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The margins of Avalonia

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Abstract – During Cambrian and earliest Ordovician times, Avalonia was an area forming an integral part of the huge Gondwanan continent, probably along the northern margin of Amazonia, until in early Ordovician (late Arenig or Llanvirn) time it split off from Gondwana, leaving a widening Rheic Ocean to its south. Today, its southern margin with Gondwana extends northeast from east of Cape Cod, Massachusetts, through Nova Scotia north of the Meguma terrane, and thence below sea level to the south of Newfoundland. On the eastern side of the present Atlantic, the southern margin may separate southwest Portugal from the rest of the Iberian Peninsula; it can be traced eastwards with more certainty from the south Cornwall nappes to a line separating the Northern Phyllite Belt (on the southern margin of the Rhenohercynian terrane) and the Mid-German Crystalline High. There is no certain evidence of Avalonian crust to the northeast of the Elbe Line. The northern margin of Avalonia extends westwards from south of Denmark to the British Isles, where it merges with the Iapetus Ocean suture between Scotland and England. Traced westwards, it crosses Ireland and reappears in northern Newfoundland to the east of New World Island, where it may follow the trace of the Dog Bay Line and the Cape Ray Fault. Recent work suggests that the northern margin of Avalonia may clip the northern tip of Cape Breton Island in Nova Scotia, and then enter the North American mainland at the Bay of Chaleur; it may then be traced from north and west of the Popelogan and Bronson Hill arcs to Long Island Sound near Newhaven, Connecticut. The Cambrian to Devonian faunas reflect the history of Avalonia: initially they were purely Gondwanan but, as Ordovician time proceeded, more genera crossed firstly the Tornquist Ocean as it narrowed between Avalonia and Baltica to close in latest Ordovician and early Silurian times, and secondly the Iapetus Ocean, so that by the early Silurian most of the benthic shelly faunas, apart from the ostracods, were the same round the adjacent margins of all three palaeocontinents.

1. Introduction

The Palaeozoic continent of Avalonia was first defined by its sequence of Cambrian to Silurian faunas (Cocks & Fortey, 1982); prior to the Llanvirn these were high latitude, in the late Ordovician they were warm temperate, and in the Silurian tropical. Subsequently, Avalonia has been shown to have a palaeomagnetic development which agrees closely with the distinctive latitudinal changes suggested by the faunas (Trench, Torsvik & McKerrow, 1992; Bachtadse *et al.* 1995; Torsvik *et al.* 1996). It is named after the Avalon Peninsula in eastern Newfoundland. Despite the apparent coherence of Avalonia on the basis of biogeography, distinct differences in the late Neoproterozoic–early Cambrian tectonometamorphic development of several arc terranes (Barr & White, 1996) suggest that they were probably not amalgamated before Cambrian times. This Avalonian collage was affected by continuous strike-slip motions during Palaeozoic times, hence Gibbons (1990) referred to it as a superterrane, an interpretation we follow herein.

Existing terranes with Avalonian faunal sequences include some of northern Germany, all of Belgium, England and Wales and much of Ireland (in Europe), and (in North America) the eastern half of Newfoundland, much of Nova Scotia and New Brunswick and eastern New England. These regions have all been studied actively for over two centuries, and much of their stratigraphy has been used as standards for global correlation. Avalonian strata near the localities of Tremadoc, Arenig, Llanvirn, Caradoc, Ashgill, Llandovery, Wenlock, Ludlow, Gedinne, Siegen, Ems, Eifel, Givet, Frasne and Famenne and other places have all been employed as types for series and stages. Some authors (e.g. Ziegler, 1990) have used the terms ‘Western’ and ‘Eastern’ Avalonia for the American and European parts of the palaeocontinent, but, although these are sometimes useful as geographical indicators, we have seen no sustainable evidence that the palaeocontinent was divided into two in this manner, as faunal distributions, such as the ostracods and fish in the late Silurian discussed in Section 3.c, have convinced us that (apart from a narrow strip of arc rocks in the northern Appalachians) Avalonia remained an entity during Ordovician and Silurian times. There is now general consensus about most of the principal terranes which constitute Avalonia; however, the boundaries of the palaeocontinent are in many cases far from clear, and it is the purpose of this paper to locate and review them. Of course most of the terranes comprising Avalonia have had a violent tectonic history since the Lower Palaeozoic, and the present-day margins and shape of the palaeocontinent bear little relationship to the original Ordovician and Silurian geography due chiefly to subsequent internal deformation, strike-slip movements and structural rotations.

2. Faunal changes with time

In Cambrian times the trilobite-dominated faunas found in southern Britain, such as in Warwickshire and Shropshire, are similar and in many cases identical to those found in Newfoundland, Canada. A cladistic analysis of faunas from these and neighbouring areas (Fortey & Cocks, 1992, fig. 3) reveals that from early Cambrian through middle Cambrian and up to early Ordovician times the Avalonian trilobite faunas (South Wales and the English Lake District) clustered with those from Bohemia, France, Spain and Turkey on the southern and eastern margins of Gondwana. This indicates that there was very substantial faunal interconnection between Avalonia and the vast neighbouring continent of Gondwana. These studies are in good agreement with continental reconstructions based on early Cambrian trilobite distributions, facies distributions and limited palaeomagnetic data (McKerrow, Scotese & Brasier, 1992); they show Baltica offshore from Avalonia at 60 °S, and Turkey adjacent to Morocco and southern Europe at lower latitudes. The presence of the trilobite *Bailiella* (Dean, 1985, p. 27) in a clast in the Dunnage Melange (in the Exploits Subzone) shows that Gondwanan fossils in Newfoundland extend as far west as the Red Indian Line and suggest that the Exploits Subzone (the eastern part of the Dunnage Zone) developed near Avalonia. By contrast, the Notre Dame Subzone (the western part of the Dunnage Zone to the west of the Red Indian Line) appears to have developed in the vicinity of Laurentia.

Many early Cambrian small shelly fossils are present in Gondwana (including Avalonia), Baltica and Siberia (Brasier, 1989) and provide supporting evidence for these reconstructions. Early Ordovician rocks in Wales (see, e.g. Fortey & Owens, 1987) yield a rich trilobite fauna which is undoubtedly faunally coincident with the Arenig faunas from Brittany and Bohemia; Shropshire and Bohemian brachiopods in the early Ordovician (Williams, 1974; Havlíček, 1977) are also closely similar. These shelly faunas were in complete contrast to the benthic trilobite and brachiopod faunas of Baltica and Laurentia on account of the wide intervening Tornquist's Sea and Iapetus Ocean (Cocks & Fortey, 1982). However, as Ordovician time went by, the situation slowly changed. By late Llanvirn times (Llandeilian stage), the shallow water brachiopods found in Brittany and Normandy and in the rocks derived from them in Budleigh Salterton, Devon (Cocks, 1993), were in great contrast to those from Wales and the Welsh Borderland (Lockley, 1983), and Avalonia had clearly become separate from Gondwana before that time. In succeeding Caradoc (Fig. 1) and Ashgill times, faunal interchange became progressively more marked, with brachiopod and trilobite genera which had originated in the continents of Baltica and Laurentia becoming more common (see Cocks & Fortey, 1990, fig. 4 for the Caradoc) and also some communality seen in some of the ostracod faunas (Schallreuter & Siveter, 1985). By early Silurian time there were few significant differences between most of the Gondwanan shelly faunas of Avalonia and Baltica and Laurentia. By contrast these Avalonian–Baltic–Laurentian faunas had by this time become markedly different from the Gondwanan shelly faunas, indicating that a widening Rheic Ocean had developed between Avalonia and Gondwana (Cocks & Fortey, 1982). However, although most of the Silurian ostracod faunas of Avalonia and Baltica became the same, they were substantially different from those in Laurentia up to latest Silurian times (Berdan, 1990), indicating that, although brachiopod and trilobite spat were able to cross the narrowing Iapetus Ocean, it was a seaway still deep enough to act as an effective barrier to young ostracods, which did not go through a pelagic stage. In contrast, by early middle Devonian times, the faunal evidence indicates that Avalonia was inseparable from Baltica and Laurentia and merely represented the seaboard margin of the large palaeocontinent of Laurussia.

3. The boundaries of Avalonia

In late Precambrian times, the northwestern margin of Gondwana was active, with calc-alkaline igneous activity extending from South America, through Avalonia to west Africa and central Europe. The presence of late Proterozoic arc rocks cannot generally be used to distinguish the different parts of this long margin, but distinctions are seen in the later Palaeozoic sedimentary facies. In the early Cambrian, Avalonia was dominated by clastic sediments with a distinctive low diversity shelly fauna, including olenellid trilobites, which was in marked contrast to the archaeocyathan-bearing carbonates of Morocco (Courjault-Rade, Debrenne & Gandin, 1992; McKerrow, Scotese & Brasier, 1992) and also the southern European distribution of bigotinid trilobites (Pillola, 1993). These facies indicators and also provenance studies (Nance & Murphy, 1994; van Staal, Sullivan & Whalen, 1996), together with palaeomagnetic evidence (Trench, Torsvik & McKerrow, 1992) suggest that, prior to its separation from Gondwana in the early Ordovician, Avalonia formed the part of Gondwana adjacent to Florida and the Amazonian craton. There is, however, little control of palaeolongitude, and other positions within Gondwana are possible. This South American position is in contrast to the original position speculated by, for example, Cocks & Fortey (1982) and repeated by many authors, for example, Pickering & Smith (1995), who placed Avalonia somewhat arbitrarily close to its present position, with England near the Armorican Peninsula of France. Pickering & Smith (1995) also placed Avalonia, Gondwana and Baltica far too closely together in early Ordovician time, particularly in view of the very disparate cratonic faunas of the latter two palaeocontinents.

During much of Ordovician time, the eastern and northern margins of Avalonia were active, related to subduction of both Tornquist's Sea and the Iapetus Ocean. These oceans eventually closed when Avalonia collided

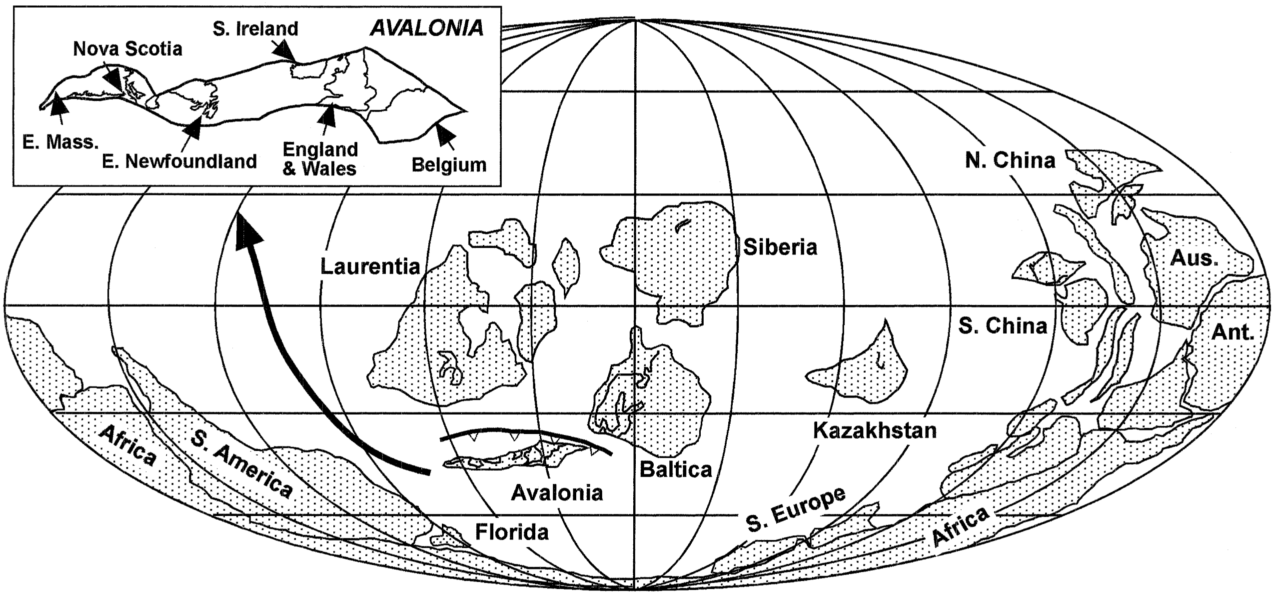

Figure 1. The world in mid-Caradoc time (455 Ma) showing the position of Avalonia. To the north of Avalonia, the Bronson Hill–Popelogan–Victoria–Grangegeeth arc is indicated (for location of outcrops see Figs 2 and 3).

with Baltica, probably in the Ashgill, and with Laurentia in the Llandovery or Wenlock. By middle Ordovician time, Avalonia became separated from Gondwana as the Rheic Ocean opened behind it (Fig. 1). We relate the Lake District arc and its temporal equivalents in eastern England (Noble, Tucker & Pharaoh, 1993) to subduction of Tornquist's Sea, since there is no temporal equivalent in the northern Appalachians in a similar tectonic setting. Avalonian benthic faunas started to mix with Baltic faunas in the Caradoc (Cocks & Fortey, 1982); subsequently, the cessation of the Lake District arc during the Ashgill may be interpreted as the beginning of collision between these continents.

In the northern Appalachians, the Avalonian margin became active during the late Arenig, but this magmatic arc was soon split (van Staal, 1987; van Staal, Winchester & Beddard, 1991; van Staal, Sullivan & Whalen, 1996) and started to move northwards more rapidly than the remainder of Avalonia (van Staal, 1994). In the northern Appalachians, this narrow strip is referred to as the Popelogan arc in New Brunswick and Maine, and the Victoria arc in Newfoundland; they are closely associated with some isolated late Neoproterozoic to early Cambrian arc plutons (van Staal, Sullivan & Whalen, 1996; Evans, Kean & Dunning, 1990). These plutons may represent the basement to the Popelogan–Victoria arcs. Such a relationship is consistent with palaeomagnetic data from the remnant part of the Popelogan arc in the Miramichi Highlands of New Brunswick (Liss, van der Pluijm & van der Voo, 1994) and also the presence of inherited Precambrian zircons in the Llandeilian (*c*. 462 Ma) calc-alkaline rhyolites of the Victoria arc (Dunning *et al.* 1987), and Pb-isotope studies (Swinden & Thorpe, 1984).

The individual margins of Avalonia are now reviewed in turn.

3.a. The southern margin

The Rheic Ocean probably originated in early Ordovician times, when Avalonia separated from the South American part of Gondwana, but the precise age of rifting is uncertain. Avalonia shows strong faunal affinities with Gondwana in the early Ordovician (Fortey & Cocks, 1992), and Sm–Nd studies on British sediments, particularly the mature quartzites, suggest derivation from a large continent throughout Tremadoc time (Thorogood, 1990) when calc-alkaline igneous rocks first appeared in the Ordovician of Wales. It is possible that the Arenig Stiperstones quartzite of Shropshire in the Welsh Borderland was also derived from Gondwana and that final rifting did not occur until late Arenig times. We know that Avalonia was palaeontologically distinct from Gondwana by the Llandeilo (Cocks & Fortey, 1982), when separation would have been greater than the range of most pelagic larvae (perhaps about 1000 km) and the two palaeocontinents had moved into different palaeolatitudinal belts. Once the Rheic Ocean had opened, the majority of shallow marine faunas on either side remained distinct until early Devonian time, but the non-marine fish (Young, 1990) and spores (Pflug & Prössl, 1991) did not get across until Emsian time. Thus the Rheic suture can be defined by most faunas between the Llandeilo and the Pragian and by non-marine organisms until the Emsian.

The Rheic suture today (Fig. 2) is largely covered by younger sediments. In Britain it lies to the south of the abundant Avalonian Cambrian to early Devonian marine and non-marine faunas of South Wales and the fish-bearing early Devonian Dartmouth Beds of south Devon (White, 1956; Dineley, 1966) and to the north of the Gondwanan marine faunas of the south Cornish nappes;

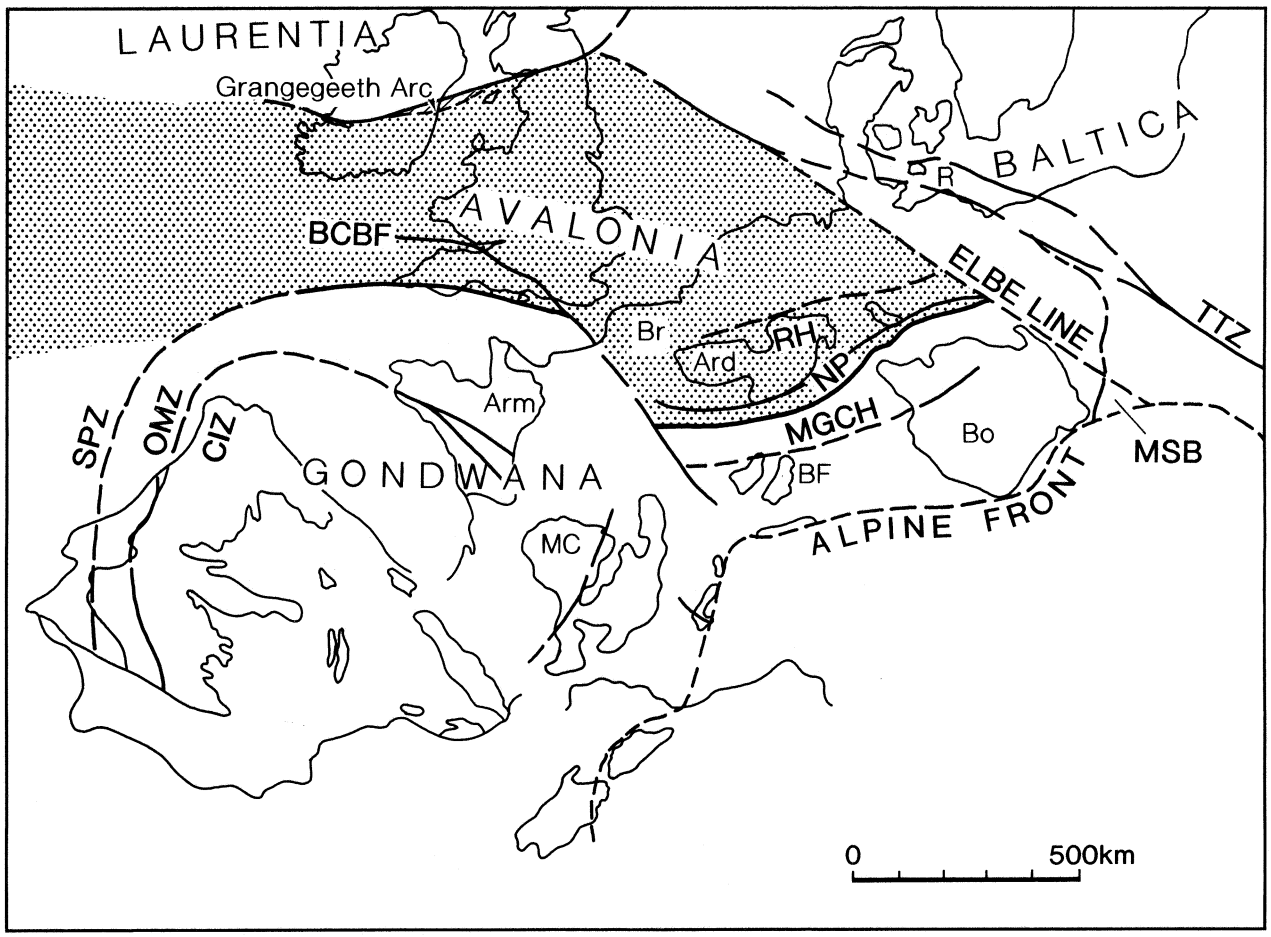

Figure 2. Central Europe before the Alpine Orogeny showing the Palaeozoic terrane boundaries (base map modified from a number of sources, including Franke, Dallmeyer & Weber (1995) and Holder & Leveridge (1986)). Ard – Ardennes; Arm – Armorica; BCBF – Bristol Channel– Bray Fault; BF – Black Forest; Bo – Bohemia; Br – Brabant Massif; CIZ – Central Iberian Zone; MC – Massif Central; MGCH – Mid-German Crystalline High; MSB – Moravo-Silesian block; NP – Northern Phyllite Belt; OMZ – Ossa-Morena Zone; R – Rügen; RH – Rhenohercynian Zone; SPZ – South Portugese Zone; TTZ – Tornquist-Teysseyre Zone.

the faunas in the latter are also present in Brittany and elsewhere in France and throughout the Iberian Peninsula (Cocks, 1993). The suture passes east from south Cornwall, below Mesozoic and younger beds. It probably extends along the English Channel as far as the dextral Bray Fault (Holder & Leveridge, 1986, fig. 1).

To the east, the Rheic suture emerges from beneath the Paris Basin to the south of the Ardennes, whose Silurian acritarchs are like Britain and the Baltic, and distinct from Gondwana (Verniers & van Grootel, 1991). The Brabant Massif, north of the Ardennes, has a distinctive stratigraphy and structure indicating that it has not always been immediately adjacent to the Ardennes (Delvaux de Fenffe & Laduron, 1991). Like much of Avalonia, these Belgian terranes have undergone considerable strike-slip faulting. The Rhenohercynian belt to the south and east of the Ardennes has intermittent outcrops ranging from the Rheinisches Schiefergebirge through the Harz mountains to near Magdeburg, Germany. Most of the autochthonous parts of this region were probably part of Avalonia, because early Devonian non-marine fish in the Taunus Massif in the south of the Rhenisches Schiefergebirge (Anderle, 1987) belong to typical English species well known from the margins of the Old Red Sandstone continent (White, 1956). The Northern Phyllite Belt, south of the Taunus Massif (Fig. 2) consists of Ordovician and Silurian turbidites overlain by andesites. These rocks are comparable with contemporary rocks of southeastern England (Pharaoh *et al.* 1991) and thus appear to lie on the southern edge of Avalonia, but there is no direct evidence to support this.

In the Rhenohercynian belt, Silurian to Pragian carbonates of the Lindener Mark, near Giessen and north of the Taunus, trilobites and ostracods are found with undoubted affinities to Bohemia and Northern Africa (see, e.g. Schallreuter, 1991). These latter deposits are suspected to be from nappes derived from the south at the time of eventual fusion in the late Devonian to early Carboniferous and which appear to have been transported northwards across the Rheic suture. To the south, the mid-German Crystalline High, which is a Silurian metavolcanic arc from which no guide fossils are known, is of a much higher metamorphic grade than the Northern Phyllite Belt or other adjacent parts of Avalonia including

Belgium and southeast England. Franke, Dallmeyer & Weber (1995) believe that the Rheic Ocean closed in Ordovician times and that a subsequent ocean, which they term the Rhenohercynian, opened in Devonian times, but this concept is contradicted by the faunal evidence which shows clearly that the Rheic remained open all through late Ordovician and Silurian times (Cocks & Fortey, 1982) and that non-marine fish did not cross from Avalonia to Gondwana until the Emsian (Young, 1990). This is strongly supported by the palaeomagnetic evidence (Bachtadse *et al.* 1995) which shows Avalonia and Gondwana to be very substantially separated until their merger in mid-Carboniferous times.

The Rheic suture can only be traced intermittently in westernmost Europe. There is increasing evidence that, once the Mesozoic and later tectonic effects have been eliminated, the zones of the Iberian Peninsula can be correlated with the deposits of Brittany, with the exception of the westernmost South Portugese Zone. This latter zone, which has been correlated with the Rhenohercynian Belt of Germany by, for example, Oczlon (1992, p. 22) and Franke, Dallmeyer & Weber (1995, p. 581) may indeed include fragments which were originally part of Avalonia, but the hypothesis is untestable palaeontologically in the Lower Palaeozoic since the earliest known fossils from the area are of late Givetian age. In addition, most of the rocks seem to have been deposited as calc-alkaline intrusives above a subduction zone (Schütz, Ebneth & Meyer, 1987), and thus it is possible that the whole zone may have only originated after Avalonia ceased to be a separate continent.

Off the east coast of North America, the Rheic suture is mainly covered by sea. It lies to the south of Newfoundland and offshore from the Avalonian terranes in New Brunswick and New England (Fig. 3). In Nova Scotia, however, the Meguma terrane had a distinct pre-Devonian development from Gondwana (Keppie, 1985) though it shares similar early Devonian granitoid plutons. The Meguma terrane contains *Paradoxides* and other Middle Cambrian trilobites not known from early Palaeozoic Laurentia. If it was derived from Gondwana independently from Avalonia (Schenk, 1983), the Minas Fault (Keppie, 1982) seems to mark the southern margin of Avalonia in Nova Scotia.

All other Gondwanan crust today in North America, including Florida and the Carolina terranes, appears to have been accreted in the Carboniferous Alleghanian orogeny (Rodgers, 1988; Nance & Murphy, 1994), so there is no evidence for Avalonia extending to the south of Rhode Island.

3.b. The northern margin

During Cambrian and early Ordovician times, the Iapetus Ocean was wide enough to separate all the platform benthic faunas on Laurentia and Avalonia (Cocks & Fortey, 1990). Subsequently, after the Llanvirn, there was a progressive migration of genera across the ocean through time (McKerrow & Cocks, 1976). The fact that genera migrated across Iapetus before species (a true rather than a monographic phenomenon) is probably explained by progressive island-hopping across palaeolatitudes with no immediate survival of larvae between the two palaeocontinents (Neuman, 1984). Many deeper-water species got across the ocean before most platform species (Fortey, 1975; Fortey & Cocks, 1992); this was because ocean waters below the thermocline are relatively uniform across latitudes.

By the latest Caradoc, many brachiopod and trilobite species had been able to cross the ocean, so that, in Silurian times, faunal distinctions across Iapetus can only be made using less mobile animal groups: non-marine fish did not cross Iapetus until the Ludlow (Turner & Turner, 1974; Young, 1990), while benthic ostracodes were distinct until Emsian times (Berdan, 1990). Thus palaeontolological indicators of the suture between Avalonia and Laurentia are much more evident in the earlier Palaeozoic, but a few indicators persist in certain shallow water and non-marine environments until early Devonian times.

The northern boundary of Avalonia lies very close to the border between England and Scotland. To the south in England, the Lake District has typical Avalonian faunas in the early and middle Ordovician, while in Scotland the northern and central belts of the Southern Uplands contain some Laurentian benthic faunas (McKerrow & Soper, 1989; Owen, Harper & Clarkson, 1996).

In Ireland and the northern Appalachians, the Avalonia–Laurentia suture is more complicated. This is partly the result of the Caradoc/Ashgill accretion of the Popelogan–Victoria arc system to Laurentia, which was then followed by the Llandovery/Wenlock accretion of Avalonia to Laurentia. For example, the Caradoc arc-related basalts and andesites of the Grangegeeth terrane of eastern Ireland (Winchester & van Staal, 1995) lie immediately south of the Navan-Silvermines fault, which has been the purported Iapetus suture. Sediments interlayered with the Grangegeeth volcanic rocks contain Caradoc Scoto-Appalachian shelly faunas, whereas Arenig rocks in the same sequence contain high latitude Atlantic province graptolites (Harper *et al.* 1990). This apparent change in biogeographic affinity is also shown by the Popelogan–Victoria arc systems in Canada, where it has been ascribed to northward drift during Ordovician times (Williams, Boyce & Colman-Sadd, 1992). Hence we can now interpret the Grangegeeth terrane as the equivalent of the middle to late Ordovician Popelogan–Victoria arc system to Laurentia, which was then followed by the Llandovery/Wenlock accretion of Avalonia to Laurentia. The Slane Fault, which separates the Grangegeeth terrane from the Bellewstown terrane with its Anglo-Welsh faunas (Brenchley *et al.* 1977) is thus part of the Iapetus suture zone.

The Popelogan–Victoria arc continues into Maine (Winchester & van Staal, 1994) and is along strike, and probably equivalent to the Bronson Hill arc in southern

New England. Late Proterozoic (613 Ma) basement in the Pelham Dome and detrital mineral suites in associated quartzites (Robinson & Tucker, 1996) resemble the basement of the remnant of the Popelogan arc in the Miramichi Highlands (van Staal, Sullivan & Whalen, 1996 and references therein). Thus Avalonia, as now defined, includes a wide swathe of terranes extending from the Avalon Peninsula of eastern Newfoundland to the Bronson Hill Arc (east of the Connecticut Valley) in New England.

Biogeographic assessment of Avalonia (and of the arcs now known to be linked to it) has been the subject of some discussions. The most useful distinctions are in the differences between the early Ordovician warm-water faunas of Laurentia and the cold-water faunas of Avalonia. As the Ordovician progressed, the separation between the two continents decreased and they both acquired warm environments. Warm-water Arenig–Llanvirn conodonts occur in the Buchans Group (Nowlan & Thurlow, 1984), which is situated immediately to the west of the Red Indian Line (Fig. 3). In Avalon, coastal New Brunswick and Maine, the Cambrian and early Ordovician faunas and facies are consistent with a position adjacent to Gondwana near the South Pole (Fortey & Cocks, 1992).

Most of the Arenig and early Llanvirn brachiopods which occur on Avalonia have been referred to the so-called 'Celtic Province'. This is a collection of genera which include a mixture of pandemic and endemic forms, the latter often occurring at only one or two localities (Neuman, 1984). They do not form a coherent faunal province (Cocks & McKerrow, 1993; Neuman *et al.* 1994) and are not all diagnostic of Avalonia, although the endemic forms which have been assigned to the 'Celtic Province' are all absent in Laurentia.

Another example of complex relationships between terranes with Avalonian and Laurentian faunas is seen in New World Island on the north coast of Newfoundland. Here undoubted Laurentian faunas occur in the Llandeilian Cobbs Arm Limestone of the Summerford Group (McKerrow & Cocks, 1977). By contrast, the early Ordovician parts of the Summerford Group have facies and faunas (including *Bailiella* in the adjacent Dunnage melange) which suggest that this terrane was at high southerly latitudes before moving north, where low-latitude Laurentian faunas prevailed by Llandeilian times. These outcrops occur south of the Lukes Arm Fault, which is now thought to be a continuation of the Red Indian Line (Williams, Colman-Sadd & Swinden, 1988); it is thus clear that the independent mobility of certain arcs and volcanic islands will now entail a separate migration path within each individual terrane.

3.c. The eastern margin

To the west of the North Sea, the Avalonian plate lies south of Laurentia, while to the east (in northern Germany) it lies south of Baltica (Fig. 2). Below the North Sea, the regional Palaeozoic rocks are poorly known. Ordovician Avalonian arc-related volcanic rocks are present in the western North Sea and in eastern Britain (e.g. Pharaoh *et al.* 1991) and are overlain by contemporary Silurian sediments, now concealed (Woodcock & Pharaoh, 1993). East of Avalonia the best-known and most prominent modern structural feature is the Tornquist-Teysseyre Zone, the northernmost component of the Trans-European Suture Zone, which was originally confused by Cocks & Fortey (1982) with the suture zone between Avalonia and Baltica, hence leading to the naming of Tornquist's Sea or Ocean between the two palaeocontinents in the Ordovician. However, the true position of the Trans-European Suture Zone is now much better defined, and is seen to lie to the north of cratonic rocks in Poland (e.g. the Upper Orthid Sandstone of the

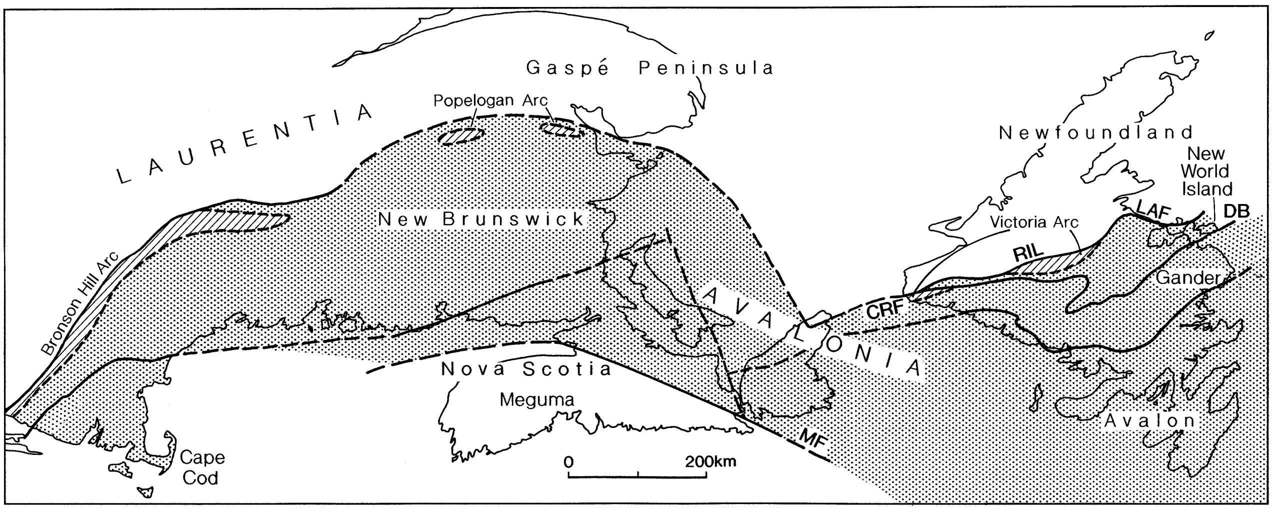

Figure 3. The Avalonian terranes in the northern Appalachians. The relationship of the early Ordovician Bronson Hill, Popelogan and Victoria arcs to Avalonia is discussed in the text. CRF – Cape Ray Fault; DB – Dog Bay Line; LAF – Lukes Arm Fault; MF – Minas Fracture; RIL – Red Indian Line.

Mójcsy Anticline in the southwestern part of the Holy Cross Mountains) which bear clastic Arenig rocks with a brachiopod fauna dominated by such genera as *Antigonambonites* and *Lycophoria* which were undoubtedly deposited in shallow waters on the craton of Baltica, indicating that the suture closing Tornquist's Sea lay to the southwest.

From a review of well data, geophysics and palaeontology, Tanner & Meissner (1996) have concluded that the southern margin of Baltica may extend as far as the Elbe Line, some 300 km southwest of the Tornquist-Teysseyre Zone (Fig. 2). Franke (e.g. 1989) shows several tracts of the Rhenohercynian terrane crossing the Elbe Line. There may well be some extensions of this terrane to the northeast of this line, but no definite Gondwanan or Avalonian faunas are known to us from northeast of the Elbe Line.

Lewandowski (1994) has provided evidence for post-Silurian dextral strike-slip movements in the Holy Cross Mountains and in the Upper Silesia Massif of southern Poland. This data would suggest that any continuation of Avalonia across the Elbe Line is likely to be found to the southeast along the line of this Variscan fracture zone. Oliver, Corfu & Krogh (1993) record Baltic faunas immediately north of the Elbe Line in Upper Silesia; they also show that the basement rocks of this area are distinct from those of Bohemia.

The classic area of Bohemia, in the Czech Republic, shows consistent faunal affinities with Gondwana during early and middle Ordovician times (Cocks & Fortey, 1990) although palaeomagnetic data suggest that it moved independently of Gondwana in Silurian and Devonian times (Tait, Bachtadse & Soffel, 1994), and a faunal review has suggested that it might have formed a separate microplate in the Ordovician which Havlíček, Vaněk & Fatka (1994) have termed Perunica. Thus, both faunal and palaeomagnetic evidence indicate that Bohemia was quite separate from Avalonia during late Ordovician and early Silurian times.

There are two further areas outside these defined limits of Avalonia, but which have been attributed to it. The first are deposits underlying the island of Rügen in the southern Baltic (Fig. 2), where boreholes underlying the outcropping Mesozoic and Cenozoic rocks penetrated folded rocks up to 3000 m thick, ranging in age from probable late Cambrian and certain Tremadoc up to the early Caradoc, underlying undeformed Devonian and Carboniferous sediments (Giese, Katzung & Walter, 1994; McCann, 1996). These authors correctly interpret the Rügen rocks as having been deposited in the Tornquist Ocean, but all the fossils found, chiefly graptolites and acritarchs, are planktonic, and evidently deposited in waters too deep to support the shallow-water shelly benthos which might have proved distinctive in attributing an origin to any particular continent. The acritarchs were considered by Servais & Katzung (1993) to be of Avalonian affinity, but these microfossils can only indicate latitudinal positioning rather than defining links with a palaeocontinent. Giese, Katzung & Walter (1994) detailed petrographic provenance studies appear to deny Gondwana as a source area for the Rügen sandstones, since no warm-water early Ordovician carbonates are known from Gondwana and the carbonate grains which they record suggest to us that perhaps these deposits were lain down as deeper-water turbidites bordering the lower-latitude Baltica, in contrast to the much thinner Ordovician deposits of Bornholm and Scania which were deposited in pericontinental shallower-water basins around the same palaeocontinent.

To the east of Bohemia, in the Upper Sudetes of south Poland, the Moravo-Silesian block contains rocks in the Jeseniky Mountains which have been compared with the Rhenohercynian Belt, in particular to the southeast part of the Rheinische Schiefergebirge (Dvorak, 1989). However, the Lower Palaeozoic faunas known from the area include *Holmia* and other Lower Cambrian trilobites of certain Baltic affinity from the Goczalkowice borehole in Upper Silesia (Orlowski, 1975), and we do not regard this block as belonging to Avalonia.

4. Conclusions

The palaeocontinent of Avalonia was relatively small, although it possessed within it a large number of standard stratigraphical type areas. It also had a relatively short independent life, from its high latitude rifting with northern Gondwana in the early Ordovician to its low latitude collision with Baltica in Ashgill and Laurentia in the Silurian. Despite the wealth of knowledge on much of it, for example, Wales and the Welsh Borderland, the disentangling of its various terrane boundaries on the two sides of the modern Atlantic is much complicated by later tectonic episodes and by the masking of the Palaeozoic sutures by later rocks and modern oceans and seas. The palaeocontinent has been recognized as a separate entity for only the past twenty years, and although since then much work by many people in diverse countries has contributed to our knowledge and this summary, much remains to be done in finally identifying the modern sites of Avalonia's ancient margins. The correct analyses of the fossil faunas present in Avalonia and its surrounding palaeocontinents will form critical elements in this future work.

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