeozoic time. Palaeobiogeographical indicators show a change at the Ordovician–Silurian boundary from subtropical and temperate faunas, to equatorial warm-water faunas (Owen *et al.* 1991). After collision with Avalonia and closure of the Tornquist Sea in Late Ordovician–Early Silurian time, and final closure of the Iapetus Ocean between Baltica and Laurentia in Siluro-Devonian time, Baltica remained in equatorial palaeolatitudes until the end of the Palaeozoic era. For further details concerning palaeomagnetic data for Baltica, its palaeogeography and the Palaeozoic evolution of the Iapetus Ocean the reader is referred to McKerrow *et al.* (1991), Torsvik *et al.* (1996) and Van Staal *et al.* (1998).

Avalonia

In earliest Ordovician time Avalonia (i.e. New England, New Brunswick, Nova Scotia, the Avalon Peninsula, Southern Britain and continental Europe north of the Rheno-Hercynian zone and south of Scandinavia) was still contiguous with the northern margin of Gondwana (Trench *et al.* 1992; Torsvik *et al.* 1993). Its faunas were coincident with those from Bohemia and the Armorican Massif, but in marked contrast to those of Baltica and Laurentia (Cocks & Fortey 1982; Cocks *et al.* 1997). By Llanvirn (Fig. 3a) times it was drifting northwards away from Gondwana. The Rheic Ocean (*sensu* McKerrow *et al.* 1991) opened in its wake, and Early Ordovician subduction-related volcanism in Southern Britain indicates the change from a passive to an active margin environment (Kokelaar *et al.* 1984; Cooper *et al.* 1993). In Llandeilo times the shallow-water faunas of Avalonia were endemic (Lockley, 1983; Cocks 1993), and palaeomagnetic data demonstrate a palaeolatitude of 45° S (Trench & Torsvik 1991); thus Avalonia was separated from Laurentia by the southern Iapetus Ocean, and from Baltica by the narrowing Tornquist Sea. Timing of closure of the Tornquist Sea is not clear from palaeomagnetic evidence alone, but from geological evidence (Pharaoh *et al.* 1993; Cocks *et al.* 1997) it is thought to have closed by Late Ordovician–Early Silurian times (Fig. 3b).

Armorican Terrane Assemblage

The Gondwana-derived European Palaeozoic massifs and terranes located south of the Rheno-Hercynian zone, but north of the Alpine realm, are referred to as the Armorican Terrane Assemblage. These units (i.e. Bohemia, Saxo-Thuringia, Iberia and Armorican Massif) were previously considered to have comprised a coherent microplate (the Armorican microplate). It is now clear from palaeomagnetic and geological evidence, however, that the Variscan fold belt is a complex tectonic collage of terranes (Franke *et al.* 1995; Tait *et al.* 1997; Tait 1999).

The presence of Cadomian basement in all these terranes shows that they are all Gondwana derived, and in Early Ordovician times they were still adjacent to the northern margin of Gondwana (Fig. 3a). Palaeomagnetic data demonstrate that by Late Ordovician times the Teplá–Barrandian zone of the Bohemian Massif was located at 40° S (Fig. 3b), and thus independent of Gondwana. No unambiguous palaeomagnetic data are available from Armorica or Iberia (see Perroud *et al.* (1983), Perroud & Van der Voo (1985) and Tait *et al.* (1997) for discussion). Strong faunal and lithological similarities in Ordovician to Devonian successions of the Armorican Massif and Central Iberia indicate similar ecological conditions and demonstrate that they were both part of the same domain

(Robardet 1996). From Ordovician data alone, it remains equivocal as to whether they, and Saxo-Thuringia, remained adjacent to northern Gondwana in Late Ordovician time, or if they rifted away in mid-Ordovician times (Perroud & Van der Voo 1985) with the Teplá–Barrandian. Faunal and lithological similarities, however, would tend to support the latter hypothesis. Palaeobiogeographical models have generally assumed that all terranes remained at high palaeolatitudes, adjacent to the northern margin of Gondwana until at least Late Ordovician time. This is based primarily on the presence of Ashgillian glacial deposits throughout the ATA. However, the lower palaeolatitude demonstrated by palaeomagnetic data is not in conflict with the presence of glacial sediments, at least in the Bohemian Massif, as it has been shown that they were deposited from seasonal or floating ice during the Late Ordovician period of global cooling which also allowed the colonization of cold-water faunas in previously warmer-water realms (Brenchley *et al.* 1991; Owen *et al.* 1991).

Late Silurian to Early Devonian palaeomagnetic data from the Teplá–Barrandian, Saxo-Thuringia and the Armorican Massif (Tait *et al.* 1994; Kößler *et al.* 1996; Tait 1999) demonstrate that they were at palaeolatitudes of between 20° and 30° S (Fig. 3c), thus continuing to move northwards towards the southern margin of Baltica and Avalonia. This is in good agreement with geological evidence for gradual closure of the Rheic Ocean, which separated Avalonia and the ATA in Ordovician and Silurian times (Sommermann *et al.* 1992). Significantly, however, these results also demonstrate that the Teplá–Barrandian and Saxo-Thuringia did not belong to a coherent microplate. Whereas the magnetic inclinations obtained from these regions are in good agreement, the declination values differ significantly, demonstrating major tectonic discontinuity between the two terranes (see Tait *et al.* (1997) for further discussion).

Palaeomagnetic data are now available for the Siluro-Devonian of the eastern Pyrenees and Catalunia of northeastern Spain (the Catalan terrane). These data indicate palaeolatitudes of 30° S (Tait *et al.* 2000). The Catalan terrane, therefore, was at similar palaeolatitudes to the ATA in latest Silurian time (Fig. 3c). Whether or not this holds for the Iberian Massif is not clear, as correlation of basement rocks between these regions is extremely difficult because of strong reactivation during the Alpine Orogeny, and the Catalan terrane may have formed an independent tectonic unit in Palaeozoic time (Robardet & Gutierrez-Marco 1990).

In summary, the similarity of latest Silurian brachiopod and trilobite faunas of Iberia and Armorica, and ostracode faunas of Bohemia and the Armorican Massif (Kriz & Paris 1982), do not allow for any oceanic separation between these terranes. These faunal data, therefore, support the interpretation from palaeomagnetic studies that all these terranes of the ATA, including the Catalan terrane, had similar drift histories throughout Palaeozoic time, and in late Silurian times were located within the latitudinal band of 20–30° S and proximal to the southern Baltica–Avalonia margin (Fig. 3c). Before Emsian–Givetian times, however, vertebrate and invertebrate faunal assemblages were significantly different between Bohemia and southern Britain, thus final closure of the Rheic Ocean did not occur until the mid-Devonian (Fig. 3d).

Proto-Alps

The Palaeozoic palaeogeography and tectonic evolution of the Alpine realm is extremely complex as a result of the poly-metamorphic and poly-deformational events suffered by these rocks. Nevertheless, a number of different Palaeozoic tectonostratigraphic terranes can be recognized, particularly in the Eastern Alps. Metamorphic and deformational signatures vary greatly throughout the various basement units of the Alpine realm. The different characteristics of the pre-Alpine metamorphic evolution have been interpreted to result from stepwise accretion of these terranes onto the active Laurussian margin from Devonian to Permian times (Frisch and Neubauer 1989; Schönlaub 1992; Neubauer *et al.* 1999; and references therein). Their Gondwana origin is clear from basement rocks in which a Neoproterozoic to Cambrian deformation event can be recognized (i.e. 'Cadomian' age U–Pb crystallization and deformation). 'Cadomian' ages obtained from $^{40}Ar^{39}Ar$ dating of detrital micas in Ordovician sediments throughout the Upper Austroalpine and Southalpine units also support this hypothesis (Dallymeyer & Neubauer 1994; Antonitsch *et al.* 1994; Handler *et al.* 1997; Thóni 1999).

In the external units of the central and western Alps, Silurian to Devonian magmatic and metamorphic events have been recognized. In contrast, no pre-Carboniferous orogenic events have been observed in the Eastern Alps (Upper Austroalpine and Southalpine units: Noric–Bosnian terrane of Neubauer & von Raumer (1993)) where there was continuous sedimentation from Ordovician to Late Carboniferous

times in a passive margin-type environment (Schönlaub 1992; Stampfli 1996; Frey *et al.* 1999; Neubauer *et al.* 1999). Palaeozoic sequences in the Noric–Bosnian terrane document Ordovician crustal thinning and rifting, deposition in a black-arc basin environment, followed by development of a passive margin with shallow-water marine sedimentation, which persisted until Late Carboniferous time (Neubauer *et al.* 1999).

Upper Ordovician fossils (including brachiopods and ostracodes) from the Noric–Bosnian terrane are more closely related to coeval warm-water faunas of Baltica and Avalonia than to those of Africa (Schönlaub & Heinisch 1993). The onset of rift-related volcanism and magmatism in mid-Ordovician times, and faunal associations, therefore, suggest separation of the Noric–Bosnian terrane from Gondwana in mid-Ordovician times (Loeschke & Heinisch 1993), and available faunal and lithic data (Schönlaub 1992) suggest a Late Ordovician palaeolatitude of 40–50° S (Fig. 3b). As yet, there are no palaeomagnetic data to confirm this. Using the nomenclature of Stampfli (1996), the so-called Palaeotethys ocean, which opened up behind the alpine terranes as they drifted away from Gondwana, closed by northward-directed subduction and collision of Gondwana with Laurussia in Carboniferous time (Stampfli 1996).

For Late Silurian times, trilobite faunas of the Alps are similar to those of Bohemia, and new palaeomagnetic data from the Greywacke zone (part of the Upper Austroalpine nappe complex) yield a palaeolatitude of 45–50° S (Fig. 3c) (Schätz *et al.* 1996). This is in general agreement with the position estimated from palaeobiogeographical evidence (Schönlaub 1992) and documents the gradual northward drift of the Proto-Alps, and, importantly, illustrates that the Alpine terranes were distinct from the ATA, which was at significantly lower palaeolatitudes in Late Silurian time (Fig. 3c).

The Devonian successions of the Alps are characterized by abundant shelly fossils, reef development and condensed pelagic cephalopod limestones (Burchette (1981) and others). There was distinct exchange of faunas with Siberia, Kazakhstan, the Urals, Australia, Avalonia and the ATA, but remarkably poor similarity of faunas between the Alps and northern Africa. Reasons for such a widespread distribution of these Devonian fossil groups in the northern hemisphere are puzzling and have been a matter of much debate. Effects such as Coriolis forces and the presence of equatorial gyres, which would aid fossil dispersion, have been proposed; for further discussion the reader is referred to Cloud (1961), Ross (1975), Klapper & Johnson (1980), Oclzon (1990) and Schönlaub (1992). Palaeomagnetic data from the Noric–Bosnian terrane (Schätz *et al.* 1996; Tait *et al.* 1998) indicate that it was positioned at 25° S in mid-Devonian time (Fig. 3d), and the sedimentary record describes a passive margin environment with development of substantial carbonate reefs in this southern Alpine realm. The more northerly units of the Alps (External Massifs) had already accreted with the active southern margin of Laurussia (von Raumer 1998).

The Carboniferous period saw drastic changes in the Alps. Restricted flysch-type sedimentation was initiated in Early Namurian time and the climax of deformation occurred between the Namurian and Late Westphalian stages as a result of consolidation of the alpine terranes and blocks with the Laurussian margin. Open marine sedimentation occurred along the southern margin of Laurussia (in the southern Alps) with development of shallow-water carbonates, marking the northern border of the Palaeotethys (von Raumer 1998). This marine connection persisted all along the southern margin of the Alpine terranes until at least Late Carboniferous time, thus arguing against any major continental collision with Gondwana before this (Stampfli 1996). Lower to mid-Carboniferous calc-alkaline magmatism documents oblique northward-directed subduction of the Palaeotethys beneath southern Europe with active subduction continuing into late Carboniferous time (Ziegler 1986; Mercolli & Oberhänsli 1988) with final collision and formation of Pangaea (Fig. 3f) by late Carboniferous to Early Permian times (Frisch & Neubauer 1989).

Conclusions

Laurentia, Baltica, Avalonia and the ATA; formation of Laurussia

Closure of the Tornquist Sea separating Baltica and Avalonia, and the northern Iapetus Ocean between Laurentia and Baltica, which resulted in the Caledonian orogenic event are now well constrained, and have been dealt with in some detail by McKerrow *et al.* (this volume) and so are not repeated here. Palaeomagnetic data from various elements of the ATA provide a number of new insights into the geodynamic evolution of the Variscan fold belt. They indicate that all elements of the ATA had drifted away from the northern margin of Gondwana by Late Ordovician times (Fig. 3b). By Late Silurian–Early Devonian time Bohemia, Saxo-Thuringia,

the Armorican Massif and the Catalan terrane were all proximal to the southern margin of Baltica–Avalonia, and formed a chain of continental blocks (ATA) within the latitudinal belt of 20–30° S (Fig. 3c). Faunal evidence demonstrates that closure of the Rheic Ocean between the ATA and Avalonia did not occur until mid-Devonian time (Fig. 3d). Final suturing and consolidation of the ATA, closure of the Saxo-Thuringian basin, and rotation of Bohemia into its present-day orientation had occurred by Late Devonian times (Fig. 3e) (Tait *et al.* 1997). Thus from lithological, faunal and palaeomagnetic data, the accretion of Gondwana-derived terranes to the southern margin of Laurussia was essentially a continuing process throughout the Palaeozoic era.

Laurussia, the Proto-Alps and Gondwana; formation of Pangaea

Palaeomagnetism, structural geology and lithostratigraphic data from the Alps indicate that the first and main collision between the European margin of Laurussia and Gondwana occurred in Mid- to Late Carboniferous times. Stepwise accretion and amalgamation of the Alpine terranes onto the southern margin of Laurussia occurred from Devonian to Mid-Carboniferous times (Fig. 3). Late Carboniferous collision of Gondwana was diachronous along the suture zone, with sinistral transpressive movement in the western regions accompanied by shearing and eastward transport of smaller terranes and blocks (von Raumer 1998). The Devonian–Carboniferous deformation in central Europe may, therefore, have been driven by collision of Gondwana-derived terranes with the southern active margin of Laurussian. The first evidence for any major continent collision from the south was in late Carboniferous time when Gondwana collided with Laurussia, resulting in formation of Pangaea (Fig. 3f).

The authors gratefully acknowledge financial support from the DFG.

References

ABOUS-DEEB, J. M. & TARLING, D. H. 1984. Upper Palaeozoic palaeomagnetic results from Algeria and Tunisia. *Tectonophysics*, **101**, 143–157.

ANTONITSCH, W., NEUBAUER, F. & DALLMEYER, R. D. 1994. Paleozoic evolution within the Gurktal Nappe Complex, Eastern Alps. *Journal of the Czech Geological Society*, **39**, 2–3.

BACHTADSE, V. & BRIDEN, J. C. 1991. Palaeomagnetism of Devonian ring complexes from the Bayuda Desert, sudan—new constraints on the apparent polar wander path for Gondwanaland. *Geophysical Journal International*, **104**, 635–646.

——, VAN DER VOO, R. & HAELBICH, I. W. 1987. Paleozoic paleomagnetism of the western Gondwana. *Earth and Planetary Science Letters*, **84**, 487–499.

BENEDETTO, J. L. 1998. Early Palaeozoic brachiopods and associated shelly fauna from western Gondwana: their bearing on the geodynamic history of the pre-Andean margin. *In*: PANKHURST, R. J. & RAPELA, C. W. (eds) *The Proto-Andean Margin of Gondwana*. Geological Society, London, Special Publications **142**, 57–83.

BERDAN, J. M. 1991. The Silurian and early Devonian biogeography of ostracodes in North America. *In*: MCKERROW, W. S. & SCOTESE, C. R. (eds) *Palaeozoic Biogeography and Palaeobiogeography*. Geological Society, London Memoir, **12**, 223–231.

BOND, G. C., NICKESON, P. A. & KOMINZ, M. A. 1984. Breakup of a supercontinent between 625 Ma and 555 Ma: new evidence and implications for continental histories. *Earth and Planetary Science Letters*, **70**, 325–345.

BRENCHLEY, P. J. M., ROMANO, T. P., YOUNG, G. C. & STORCH, P. 1991. Hirnantian glaciomarine diamicitites—evidence for the spread of glaciation and its effect on Upper Ordovician faunas. *In*: BARNES, C. R. & WILLIAMS, S. H. (eds) *Advances in Ordovician Geology*. Geological Survey of Canada, 325–336.

BURCHETTE, T. P. 1981. European Devonian reefs: a review of current concepts and models. *In*: MOONEY, D. F. (ed.) *European Fossil Reef Models*. SEPM Special Publications, **30**, 85–142.

CHEN, Z., LI, X., POWELL, M. & BALME, B. E. 1993. Palaeomagnetism of the Brewer Conglomerate in central Australia, and fast movement of Gondwanaland during the Late Devonian. *Geophysical Journal International*, **115**, 564–574.

——, ——, —— & —— 1994. An Early Carboniferous paleomagnetic pole for Gondwanaland: new results from the Mount Eclipse Sandstone in the Ngalia Basin, central Australia. *Journal of Geophysical Research*, **99**, 2909–2924.

——, —— & —— 1995. Paleomagnetism of the Upper Devonian reef complexes, Canning Basin, Western Australia. *Tectonics*, **14**, 154–167.

CLOUD, P. E. 1961. Paleobiogeography of the marine realm. *American Association for the Advancement of Science Publications*, **67**, 151–200.

COCKS, L. R. M. 1993. Triassic pebbles, derived fossils and the Ordovician to Devonian palaeogeography of Europe. *Journal of the Geological Society, London*, **150**, 219–226.

—— & FORTEY, R. A. 1982. Faunal evidence for oceanic separations in the Palaeozoic of Britain. *Journal of the Geological Society, London*, **139**, 465–478.

——, MCKERROW, W. S. & VAN STAAL, C. R. 1997. The margins of Avalonia. *Geological Magazine*, **134**, 627–636.

COLLINS, W. J. & VERNON, R. H. 1992. Palaeozoic arc growth, deformation and migration across the Lachlan Fold Belt, southeastern Australia. *Tectonophysics*, **214**, 381–400.

CONEY, P. J. 1992. The Lachlan belt of eastern Australia and Circum-Pacific tectonic evolution. *Tectonophysics*, **214**, 1–25.

COOPER, A. H., MILLWARD, D., JOHNSON, E. W. & SOPER, N. J. 1993. The early Palaeozoic evolution of northwest England. *Geological Magazine*, **130**, 711–724.

CORNER, B. & NETHORN, D. I. 1978. *Results of a palaeomagnetic survey undertaken in the Damara Mobile Belt, South West Africa, with special reference to the magnetisation of the Uraniferous Pegmatitic Granites*. PEL-260, Atomic Energy Board, Pretoria.

DALLMEYER, R. D. & NEUBAUER, F. 1994. Cadomian $^{40}Ar/^{39}Ar$ apparent age spectra of detrital muscovites from the Eastern alps. *Jounral of the Geological Society, London*, **151**, 591–598.

DALY, L. & IRVING, E. J. 1983. Paléomagnetisme des roches carbonifères du Sahara central; analyse des aimantation juxtaposées; configuration de la Pangée. *Annales Geophysicae*, **1**, 207–215.

—— & POZZI, J. P. 1976. Résultats paléomagnetiques du Permien inférieur et du Trias Marocain: comparaison avec les données africaines et sud-americaines. *Earth and Planetary Science Letters*, **29**, 71–80.

DALZIEL, I. W. D. 1992. Antarctica: a tale of two supercontinents. *Annual Review of Earth and Planetary Sciences*, **20**, 501–526.

DERDER, M. E., HENRY, B., MERABET, N. E. & DALY, L. 1994. Palaeomagnetism of the Stephano-Autunian Lower Tiguentourine formations from stable Sharan craton (Algeria). *Geophysical Journal International*, **116**, 12–22.

EMBLETON, B. J. J. 1972. The palaeomagnetism of some Palaeozoic sediments from central Australia. *Journal and Proceedings, Royal Society of New South Wales*, **105**, 86–93.

FISHER, R. A. 1953. Dispersion on a sphere. Proceedings of The Royal Society of London, Series A, **217**, 295–305.

FORTEY, R. A. & COCKS, L. R. M. 1988. Arenig to Llandovery faunal distributions in the Caledonides. *In*: HARRIS, A. L. & FETTES, D. J. (eds) *The Caledonian–Appalachian Orogen*. Geological Society, London, Special Publications, 233–246.

FRANKE, W., DALLMEYER, D. & WEBER, K. 1995. Geodynamic evolution. *In*: DALLMEYER, R. D., FRANKE, W. & WEBER, K. (eds) *Pre-Permian Geology of Central and Eastern Europe*. Springer, Berlin, 579–593.

FREY, M., DESMONSSS, J. & NEUBAUER, F. 1999. The new metamorphic map of the Alps: introduction. *Schweizerische Mineralogische und Petrographisophe Mitteitungen*, **79**(1), 1–4.

FRISCH, W. & NEUBAUER, F. 1989. Pre-Alpine terranes and tectonic zoning in the eastern Alps. *In*: DALLMEYER, R. D. (ed.) *Terranes in the Circum-Atlantic Palaeozoic Orogens*. Geological Society of America, Special Papers, **230**, 91–100.

GLEN, R. A. 1993. Palaeomagnetism and terranes in the Lachlan Orogen. *Exploration Geophysics*, **24**, 247–256.

——, WALSHE, J. L., BARRON, L. M. & WATKINS, J. J. 1998. Ordovician convergent-margin volcanism and tectonism in the Lachlan sector of east Gondwana. *Geology*, **26**(8), 751–754.

GRAY, D. R., FOSTER, D. A. & BUTCHER, M. 1997. Recognition and definition of orogenic events in the Lachlan Fold Belt. *Australian Journal of Earth Sciences*, **44**, 489–501.

GRUNOW, A. 1995. Implications for Gondwana of new Ordovician paleomagnetic data from igneous rocks in southern Victoria Land. *Journals of Geophysical Research*, **100**(B7), 12589–12603.

HANDLER, R., DALLMEYER, R. D. & NEUBAUER, F. 1997. $^{40}Ar/^{39}Ar$ ages of detrital white mica from Upper Austroalpine units in the Eastern Alps, Austria evidence for Cadomian and contrasting Variscan sources. *Geologische Rundschau*, **86**, 69–80.

HARGRAVES, R. B., DAWSON, E. M. & VAN HOUTEN, F. B. 1987. Paleomagnetism and age of mid Palaeozoic ring complexes in Niger, West Africa, and tectonic implications. *Geophysical Journal of the Royal Astronomical Society*, **90**, 705–729.

HENRY, B., MERABET, N., YELLES, A., DERDER, M. M. & DALY, L. 1992. Geodynamical implications of a Moscovian palaeomagnetic pole from the stable Sahara craton (Illizi basin, Algeria). *Tectonophysics*, **201**, 83–96.

HURLEY, N. F. & VAN DER VOO, R. 1987. Paleomagnetism of Upper Devonian reefal limestones, Canning Basin, Western Australia. *Geological Society of America Bulletin*, **98**, 138–146.

JOKIEL, P. L. 1990. Long-distance dispersal by rafting: reemergence of an old hypothesis. *Endeavour*, **14**, 66–73.

KENT, D. V. & SMETHURST, M. A. 1998. Shallow bias of paleomagnetic inclinations in the Paleozoic and Precambrian. *Earth and Planetary Science Letters*, **160**(3–4), 391–402.

KLAPPER, G. & JOHNSON, J. G. 1980. Endemism and dispersal of Devonian conodonts. *Journal of Palaeontology*, **54**, 400–455.

KOKELAAR, B. P., HOWELLS, M. F., BEVINS, R. E., ROACH, R. E. & DUNKLEY, P. N. 1984. The Ordovician marginal basin of Wales. *In*: KOKELAAR, B. P. & HOWELLS, M. F. (eds) *Marginal Basin Geology*, Geological Society, London, Special Publications, **16**, 245–269.

KÖßLER, P., TAIT, J., BACHTADSE, V., SOFFEL, H. C. & LINNEMAN, U. 1996. Palaeomagnetic investigations of lower Palaeozoic rocks of the Thueringisches Schiefergebirge. *Terra Nostra*, **96**(2), 114–116.

KRIZ, J. & PARIS, F. 1982. Ludlovian, Pridolian and Lochkovian in La Meignanne (Massif Armoricain): biostratigraphy and correlations based on bivalvia and chitinozoa. *Geobios*, **15**(3), 391–421.

LANZA, R. & TONARINI, S. 1998. Palaeomagnetic and geochronological results from the Cambro-Ordovician Granite Harbour Intrusives inland of Terra Nova Bay (Victoria Land, Antarctica).

Geophysical Journal International, **135**, 1019–1027.

LAWVER, L. A. & SCOTESE, C. R. 1987. A revised reconstruction of Gondwanaland. *In*: MCKENZIE, G. D. (ed) *Gondwana Six: Stratigraphy, Sedimentology and Paleontology*. Geophysical Monography, American Geophysical Union, **40**, 17–23.

LI, Z. X., POWELL, C. M., EMBLETON, B. J. J. & SCHMIDT, P. W. 1991. New palaeomagnetic results from the Amadeus Basin and their implications for stratigraphy and tectonics. *In*: KORSCH, R. J. & KENNARD, J. M. (eds) *Geological and Geophysical Studies in the Amadeus Basin, Central Australia*. Bureau of Mineral Resources, Canberra, Australia, 349–360.

——, SCHMIDT, P. W. & EMBLETON, B. J. J. 1988. Paleomagnetism of the Hervey Group, central New South Wales, and its tectonic implications. *Tectonics*, **7**, 351–367.

LOCKLEY, M. G. 1983. A review of brachiopod dominated palaeocommunities from the type Ordovician. *Palaeontology*, **26**, 111–145.

LOESCHKE, J. & HEINISCH, H. 1993. Palaeozoic volcanism of the Eastern Alps and its palaeotectonic significance. *In*: RAUMER, J. VON & NEUBAUER, F. (eds) *The Pre-Mesozoic Geology in the Alps*. Springer, Berlin, 441–455.

MACNIOCAILL, C. & SMETHURST, M. A. 1994. Palaeozoic palaeogeography of Laurentia and its margins: a reassessment of palaeomagnetic data. *Geophysical Journal International*, **116**, 715–725.

MCELHINNY, M. W. 1968. Palaeomagnetic directions and pole positions—VIII, pole numbers 8/1 to 8/186. *Geophysical Journal of the Royal Astronomical Society*, **15**, 409–430.

—— & OPDYKE, N. D. 1968. Paleomagnetism of some Carboniferous glacial varves from Central Africa. *Geophysical Journal of the Royal Astronomical Society*, **73**, 689–696.

——, EMBLETON, B. J. J., DALY, L. & POZZI, J. P. 1976. Paleomagnetic evidence for the location of Madagascar in Gondwanaland. *Geology*, **4**, 455–457.

MCKERROW, W. S., DEWEY, J. F. & SCOTESE, C. F. 1991. The Ordovician and Silurian development of the Iapetus Ocean. *Special Paper, in Palaeontology*, **44**, 165–178.

——, MACNIOCAILL, C., AHLBERG, P. E., CLAYTON, G., CLEAL, C. J. & EAGER, R. M. C. 2000. The late Palaeozoic relations between Gondwana and Laurussia. *This volume*.

MERABET, N., BOUABDALLAH, H. & HENRY, B. 1998. Paleomagnetism of the Lower Permian redbeds of the Abadla Basin (Algeria). *Tectonophysics*, **293**(1–3), 127–136.

MERCOLLI, I. & OBERHÄNSLI, R. 1988. Variscan tectonic evolution in the Central Alps: a working hypothesis. *Schweizerische Mineralogische and Petrographische Mitteilungen*, **68**, 491–500.

MOREAU, C., DEMAIFFE, D., BELLION, Y. & BOULLIER, A.-M. 1994. A tectonic model for the location of Palaeozoic ring complexes in Aïr (Niger, West Africa). *Tectonophysics*, **234**, 129–146.

MOREL, P. & IRVING, E. 1978. Tentative paleocontinental maps for the early Phanerozoic and Proterozoic. *Journal of Geology*, **86**, 535–561.

NEUBAUER, F. & RAUMER, J. VON 1993. The Alpine basement: a linkage between Variscides and East-Mediterranean mountain belt. *In*: RAUMER, J. VON & NEUBAUER, F. (eds) *The Pre-Mesozoic Geology in the Alps*. Springer, Berlin, 641–663.

——, HOINKES, G., SASSI, F. P., HANDLER, R., HÖCK, V., KOLLER, F. & FRANK, W. 1999. Pre-Alpine metamorphism of the Eastern Alps. *Schweizerische Mineralogische Petrograchische Mitteilungen*, **79**(1), 41–62.

NYBLADE, A. A., LEI, Y., SHIVE, P. N. & TESHA, A. 1993. Paleomagnetism of Permian sedimentary rocks from Tanzania and the Permian paleogeography of Gondwana. *Earth and Planetary Science Letters*, **118**, 181–194.

OCLZON, M. S. 1990. Ocean currents and unconformities: the North Gondwana Middle Devonian. *Geology*, **18**, 509–512.

OPDYKE, N. D. 1964. The paleomagnetism of the Permian redbeds of southwest Tanganyika. *Journal of Geophysical Research*, **69**, 2477–2487.

OWEN, A. W., HARPER, D. A. T. & JIA-YU, R. 1991. Hirnantian trilobites and brachiopods in space and time. *In*: BARNES, C. R. & WILLIAMS, S. H. (eds) *Advances in Ordovician Geology*. Geological Survey of Canada, 179–190.

PERROUD, H. & VAN DER VOO, R. 1985. Palaeomagnetism of the Late Ordovician Thouars Massif, Vendée province, France. *Journal of Geophysical Research*, **90**, 4611–4625.

——, BONHOMMET, N. & VAN DER VOO, R. 1983. Palaeomagnetism of the Ordovician dolerites of the Crozon Peninsula (France). *Geophysical Journal of the Royal Astronomical Society*, **72**, 307–319.

——, ROBARDET, M. & BRUTON, D. L. 1992. Palaeomagnetic constraints upon the palaeogeographic position of the Baltic Shield in the Ordovician. *Tectonophysics*, **201**, 97–120.

PHARAOH, T. C., BREWER, T. S. & WEBB, P. C. 1993. Subduction-related magmatism of late Ordovician age in eastern England. *Geological Magazine*, **130**, 647–656.

POWELL, C. M. 1983. Tectonic relationship between the Late Ordovician and Late Silurian palaeogeographies of south eastern Australia. *Journal of the Geological Society of Australia*, **30**, 353–373.

—— 1984. Silurian to Mid-Devonian. *In*: VEEVERS, J. J. (ed.) *Phanerozoic Earth History of Australia*, Oxford University Press, Oxford, 309–328.

ROBARDET, M. & GUTIERREZ-MARCO, J. C. 1990. Sedimentary and faunal domains in the Iberian peninsula during lower Paleozoic times. *In*: DALLMEYER, R. D. & MARTINEZ-GARCÍA, E. (eds) *Pre-Mesozoic Geology of Iberia*. Springer, Berlin.

——, VERNIERS, J., FEIST, R. & PARIS, F. 1994. Le Paléozoique anté-varisque de France, contecte paléogéographique et géodynamique. *Géologie de la France*, **3**, 3–31.

Ross, R. J. 1975. Early Paleozoic trilobites, sedimentary facies, lithospheric plates, and ocean current. *Fossils and Strata*, **4**, 307–329.

Schallreuter, R. E. L. & Siveter, D. J. 1985. Ostracodes across the Iapetus Ocean. *Palaeontology*, **28**(3), 577–598.

Schätz, M., Bachtadse, V., Tait, J., Soffel, H. C. & Heinisch, H. 1996. New palaeomagmatic results from the southern flank of the European Variscides from the Northern Greywacke Zone, E-Alps. *Terra Nostra, Alfred-Wegener-Stiftung*, **96/2**, Köln, 165–168.

Scheibner, E. & Basden, H. 1996. *Geology of New South Wales—Synthesis. Volume 1. Structural Framework*. Geological Survey of New South Wales, Memoir, Geology, **13**(1).

Schmidt, P. W. & Embleton, B. J. J. 1990. The palaeomagnetism of the Tumblagooda Sandstone, Western Australia: Gondwana Palaeozoic apparent polar wandering. *Physics of the Earth and Planetary Interiors*, **64**, 303–313.

——, Cudahy, T. J. & Powell, C. M. 1986. Pre-folding and premegakinking magnetizations from the Devonian Comerong volcanics, New South Wales, Australia, and their bearing on the Gondwana pole path. *Tectonics*, **5**, 135–150.

—— & Palmer, H. C. 1987. Pre- and post-folding magnetizations from the early Devonian Snowy River Volcanics and Buchan Caves Limestone, Victoria. *Geophysical Journal of the Royal Astronomical Society*, **91**, 155–170.

——, Powell, C. M. Li, Z. Z & Thrupp, G. A. 1990. Reliability of Palaeozoic palaeomagnetic poles and APWP of Gondwanaland. *Tectonophysics*, **184**, 87–100.

Schönlaub, H. P. 1992. Stratigraphy, biography and paleoclimatology of the Alpine Paleozoic and its implications for plate movements. *Jahrbuch der Geologischen Bundesanstalt*, **135**(1), 381–418.

—— & Heinisch, H. 1993. The classic fossiliferous Palaeozoic units of the Eastern and Southern Alps. *In*: Raumer, J. von & Neubauer, F. (eds) *The Pre-Mesozoic Geology in the Alps*. Springer, Berlin, 395–422.

Scotese, C. R., Boucot, A. J. & McKerrow, W. S. 1999. Gondwanan palaeogeography and palaeoclimatology. *Journal of African Earth Sciences*, **28**(1), 99–114.

Smethurst, M. A., Khramov, A. N. & Torsvik, T. H. 1998. The Neoproterozoic and Palaeozoic palaeomagnetic data for the Siberian Platform: from Rhodinia to Pangaea. *Earth-Science Reviews*, **43**, 1–24.

Soffel, H. C., Saradeth, S., Briden, J. C., Bachtadse, V. & Rolf, C. 1990. The Sabaloka Ring Complex revisited: palaeomagnetism and rock magnetism. *Geophysical Journal of the Royal Astronomical Society*, **102**, 411–420.

Sommermann, A.-E., Meisl, S. & Todt, W. 1992. Zirkonalter von drei verschiedenen Metavulkaniten aus dem Südtaunus. *Geologisches Jahrbuch Hessen*, **120**, 67–76.

Stampfli, G. M. 1996. The intra-alpine terrain: a paleotethyan remnant in the Alpine Variscides. *Eclogae Geologicae Helvetiae*, **89**(1), 13–42.

Tait, J. 1999. New Early Devonian paleomagnetic data from NW France: paleogeography and implications for the Armorican microplate hypothesis. *Journal of Geophysical Research*, **104**(B2), 2831–2839.

Tait, J. A., Bachtadse, V. & Dinarès-Turell, J. 2000. Paleomagnetism of Siluro-Devonian sequences, NE Spain. *Journal of Geophysical Research*, **105**, **B10**, 23595–23604.

——, ——, Franke, W. & Soffel, H. C. 1997. Geodynamic evolution of the European Variscan fold belt: palaeomagnetic and geological constraints. *Geoligische Rundschau*, **86**, 585–598.

——, —— & Soffel, H. 1994. Silurian paleogeography of Armorica: new paleomagnetic data from central Bohemia. *Journal of Geophysical Research*, **99**(B2), 2897–2907.

Tait, J., Schätz, M., Bachtadse, V. & Soffel, H. 1998. Paleogeography of paleozoic terranes in the Variscan and Alpine fold belts. *Schriften des Staatlichen Museums für Mineralogie und Geologie zu Dresden*, **9**, 192–193.

Thöni, M. 1999. A review of geochronological data from the Eastern Alps. *Schweizeriehe Mineralogische and Petrographische Mitterlungen*, **79**(1), 209–230.

Thrupp, G. A., Kent, D. V., Schmidt, P. W. & Powell, C. M. 1991. Palaeomagnetism of red beds of the Late Devonian Worange Point Formation, SE Australia. *Geophysical Journal International*, **104**, 179–201.

Torsvik, T. H., Oleson, O., Ryan, P. D. & Trench, A. 1990. On the palaeogeography of Baltica during the Palaeozoic: new palaeomagnetic data from the Scandinavian Caledonides. *Geophysical Journal International*, **103**, 261–279.

——, Smethurst, M. A., Meert, J. G. *et al.* 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic: a tale of Baltica and Laurentia. *Earth-Science Reviews*, **40**, 229–258.

——, van der Voo, R., Trench, A., Abrahamsen, N. & Halvorsen, E. 1992. BALTICA—a synopsis of Vendian–Permian palaeomagnetic data and their palaeotectonic implications. *Earth-Science Reviews*, **33**, 133–152.

——, Trench, A., Svensson, I. & Walderhaug, H. J. 1993. Palaeogeographic significance of mid-Silurian palaeomagnetic results from southern Britain: major revision of the apparent polar wander path for eastern Avalonia. *Geophysical Journal International*, **113**, 651–668.

Trench, A. & Torsvik, T. H. 1991. A revised Paleozoic apparent polar wander path for south Britain (eastern Avalonia). *Geophysical Journal International*, **104**, 227–233.

——, ——, Denith, M. C., Walderhaug, H. & Traynor, J.-J. 1992. A high southerly palaeolatitude for Southern Britain in Early Ordovician

times: palaeomagnetic data from the Treffgarne Volcanic Formation SW Wales. *Geophysical Journal International*, **108**, 89–100.

VAN STAAL, C. R., DEWEY, J. F., MACNIOCAILL, C. & MCKERROW, W. S. 1998. The Cambrian–Silurian tectonic evolution of the Northern Appalachians and British Caledonides; history of a complex, west and southwest Pacific-type segment of Iapetus. *In*: BLUNDELL, D. J. & SCOTT, A. C. (eds) *Lyell; the Past is the Key to the Present*. Geological Society, London, Special Publications, **143**, 199–242.

VAN DER VOO, R. 1990. The reliability of paleomagnetic data. *Tectonophysics*, **184**, 1–10.

—— 1993. *Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans*. Cambridge University Press, Cambridge.

VON RAUMER, J. F. 1998. The Palaeozoic evolution in the Alps: from Gondwana to Pangea. *Geologische Rundschau*, **87**, 407–435.

WITZKE, B. J. 1990. Paleoclimatic constraints for Paleozoic paleolatitudes of Laurentia and Euramerica. *In*: MCKERROW, W. S., SCOTESE, C. R. (eds) *Palaeozoic Biogeography and Palaeobiogeography*. Geological Society, London, Memoir, **12**, 57–73.

ZIEGLER, P. A. 1986. Geodynamic model for the Palaeozoic crustal consolidation of Western and Central Europe. *Tectonophysics*, **126**(2–4), 303–328.