Revised World maps and introduction

C. R. SCOTese1 & W. S. MEKerROW2
1 Bellaire Research Center, Shell Development Company, PO Box 481, Houston TX 77001, USA
2 Department of Earth Sciences, Oxford University, Parks Road, Oxford OX1 3PR, UK

Abstract: We review the highlights of the 1988 symposium on Palaeozoic Biogeography and Palaeogeography, and present a revised set of 20 Palaeozoic base maps that incorporate much of the new data presented at the symposium. The maps include 5 major innovations: (1) A preliminary attempt has been made to describe the motion of the Cathaysian terranes during the Palaeozoic; (2) a more detailed description of the events surrounding the Iapetus Ocean is presented; (3) an alternative apparent polar wandering path for Gondwana has been constructed using the changing distributions of palaeoclimatically restricted lithofacies; (4) new palaeomagnetic data have been incorporated that places Laurentia and Baltica at more southerly latitudes, and adjacent to Gondwana, during the Early Devonian; Siberia is also placed further south in the light of biogeographic data presented at the symposium; (5) Kazakhstan is treated as a westward extension of Siberia, rather than as a separate palaeocontinent. The relationships between climatic changes, sea level changes, evolutionary radiations and intercontinental migrations are discussed.

A symposium on Palaeozoic Biogeography and Palaeogeography, sponsored by the Geological Society of London, the Palaeontological Association and the International Lithosphere Program, was held at the Department of Earth Sciences, Oxford University in August, 1988. The 40 papers in this volume include new data and new syntheses on palaeomagnetism, palaeoclimatology and the distribution of certain lithologies, but the majority of contributions are on Palaeozoic biogeography. Following the procedure adopted by the previous (and first) global palaeobiogeographical symposium, held at Cambridge University in 1971 (Hughes 1973), experts on major Palaeozoic fossil groups were invited to plot faunal and floral distributions on maps supplied before the symposium. An important goal of this symposium was to produce a revised set of Palaeozoic base maps (Figs 2 to 22). After a brief light of these comments, and some new data, we have prepared a map of the Cathaysian terranes during the Palaeozoic; (2) a more detailed description of the events surrounding the Iapetus Ocean is presented; (3) an alternative apparent polar wandering path for Gondwana has been constructed using the changing distributions of palaeoclimatically restricted lithofacies; (4) new palaeomagnetic data have been incorporated that places Laurentia and Baltica at more southerly latitudes, and adjacent to Gondwana, during the Early Devonian; Siberia is also placed further south in the light of biogeographic data presented at the symposium; (5) Kazakhstan is treated as a westward extension of Siberia, rather than as a separate palaeocontinent. The relationships between climatic changes, sea level changes, evolutionary radiations and intercontinental migrations are discussed.

Palaeozoic biogeography

The reader will note that the biogeographic terminology used by the authors in this memoir is not consistent from one contribution to another. The editors considered trying to impose greater uniformity in the use of such terms as province, realm, region, etc., but, a consensus on terminology among the symposium participants does not exist. Although one of us (McKerrow & Cocks 1986, p. 185) has made a plea for distinguishing 'Provinces' (separated by barriers) from 'Realms' (climatically controlled), we have decided to allow each contributor to use his own definitions of these terms.

Apart from personal and national prejudices, there is also an underlying scientific reason for the diversity in terminology: different animals and plants have different ecological controls affecting their biogeography. Some are obviously marine and others non-marine, so that continents or oceans which are barriers to some are the channels for migration of others. Moreover, different taxa have different degrees of mobility: terrestrial forms are often good indicators of land masses separated by only narrow stretches of sea, as are benthic ostracodes (see Berdan, this volume), which have no pelagic larval stage. Forms which are pelagic for part or all of their ontogeny may be more or less reflective of climate or of water masses with limited temperature changes.

Thus, different terminologies are used to describe the biogeography of the different groups. The time has not yet arrived when we can attain consistency in terminology, but we hope that this volume, by showing up the different terms still employed, may help to accelerate the development of a unified approach to palaeobiogeography (see Bambach & G. Young, this volume).

Most contributors have plotted their data on the symposium maps, but some have not. Many contributions also include accounts of the evolution of the various fossil groups. This has resulted in a certain unevenness in presentation, but it has also drawn attention to some significant new conclusions about controls on migration through time.

Evolutionary radiations during times of rising sea level often appear to have been accompanied by migration of marine faunas and floras. Sea level changes in the Arenig and Llanvirn appear to have affected the migration of some groups (Finney, T. Young, this volume), but the more prominent changes in the Late Ordovician, known to be related to glacial episodes, have affected the biogeography of nautiloids (Crick), blastoids (Waters), graptolites (Berry & Wilde; Rickards et al.), stromatoporoids (Nestor) and brachiopods (Sheehan & Coorough). Similar changes in the Devonian and Carboniferous are also suggested for nautiloids (Crick), for stromatoporoids (Stock), for blastoids (Waters), and for brachiopods (Kelley et al.). Clearly, the comparison of sea level changes and migration times of different animal groups will reward further study.

Palaeozoic palaeocontinents

The boundaries of the larger continents used in the revised base maps (Fig. 1) are essentially the same as those defined previously (Ziegler et al. 1977a, b; Scotese et al. 1979), but some small terranes are now also included.

In the light of the new data presented in this volume, we have
preparing a revised set of base maps for the 20 Palaeozoic time intervals used previously (Figs 2 to 21). The data used to construct these maps and the outstanding uncertainties and controversies are discussed next.

Laurentia

The North American palaeocontinent included northwest Ireland, Scotland, Greenland, the North Slope of Alaska and the Chukotsk peninsula of NE USSR. The Barents Sea continent (including Svalbard) was probably attached to Laurentia before the Early Ordovician; it may have collided with NE Greenland in the late Llandovery, so we infer that it was possibly separate from Laurentia in the Late Ordovician and Early Silurian. Mexico, Baja California and the Chortis block of Honduras have been rotated 11° clockwise with respect to cratonic Laurentia along a line parallel to the Torreon-Monterrey shear zone. The rotation parameters used to reassemble Laurentia are given in Table 1.

The Early Palaeozoic margin of Laurentia can be recognized in the Appalachians by the transition from platform carbonates to deeper water slope and offshore deposits (Rodgers 1968; Fortey & Cocks 1986). In the British Isles and East Greenland, the continental margin is marked by very thick Late Precambrian clastic sequences: the Dalradian Supergroup in Scotland (Harris et al. 1978) and the Eleonore Bay and Tillite Groups in East Greenland between present latitudes 70° and 76°N (Henriksen 1985), and possibly the Hecla Hoek sequences in Svalbard (Harland 1985).

During the Cambrian and Early Ordovician, shallow cratonic environments of Laurentia were characterised by endemic faunas (Cocks & Fortey 1982), including bathyurid trilobites and several brachiopod genera (Cocks & Fortey, this volume), nautiloids (Crick, this volume) and the conodont Midcontinent Faunal Region (Bergström, this volume). The deeper water faunas show a greater correlation with climate (Cocks & Fortey, Finney & Chen, Berry & Wilde, Rickards et al., this volume), and are consistent with Laurentia lying near the equator. By the Silurian, most faunas in Laurentia were cosmopolitan, but the benthic ostracodes (Berdan, this volume) and some terrestrial taxa were still distinct (Cocks & Fortey 1982). Continental collisions occurred between Laurentia and Baltica in the Late Silurian Scandian Orogeny, and between Avalonia and Laurentia in the Emsian/Eifelian Acadian Orogeny (McKerrow 1988a, b), so that the Laurentian faunas lost much of their regional identity during the Silurian and Devonian.

The Cambrian through Devonian orientation of Laurentia is based on the recent syntheses of Van der Voo (1988) and Kent & Van der Voo (this volume). The Devonian position of Laurentia was 20° to 30° further south than previously thought (Scotese et al. 1979, 1985). This latitudinal shift is based on new palaeomagnetic determinations for the Early Devonian (Miller & Kent 1988; Stearns et al. 1989) and the Late Devonian (Miller & Kent 1986). These new data agree well with palaeomagnetic results from Scotland (Briden et al. 1984; Torsvik et al., this volume) and the southerly location is in better agreement with Devonian biogeographic and palaeoclimatic indicators (see Witzke, this volume, and discussion above).

The Early Carboniferous orientation of Laurentia is based on revised palaeomagnetic determinations from the Mauch Chunk red beds of the Central Appalachians (Kent & Opdyke 1985) and from Maritime Canada (Scotese et al. 1984). By the Late Carboniferous and Permian, Laurentia had collided with Gondwana and had become part of the supercontinent Pangea. The Late Carboniferous and Permian orientation of Laurentia is based on the combined palaeomagnetic poles from all the Pangean continents (Van der Voo et al. 1984) and is similar to the Permian maps of Lottes & Rowley (this volume).

Baltica

Baltica consists of the major part of northern Europe; it is bounded on the west by the Iapetus suture, on the east by the Ural suture, on the south by the Variscan/Hercynian suture, and on the SW by the suture of the Tornquist Sea (Cocks & Fortey 1982), which closed in the Ashgill, and lies near, but not along, the Tornquist Line.

In the Early Ordovician, Baltica is characterised by a distinctive group of asaphid trilobites (Cocks & Fortey, this volume). This
fauna extends south to the Holy Cross Mountains in southern Poland, where deeper facies are present. The planktonic graptolites and the pelagic trilobites of Baltica show mixtures between low latitude (Laurentian) forms and high latitude (Gondwanan) forms (Cocks & Fortey 1982); their distributions appear to be related to climate (Cocks & Fortey, this volume) and suggest that Baltica was at an intermediate latitude in the Early Ordovician. There are no reliable palaeomagnetic poles from the Cambrian or Ordovician of Baltica (Torsvik et al., this volume), but the faunal evidence for intermediate latitudes is confirmed by some sedimentary facies. Middle Ordovician detrital limestones provide no evidence for a warm climate, but, in the Late Ordovician, reefs are present and suggest that by this time Baltica, like Laurentia, was close to the equator (Webby 1984; Bruton et al. 1985).

After the Late Silurian Scandian Orogeny, some sinistral strike slip movements continued through the Early Devonian. The position of Baltica with respect to Laurentia after this closure of the Iapetus Ocean (Fig. 12) is a 'tight' fit, which compensates for the extension that occurred along the margins of the North Atlantic Ocean prior to the Late Cretaceous/Early Tertiary continental rifting. A tight fit of the continents is also required to superimpose Middle and Late Palaeozoic poles from Europe and North America (Frei & Cox 1987; Lottes & Rowley, this volume).

**Avalonia**

The Ardennes of Belgium and northern France, England, Wales, southeastern Ireland, the Avalon Peninsula of eastern Newfoundland, much of Nova Scotia, southern New Brunswick and some coastal parts of New England constitute Avalonia. These areas are characterized by the following.

(1) A basement, which includes Late Precambrian (c. 600 Ma) arc rocks, and appears to have developed on a margin of Gondwana, though the precise location is uncertain.

(2) Cambrian and Early Ordovician shallow water faunas similar to western Gondwana, but with Baltic faunas in the Late Ordovician (Cocks & Fortey, this volume). Silurian ostracodes are identical with those of Baltica (Berdan, this volume), suggesting a shallow water connection by the end of the Ordovician.

(3) No warm water sediments prior to the Wenlock.

In southern Nova Scotia, the very thick clastic sequence of the Meguma Group extends upwards to include Early Ordovician sediments. No comparable sequence in known in Avalonia, and
it may be that the Meguma terrane separated from Gondwana independently from Avalonia. It was, however, linked to the rest of Nova Scotia by the Early Devonian when numerous plutons are present in both terranes (Keppie 1985).

It appears that at some time during the Early Ordovician, Avalonia rifted from Gondwana, perhaps when calc-alkaline igneous activity started in the Ardenness, Wales (Kokelaar et al. 1984) and SE Ireland with consumption of the Tornquist Sea oceanic crust. Avalonia probably collided with Baltica in the early Ashgill (McKerrow 1988a) with the closure of the Tornquist Sea and the appearance of oozes from Baltica. It then collided with Laurentia in the Emsian/Eifelian Acadian Orogeny (McKerrow 1988b). The movements of Avalonia (Figs 6–8) by this hypothesis are consistent with the palaeomagnetic data, which places it at temperate latitudes during the Ordovician (Johnson et al. 1988). There are few Cambrian and Early Ordovician poles from England, but Late Ordovician through Devonian results (Torsvik et al., this volume) place England in subtropical latitudes (Figs 7–12).

Gondwana

The continents forming the core of Gondwana are: South America, Africa, Madagascar, India, Antarctica and Australia; the present reconstruction is similar to the fit originally proposed by du Toit (1937), and differs primarily in the ‘tightness’ of the fit in order to compensate for pre-drift extension. The poles of rotation used here are given in Table 1. Though the relative positions of the 6 core continents are well constrained, the locations of numerous small continental blocks that bordered Gondwana are less certain. The following have all been adjacent to Gondwana at some time during the Palaeozoic: Yucatan, Florida, Avalonia, central and southern Europe (Robardet et al. and T. Young, this volume) and the Cimmerian terranes of Turkey, Iran, Afghanistan, Tibet and Southeast Asia (Sengör 1984, 1987).

The orientation of Gondwana used here is based on an apparent polar wander (APW) path determined from palaeoclimatic, rather than palaeomagnetic, data (Scotese & Barrett this volume). During the Cambrian and Early Ordovician, the South Pole was located 20–40° to the south of (present day) North Africa (Figs 2–7). The pole moved rapidly across North Africa in the Late Ordovician and reached Brazil by the end of the Silurian (Fig. 12). In the Devonian, the rate of apparent wandering slowed and the trajectory shifted, first south to Argentina in the Late Devonian (Fig. 16) and then cast towards South Africa in the Carboniferous (Fig. 18), and by the Early Permian it was near central Antarctica (Fig. 19).

Earlier published APW paths for Gondwana linked Late Ordovician poles with Carboniferous poles by means of a path through central Africa (McElhinny & Embleton 1974; Schmidt & Morris 1977; Brock 1981). The Devonian portion of the Gondwana APW path used here also differs from the APW paths proposed in this volume by Bachtadse & Briden and by Kent & Van der Voo. Though the Early and Late Palaeozoic portions of the APW path proposed here are similar to the APW path of Bachtadse & Briden, the Devonian portion is different. The Devonian APW path proposed by these authors makes a rapid loop from southern Argentina into central Africa, whereas the palaeomatically determined path, which we favour, follows a smooth trajectory from Argentina towards South Africa.

Central and southern Europe

The relationships between the Palaeozoic terranes of Iberia, France, Germany and Bohemia is still uncertain. Palaeomagnetic data from western France (Perroud & Van der Voo 1985) and Spain (Perroud 1983; Perroud et al. 1984) indicate that these areas were at high southern latitudes during the Early Palaeozoic (see Torsvik et al., this volume), which is consistent with a position adjacent to the north African margin of Gondwana. Faunal evidence supports the view that much of central and southern Europe had low diversity temperate shelf faunas in the Silurian, similar to other areas bordering Gondwana (Cocks & Fortey 1988; Robardet et al., this volume). The Early Palaeozoic sequences of Morocco, Spain, France and Bohemia are dominated by clastics; the absence of warm water carbonates (prior to the Middle Devonian) is consistent with their being at high southern latitudes.

Siberia and Kazakhstan

The Palaeozoic continent of Siberia is bounded on the west by the northern half of the Ural and the Irtysch Crush zone, on the south by the South Mongolian arc, and on the northeast by the Verkhoyansk Fold Belt. Throughout most of the Palaeozoic, Siberia was oriented 180° from its present alignment, so that its southern, active, Andean-style margin faced to the north. Kazakhstan now lies southwest of Siberia. Previous reconstructions (e.g. Scotese et al. 1979) have treated the region as a separate and independent continent. We now consider Kazakhstan to be an extension of the Palaeozoic Siberian continent; its configuration may have been similar to the present day relationship of the Malay Peninsula, Sumatra and Java to Southeast Asia. The link with Siberia was possibly an extension of the South Mongolian arc and we consider that Kazakhstan grew during the Palaeozoic by the accretion of volcanic arcs and related trenched deposits. The complex and often mixed aspect of the Kazakhstan faunas may be explained, in part, by accretion of exotic and far-travelled terranes.

The orientation of Siberia and Kazakhstan (Figs 2–21) is based on the palaeomagnetic compilations of Khramov et al. (1981) and Khramov & Rodionov (1980). Several contributors to this symposium have suggested that these palaeomagnetic poles place Siberia unacceptably far north during the Silurian and Devonian, and we have made some adjustments accordingly. Nestor (this volume) shows that stromatoporoids are normally confined to latitudes within 30° of the equator, but that the Tuva region of (present day) south Siberia was shown to be 40°–45°N. On the Wenlock and Ludlow symposium maps. Similarly, coral (Pedder & Oliver), gastropod (Blodgett et al.), algae (Poncet) and miospore (Streel et al.) distributions, as well as climatic constraints (Witzke), suggest that Siberia was shown too far to the north during the Devonian.

From the Cambrian to the Early Carboniferous, Siberia and Kazakhstan moved northwards. During the mid-Carboniferous they rotated clockwise, colliding with Baltica along the Ural Mountains in the Late Carboniferous/Early Permian.

China and Tarim

It is now recognized that China consisted of at least 3 Palaeozoic continents (Nie et al., this volume): North China (Sino-Korea), South China (the Yangtze platform) and Tarim. The Qilian Shan, an Early Palaeozoic arc, separates Tarim from North China. Though we recognize that Tarim and North China were separate palaeocontinents, for simplicity, we have shown them joined together. Tarim appears to have collided with Siberia and Kazakhstan during the Late Carboniferous/Early Permian (Nie et al., this volume), whereas North China and South China did not join Asia until the Late Triassic/Early Jurassic Indosinian Orogeny.

Biogeographic affinities with eastern Gondwana (G. Young, Hou & Boucot, Liao, this volume) suggest that South China was located near Australia during most of the Palaeozoic. The orientation of South China is based on Cambrian (Lin et al. 1985a, b), Silurian (Opdyke et al. 1987), Devonian (Fang & Van der Voo 1989), Carboniferous and Permian (Chan et al. 1984; Zhao &...
INTRODUCTION

Coe 1987) palaeomagnetic data. Because the polarity of the Early Palaeozoic poles from South China is not well established, it is uncertain whether the NW or SE margin faced Gondwana. Palaeogeographic arguments can be made for either orientation. We have chosen to show the present SE margin facing Gondwana in order to minimise the amount of post-rifting rotation.

Though South China and North China were probably associated with eastern Gondwana during the Early Palaeozoic, they had rifted off by the Late Palaeozoic. This separation is shown by palaeomagnetic data, by biogeographic differences, and by palaeoclimatic evidence which indicates that, while eastern Gondwana was being glaciated, both South and North China enjoyed tropical climates. Relative plate motions suggest that rifting from Gondwana must have begun by the Middle Devonian (Fig. 15).

The location of North China and Tarim during the Early and Middle Palaeozoic is uncertain. There are few reliable Early Palaeozoic palaeomagnetic results from North China, and much of the Middle Palaeozoic stratigraphic record is missing. Cambrian and Early Ordovician faunas from North China are similar to those of Australia, while South China has more affinities with India (Burrett et al., this volume), but in our maps we show North China attached to South China in the vicinity of Korea, though separated from South China by the V-shaped Qin Ling Ocean (Zhao & Coe 1987).

Cimmeria

Turkey, Iran, Tibet (Qiang Tang and Lhasa), Shan Thai-Malaya and Indo-China are shown (Figs 2 to 21) as several small terranes along the margin of Gondwana; these comprise the Cimmerian continent of Sengör (1984, 1987).

During the Early and Middle Palaeozoic, Cimmeria was the site of an active, Andean-style margin. By the Carboniferous, some of the Cimmerian terranes (Qiang Tang and Shan Thai-Malaya) have glacial-related deposits which indicate that they were still located at high southerly latitudes adjacent to Gondwana; this is unlike China, whose equatorial faunas and floras show that it had separated from Gondwana by this time. Palaeomagnetic data confirm a temperate location for the Shan Thai-Malaya terrane during the Late Palaeozoic (McElhinney et al. 1981; Fang & Van der Voo 1989). In the Late Palaeozoic, Cimmeria rifted away from Gondwana (Panjal Traps) and crossed the Palaeo-Tethys Ocean, eventually colliding with the southern margin of Asia during the Middle to Late Triassic Cimmerian Orogeny (Sengör 1984, 1987).

Chronological review

Latest Precambrian and Cambrian (Figs 2 to 5)

Many of the passive margins of Laurentia appear to have been formed between 750 and 600 Ma ago, suggesting to several authors that there may have been a Late Precambrian Pangea (Morel & Irving 1978; Bond et al. 1984; Piper 1983, 1987). One possible Precambrian supercontinent, composed of Laurentia, Baltica and Siberia, is shown in Fig. 2. The involvement of Gondwana in a Late Precambrian Pangea is problematic. The Pan-African Orogeny, which dates from this time (c. 600 Ma), records a series of continental collisions that led to the formation of Gondwana. If this is the case, the Late Precambrian was a time characterized by the break-up of one supercontinent and the assembly of another.

Though the relative positions of Laurentia, Baltica and Siberia are uncertain, their break-up would have led to the formation of new oceans; one of these was the Iapetus Ocean. In Figs 2 to 5, we show the Iapetus widening as Laurentia diverges from Baltica and Siberia during the Cambrian. At the same time, Gondwana moved steadily southwards so that the Cambrian faunas of Laurentia, Baltica and Siberia remained isolated enough to develop some faunal endemism (Palmer 1973; Bergström & Gee 1985, p. 266).
Fig. 3. Early Cambrian.

Fig. 4. Middle Cambrian.
**INTRODUCTION**

Fig. 5. Late Cambrian.

**Ordovician (Figs 6 to 9)**

By the Early Ordovician, the Iapetus Ocean and the Tornquist Sea had begun to narrow, with arcs present on the east of Laurentia and in Avalonia (McKerrow 1988a). Apart from pandemic deep water forms, the marine faunas of Laurentia, Baltica and Gondwana remained distinct, suggesting that they were separated by oceans at least 1000 km wide (McKerrow & Cocks 1986). The shallow marine benthic trilobites occur in the tropics of Siberia and North China as well as in Laurentia (Cocks & Fortey, this volume), suggesting, not only that these three continents were near the Equator, but that they had separations of less than 1000 km.

During the Early Ordovician, carbonates are abundant on the cratons of Laurentia, Siberia and the Indo-Australian region of Gondwana, whereas clastic rocks are dominant in Baltica and the North African margin of Gondwana. Warm water carbonates appear in the Late Ordovician of Baltica (Webby 1984; Bruton et al. 1985), suggesting a slow northward movement into lower latitudes (Fig. 8).

West Gondwana continued to move southwards during the Ordovician, and it began to cross the South Pole in the Caradoc (Fig. 8). By the Ashgill (Fig. 9), an ice cap covered the whole of North Africa from Morocco to Arabia. Adjacent parts of Gondwana, including Spain and Brittany, have Ashgill sediments which have been interpreted as periglacial (T. Young, this volume). There are no Ashgill tillites in eastern Avalonia, which was probably connected to Baltica, where warm water carbonates were established (see above).

Avalonia probably started to rift from Gondwana in the late Tremadoc (compare Figs 6 and 7), when calc-alkaline rocks appeared in the southern British Isles (Kokelaar et al. 1984) and possibly in the Ardennes, and when subduction of the SW margin of the Tornquist Sea originated. In the Middle Ordovician (Fig. 8), the shallower benthic faunas of eastern Avalonia started to lose their affinities with Gondwana and shre links with Baltica, and by the late Caradoc these faunas were identical with Baltica (Cocks & Fortey 1986 and this volume), indicating that shallow benthos with pelagic larval stages could cross the Tornquist Sea. This connection occurs significantly earlier than the Hirnantian stage of the late Ashgill (Fig. 9), when the corresponding faunas became identical across the Iapetus Ocean between Laurentia and Baltica (Sheehan & Cooragh, this volume). It is estimated that an ocean around 1000 km wide would be narrow enough for such complete integration of shallow water benthos with pelagic larvae (McKerrow & Cocks 1986).

The location of the south-western portion of Avalonia is more uncertain. A tillite may exist in the Roxbury Conglomerate of the Boston Bay Group (Bailey et al. 1976), but its age is unknown. A tillite is also recorded from the Ordovician of the Meguma terrane of Nova Scotia (Schenk 1972). If the presence of late Ashgill tillites is confirmed in southwestern Avalonia, higher latitudes are indicated.

During the Early Ordovician, several island arcs were present off the eastern margin of Laurentia; they can be readily defined in the Northern Appalachians (Bronson Hill, Tetagouche, Lushs Bight), but are less certain in the British Isles (McKerrow 1988a) and Scandinavia (Stephens & Gee 1985). These arcs appear to have collided with Laurentia progressively, starting in the north during the Early Ordovician and ending with the Caradoc Taconian Orogeny in New England. During the earlier stages of their development, some of these arcs may have been located well out in the Iapetus Ocean. Many of them contain some Early Ordovician brachiopod genera (the 'Celtic Province') which have been considered to be unique to oceanic islands (Neuman 1984); however, more recent records of the same taxa from both Laurentia and Avalonia would suggest that the 'Celtic Province' consists of widely travelled forms (perhaps with a longer than average larval duration) which could colonize volcanic islands, but which are by no means diagnostic of a mid-oceanic setting (McKerrow & Cocks 1986).
Fig. 6. Basal Ordovician (Tremadoc).

Fig. 7. Early Ordovician (Arenig).
Late Ordovician (Llandeilo–Caradoc)

Fig. 8. Middle to Late Ordovician (Llandeilo–Early Caradoc).

Latest Ordovician (Ashgill)

Fig. 9. Latest Ordovician (Ashgill).
Silurian (Figs 10 to 12)

In the late Llandovery (Fig. 10), west-verging nappes were emplaced in north-east Greenland (Hurst et al. 1983); this was due perhaps, to the collision of Greenland with Barentsia (the Barents Sea micro-continent including Svalbard). During the Silurian, Laurentia moved southeasterwards relative to Baltica, and their collision is marked by the east-verging nappes of the Late Silurian Scandian Orogeny (Stephens & Gee 1985). The collision took place before the completion of all of the strike slip faulting which is so prominent in Scotland and northwest Ireland. The reconstructions (Figs 11 and 12) show Baltica, Avalonia and Barentsia about 10° further south than in most previous North Atlantic reconstructions (Sclater et al. 1977). This adjustment allows for the known post-Silurian movements on the Scottish faults (McKerrow & Elders 1989) and it also allows the west-verging Llandovery nappes of northeast Greenland to be situated clear to the north of the east-verging Late Silurian Scandian nappes (McKerrow 1988a). It requires approximately 750 km of sinistral strike-slip movement to be of post-Wenlock age.

After the Scandian Orogeny, the southern parts of the Iapetus Ocean still remained open between Avalonia and Laurentia (Figs 11 and 12), with an arc on the Laurentian margin (McKerrow 1988a). However, there is increasing evidence for north-westward subduction of Avalonian continental crust in the British Isles during the Late Silurian and Early Devonian (McKerrow & Soper 1989), so the northern parts of Iapetus were not necessarily floored by oceanic crust after the Wenlock.

During the Silurian, carbonates were common in Laurentia, northeastern Avalonia, Baltica, Siberia and equatorial Gondwana. The warm water facies, which had persisted throughout the Early Palaeozoic of Laurentia and appeared in the Caradoc of Baltica, now spread over wider areas of these continents and by the Wenlock, the first coral reefs appeared in England (Fig. 11). The low diversity Clarkeia fauna, which is characteristic of the south polar regions, was present in Gondwana, Spain, France and southwestern Avalonia (Cocks & Fortey, this volume).

In the latest Silurian, evaporites occur in the United States, consistent with a sub-tropical position (Fig. 12).

The Silurian reconstructions presented here differ from those of Kent & Van der Voo (this volume) in the position of Gondwana. Kent & Van der Voo (this volume) and Bachtadse & Briden (this volume) use an Early Silurian palaeomagnetic pole from an igneous ring complex of Niger (Hargraves et al. 1987) to orient Gondwana. This result places the South Pole in southernmost Argentina and requires unusually high rates of plate motion (>15 cm a⁻¹) for Gondwana during the Late Ordovician and Silurian. In the absence of confirming palaeomagnetic results, we have used palaeoclimatic evidence to orient Gondwana (see Scoteze & Barrett, this volume, and discussion under Gondwana, above).

Devonian (Figs 13 to 16)

By the Early Devonian, most of the movement between Laurentia and Baltica/Avalonia was sinistral strike slip though oblique subduction continued below the Laurentian margin until the Emsian (McKerrow 1988a, b). Palaeomagnetic data from North America places the Appalachian margin at 40° during the Early Devonian (Miller & Kent 1988). This result is in good agreement with palaeomagnetic results from Britain, which indicate palaeolatitudes for southern Scotland of 20°–25° S. This more southerly position for Laurentia and Baltica (Euramerica) requires that their contact with Gondwana was earlier than previously supposed. Both the palaeomagnetic and faunal (G. Young, this volume) evidence suggests that no wide ocean existed between Euramerica and Gondwana during the Devonian.

The closure of the northern Iapetus in the Scandian Orogeny and the southern Iapetus in the Acadian Orogeny resulted in a high mountain belt between Laurentia and Baltica/Avalonia. These mountains served as a barrier to separate the benthos
INTRODUCTION

Fig. 11. Middle Silurian (Wenlock).

Middle Silurian (Wenlock)

Fig. 12. Late Silurian (Ludlow).

Late Silurian (Ludlow)
Fig. 13. Early Devonian (Gedinnian).

Fig. 14. Late Early Devonian (Emsian).
Fig. 15. Middle Devonian (Givetian).

Fig. 16. Late Devonian (Famennian).
of the Appalachian Province of Laurentia from the Rhenish–Bohemian Province (Boucot et al. 1969). In western Gondwana, the Appalachian Province occurs in South America (Barrett 1985), while the Rhenish–Bohemian Province is present in North Africa. This separation in both northern and southern continents is hard to explain if there is a wide Devonian ocean north of western Gondwana.

We follow the scenario of Neugebauer (1988), which suggests that, during much of the Devonian, Euramerica and Gondwana were in contact, but not in collision.

Throughout the Devonian, western Gondwana and Euramerica continued to move northward (Figs 13 to 16). This movement is accompanied by the appearance of warm water carbonates in the Middle Devonian of Morocco (Wendt 1985), Brittany and SW England.

Just as the elimination of subduction after the collision of India with Asia resulted in major changes in plate motion during the Tertiary (Scotese et al. 1988), so too, the end of subduction on the margins of the Iapetus Ocean can be linked with major changes in plate motion during the Middle and Late Devonian. Most of the effects of this plate reorganisation were seen around Laurentia, where, in addition to the Caledonian/Appalachian mountain belts, new orogens developed along its western (Antler and Caribou Orogenies) and northern (Ellesmerian Orogeny) margins. The Ellesmerian Orogeny may also reflect the collision of Siberia with Laurentia. Elsewhere, rifting occurred on some continental margins: back arc basins developed along the northern margin of Gondwana (Wendt 1985), the Viluy Trough formed in northeastern USSR (Khain 1985), and the Donetz aulacogen originated on the southeastern margin of Baltica. As proposed above, it is also likely that South and North China had started to rift from eastern Gondwana by Early or Middle Devonian times.

The Early Devonian reconstructions presented here (Figs 13 and 14) are similar to those of Kent & Van der Voo (this volume). The main difference is in the relative longitudinal positions of Laurentia and Baltica with respect to Gondwana. Palaeomagnetic data predicts approximately 10° of overlap between Laurentia and Gondwana in the Early Devonian. Kent & Van der Voo avoid this overlap by shifting Laurentia and Baltica 60° westwards. We, on the other hand, prefer a ‘tight fit’ that brings the continents as close as possible, and maintains their relative longitudinal positions.

Our Late Devonian reconstruction (Fig. 16) is also different from Kent & Van der Voo (this volume) due to the choice of poles for Gondwana. Based on palaeoclimatic evidence, we place the Late Devonian South Pole in north-central Argentina (Scotese & Barrett, this volume), whereas Kent & Van der Voo use data (Hurley & Van der Voo 1987) which place the pole in central Africa.

Carboniferous (Figs 17 to 19)

During the Carboniferous and Early Permian, the closure of several oceans resulted in the amalgamation of the western half of Pangea; these included the Rheic Ocean between northern Europe and Gondwana, the Phoibic Ocean between Laurentia and Gondwana, and the Pleionic Ocean between Baltica and Siberia/Kazakhstan (McKerrow & Ziegler 1972).

Though Gondwana and northern Europe were adjacent during most of the Devonian, there appears to have been little deformation until the Late Devonian or Early Carboniferous (Holder & Leveridge 1986). The Hercynian and Variscan Orogenies had their climax in the Westphalian; they record deformation along the southern margins of Baltica and Avalonia, and in the numerous small terranes of southern Europe, some of which were attached to Gondwana. The collisions between Gondwana and northern Europe had a large oblique component related to the clock-wise rotation of Gondwana relative to northern Europe (Neugebauer 1988) (Figs 17 to 19). The small terranes of central and southern Europe were deformed in the transpressive shear zone that resulted
Early Late Carboniferous (Namurian)

Fig. 18. Early Late Carboniferous (Namurian).

Late Carboniferous (Westphalian)

Fig. 19. Late Carboniferous (Westphalian).
from this rotation. The numerous examples of synchronous local compression and tension in adjacent regions in the Variscan/Hercynian Orogen can also be explained by this mechanism.

Due to the clock-wise rotation of Gondwana, the climax of deformation generally progressed from NE to SW along the Hercynian, Variscan, Appalachian/Mauritanide and Ouachita fronts. In eastern Laurentia, the first rumblings of the Alleghanian Orogeny occurred in the Visean (Perry 1978), and the orogen was uplifted and deformed throughout the remainder of the Carboniferous. The youngest folded beds in the Central Appalachians (Monongahela group) are latest Carboniferous in age. On the Allegheny Plateau, the Early Permian Dunkard Group was gently folded during the final phase of deformation.

The Ouachita Mountains of Oklahoma record the final phase of collision between Laurentia and Gondwana. In the Early Carboniferous, Gondwana collided with an island arc on the SE margin of Laurentia; this arc was thrust northward and buried beneath a thick prograding sedimentary wedge during the Late Carboniferous. The final phase of collision in the Early Permian was marked by these deposits being thrust up to form the Ouachita Mountains.

During the Early Carboniferous (Fig. 17), Siberia rifted away from the Arctic margin of Laurentia, opening the Sverdrup Basin (Sweeney 1977). By the mid-Carboniferous, the island arcs of Kazakhstan collided with the SW margin of Siberia, forming the Irtysch and Dzungar fold belts (Fig. 18). Through the remainder of the Carboniferous, Siberia and Kazakhstan rotated clock-wise, and by Late Carboniferous (Fig. 19) were approaching the Uralian margin of Baltica (Nalivkin 1973); this collision occurred in the Early Permian. Recently, it has also been suggested that the Tarim terrane of NW China began to collide with the SW margin of Siberia during the Late Carboniferous (Nie et al., this volume).

As these collisions developed, many parts of the continents became emergent, and in the Namurian (mid-Carboniferous) the pole-to-equator temperature gradient began to strengthen (Raymond et al. 1989; Kelley et al., this volume). The Late Carboniferous was a time of climatic contrasts. Warm, rainy, equatorial swamps extended from the Russian platform across north-central Europe to England and Maritime Canada, and into the mid-continent of North America. Though floristically distinct, similar coal-producing environments occurred in North and South China (Ziegler, this volume). Thick evaporite deposits accumulated at sub-tropical latitudes of Hudsons Bay and the Amazon Basin (Ziegler et al. 1979; Ronov et al. 1984). In the south polar regions, a large ice sheet extended from Argentina across southwestern Africa to Madagascar, southern Arabia, India, Antarctica and Australia (Caputo & Crowell 1985).

Permian (Figs 20 and 21)

Many of the continental collisions which began in the Carboniferous were completed in the Permian. The western half of Pangea was assembled, and the new supercontinent, ringed by subduction zones, moved steadily northward. The configuration of the Atlantic-bordering continents is now generally agreed. Our reconstruction (Figs 20 and 21) differs only slightly from that of Lottes & Rowley (this volume); both show a tighter fit than previously published maps (e.g. Sclater et al. 1977) in order to compensate for the pre-rifting extension of the crust along the continental margins.

The configuration of the blocks that were eventually to form the eastern half of Pangea (China and SE Asia) is still problematic. Nie et al. (this volume) describe no less than 11 terranes in the assembly of Asia. Five of these terranes are shown in Figs 1, 20 and 21: South China (Yangtze), Indochina, Shan Thai–Malaya, Iran and Afghanistan (Helmand). Another five have been combined into composite blocks: Tarim and Sino-Korea are shown as North China; and the West Qiang Tang, East Qiang Tang and Lhasa blocks of Nie et al. (this volume) are combined in our Tibetan block (Fig. 1). The terranes of northern Manchuria have inadvertently been omitted here. As Nie et al. (this volume) show, these terranes were located originally along the southern
Fig. 21. Late Permian (Kazanian).

Late Permian (Kazanian)

INTRODUCTION

In the Permian, the allochthonous terranes of Asia can be divided into two groups: Cathaysian and Cimmerian. The Cathaysian terranes (South China, North China and Indochina) had probably rifted from Gondwana during the Middle Palaeozoic and occupied an equatorial position in the Permian (Figs 20 and 21). During the Early Permian, the western end of North China (Tarim) collided with Siberia (Rowley et al. 1985; Nie et al. this volume); and by the Late Permian the NE end (Sino-Korea) had sutured to northern Manchuria (see Nie et al., this volume).

South China is shown attached to North China at a hinge near Korea (after Zhao & Coe 1987). The Qinling Ocean, which separated these blocks, closed during the Late Triassic as a result of the scissors-like rotation of these two blocks. Though climatic, biogeographic and palaeomagnetic information constrain the latitude of South China, its longitudinal position in the Late Palaeozoic is more uncertain.

Nie et al. (this volume) show South China in the western part of Proto-Tethys; we on the other hand would place it in the eastern Proto-Tethys, so that its intrusive rocks formed a link between the active margins of the SE China and Indochina and the Tasman arc of Australia (Figs 20 and 21).

The second group of terranes (Turkey, Iran, Tibet, Shan Thai-Malaya) are considered to have formed the elongate continent of Cimmeria by Sengör (1984, 1987). The rifting of Cimmeria from Gondwana in the Permian (compare Figs 20 and 21) is described in more detail by Rowley et al. (1985) and Nie et al. (this volume).

The assembly of western Pangea during the Early Permian had profound climatic and biogeographic effects. In the equatorial regions, the rising Variscan, Appalachian and Mauritanide mountains blocked the wet equatorial easterly winds, casting a rain shadow over much of central Pangea. As northern Europe and the mid-continent of North America moved northward, the coal swamps of the Carboniferous were succeeded by deserts and saline inland seas. In the south temperate and polar regions, the Gondwana ice cap retreated, to be replaced by bogs and peat swamps. The emergence of many continental areas above sea level started the pattern of seasonal monsoons that would become more dominant during the Mesozoic (Crowley et al. 1989; Kutzbach & Gallimore 1989).

The emergent Pangea supercontinent, spanning the Earth from pole to pole, provided a wide range of environments suitable for specialised ecological adaptations. Ziegler (this volume) describes an actualistic approach to mapping floral distributions. Bambach (this volume) suggests that the increase in Late Palaeozoic provinciality in the marine realm was the result of a decrease in the range of regionally distributed genera, rather than any increase in either endemism or the number of recognizable biogeographic units.

Palaeozoic climates

A poster session at the symposium in Oxford was devoted to an informal attempt to characterize climatic changes through the Palaeozoic. Participants were asked to describe the climate in selected palaeogeographic regions as either cold, cool, warm or hot for a succession of time intervals. The results of this exercise are shown in Fig. 22.

It was recognized that the climatic changes for each region result from a combination of secular changes in global climate and the changing latitude of each region through time. Though changes in climate due to latitudinal shift of the continents predominate, a few global climatic events could be recognised, especially the major cooling events in the Late Ordovician (late Ashgill) and the mid-Carboniferous (late Namurian). A less well defined cooling event may have taken place during the Late Devonian (late Frasnian). Prior to these cooling events, faunas were diverse and endemic. During the cooling events, widespread extinctions took place (e.g. Sheehan & Coorough, this volume).

During the Namurian event, the latitudinal range of floras was compressed towards the Equator (Kelley et al., this volume). As stated above (in the Palaeozoic Biogeography section), changes in climate are often correlated with sea level changes, and these
in turn affect evolutionary radiations and migrations. The correlations between these events deserve much further study.

Conclusions

The symposium provided an opportunity for palaeontologists, palaeobotanists, stratigraphers and palaeomagnetists to meet and exchange ideas and data on the development of the world during the Palaeozoic Era. One of the messages that came across loud and clear was that we can no longer rely on a single line of evidence to reconstruct the Palaeozoic world. We must take an approach that integrates all relevant data from the Earth Sciences; biogeography, tectonics, stratigraphy, palaeomagnetism, sedimentology and palaeoclimatology all have key roles to perform.

The maps presented here have benefitted from using such diverse data. They incorporate five major changes from their predecessors (Scotese et al. 1979; Scotese 1984, 1986).

1. The Cathaysian terranes are shown progressing from north

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![Image of climatic changes during the Palaeozoic](http://mem.lyellcollection.org/)

**Fig. 22.** Climatic changes during the Palaeozoic. The upper diagram shows changes in 9 separate geographic regions (B to I) which are shown in the lower diagram. The density of the stipple in the upper diagram represents temperature determined from faunas and lithofacies.
of East Gondwana to a linear arrangement along an arc postulated to lie between the South Mongolian arc and the east Australian arc.

(2) The terranes bounding the Iapetus Ocean are shown in more detail.

(3) A new polar wandering path for western Gondwana has been constructed using climatically linked lithofacies (Scotese & Barrett, this volume).

(4) New palaeomagnetic data has been incorporated (Kent & Van der Voo, this volume) that places Laurentia and Baltica further south, adjacent to Gondwana in the Early Devonian; and Siberia is also moved south in the light of biogeographical data.

(5) Kazakhstan is treated as a westward extension of Siberia, rather than as a separate continent.

In many respects, the maps we present here are similar in their precision to the maps of Asia and the New World produced by 16th Century explorers. In the 500 years since the voyages of these early discoverers, we have mapped the Earth 'in space'. We are now embarking on a voyage to map the Earth 'in time'. To do this, we need to assemble systematically a database of palaeogeographic information from the Palaeozoic rocks of every country. To do this well we should take better advantage of recent advances in computer technology, to allow us to manipulate and manage the vast amounts of information. The patterns are becoming too complex and too subtle to unravel using traditional techniques.

The next step, which we are just beginning to take, will be to map the plate boundaries of the Palaeozoic (Zonenshain et al. 1985). At the moment we can recognise some trenches along active margins, but the location of spreading ridges and the motion of the plates (as opposed to motions of the continents) is more difficult to deduce. Plate boundaries, even if preliminary, will provide new insights and important constraints regarding the movements of the continents through time.

Our maps are still provisional. Their accuracy will only be measured by how well they explain stratigraphic, tectonic, climatic and biogeographic patterns through time. The authors welcome comments and criticisms of the maps. Larger format copies are available upon request to Scotese; and a computer program for microcomputers can be provided, which will allow users to replot the maps at any scale and in a variety of projections (Scotese & Denham 1987).

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