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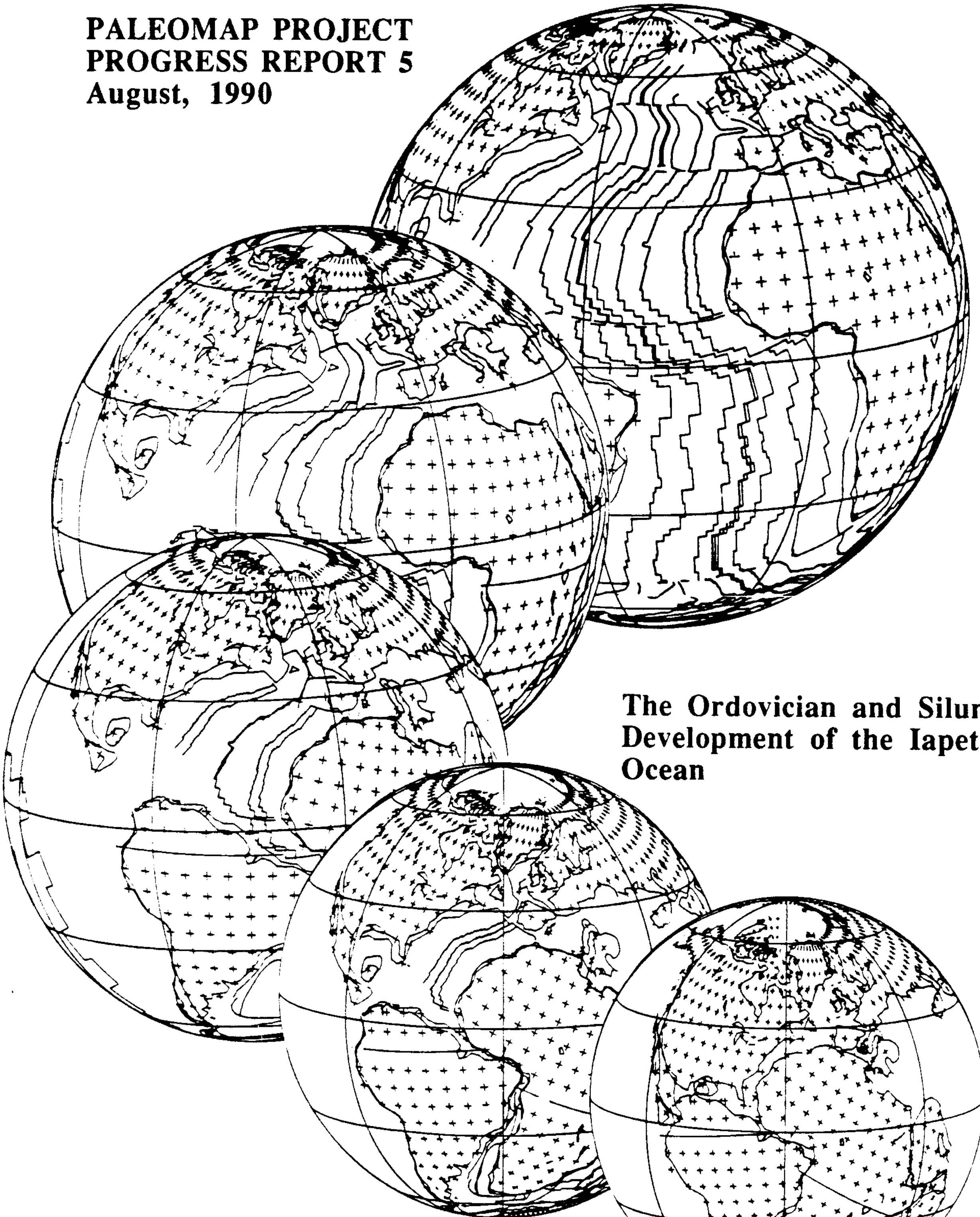

The Ordovician and Silurian Development of the Iapetus Ocean

by

W. S. McKerrow, J. F. Dewey, and C. R. Scotese

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THE ORDOVICIAN AND SILURIAN DEVELOPMENT OF THE IAPETUS OCEAN

by W. S. MCKERROW, J. F. DEWEY *and* C. R. SCOTESE

ABSTRACT. Iapetus was a complex multiphase ocean surrounded by very different types of margins and marginal platforms. To the south, the Cadomian active margin on the north of western Gondwana had already existed for a long time prior to the Cambrian. To the north, the Laurentian margin originated by late Precambrian (600 Ma) rifting; the rifting continent may have been Baltica or Siberia. The thick Dalradian sequences on the Laurentian margin preceeded this rifting event. A second episode of rifting occurred in the Tremadoc, when small slivers of marginal continental crust became detached, and a dextral transform/ridge complex developed forming the Neo-Iapetus Ocean. The south-east boundary of Neo-Iapetus converted almost immediately into a north-west-facing arc and subduction zone. This arc, with its ophiolitic fore-arc, then collided diachronously with Laurentia causing the successive Athollian (i.e. late Grampian)/ Humberian/Taconian orogenies from the early Ordovician to the Caradoc. The arc collision resulted in a polarity flip, which marked a change from dextral to sinistral motion along the Laurentian margin of Iapetus, and by the end of the Llandeilo, subduction–accretion started in the (Southern Uplands) fore-arc of the new south-facing arc. In this fore-arc, sediments derived from the north-east are believed to have had a provenance in the Mongolian arc on the north margin of Siberia, as Laurentia had no suitable orogenic source area. Oblique convergence of Iapetus with laurentia resulted in the north-east movement of several small terranes along the Laurentian margin in Ireland and Scotland. In the Tremadoc, volcanics appear in north-east Avalonia and reflect the subduction of the Tornquist Sea and the rifting of Avalonia from Gondwana margin of Iapetus. Baltica also moved north during the Ordovician, but Avalonia moved more rapidly and the intervening Tornquist Sea closed in the Ashgill. Iapetus closed with three successive collisions on the eastern margin of Laurentia: Barentsia with north-east Greenland in the late Llandovery; Baltica with Scotland in the Ludlow (Scandian Orogeny); and Avalonia with southern Scotland, north-west Ireland, the Maritimes and New England in the Emsian/Eifelian (Acadian Orogeny). The last phase of closure, between Avalonia and the Laurentian margin soutn-east of Scotland, probably involved some subduction of Avalonian continental crust with rapid late Silurian subsidence in northern England and central Ireland.

THE evolution of the Iapetus Ocean is described here in conjunction with a series of fundamental kinematic and dynamic 'rules' of plate tectonics that are based on the interpretation of present day plate motions and the tectonic settings of different igneous and sedimentary sequences. These rules must guide all palaeogeographical reconstructions, because, without them, there are no viable constraints. The maps (Text-figs 1–6) show suggested slip vectors between the main plates in sequential reconstructions from the early Ordovician (Tremadoc) to the end of the early Devonian (Emsian).

EARLY ORDOVICIAN

Palaeozoic world maps based on palaeomagnetism, palaeobiogeography and climatically-related lithofacies (Scotese and McKerrow 1990) show that, in the early Ordovician Period, the Iapetus Ocean (Text-fig. 1) was bounded by Laurentia to the north, by Baltica to the south-east, and by western Gondwana to the south-west; Siberia (with its modern Arctic coast towards the south) lay about 1,000 km to the north-east of Greenland on the eastern margin of laurentia (Text-fig. 1).

Warm water carbonates are absent in Baltica and western Gondwana, consistent with their higher southerly latitudes, while Laurentia is largely covered by warm water carbonates consistent with its

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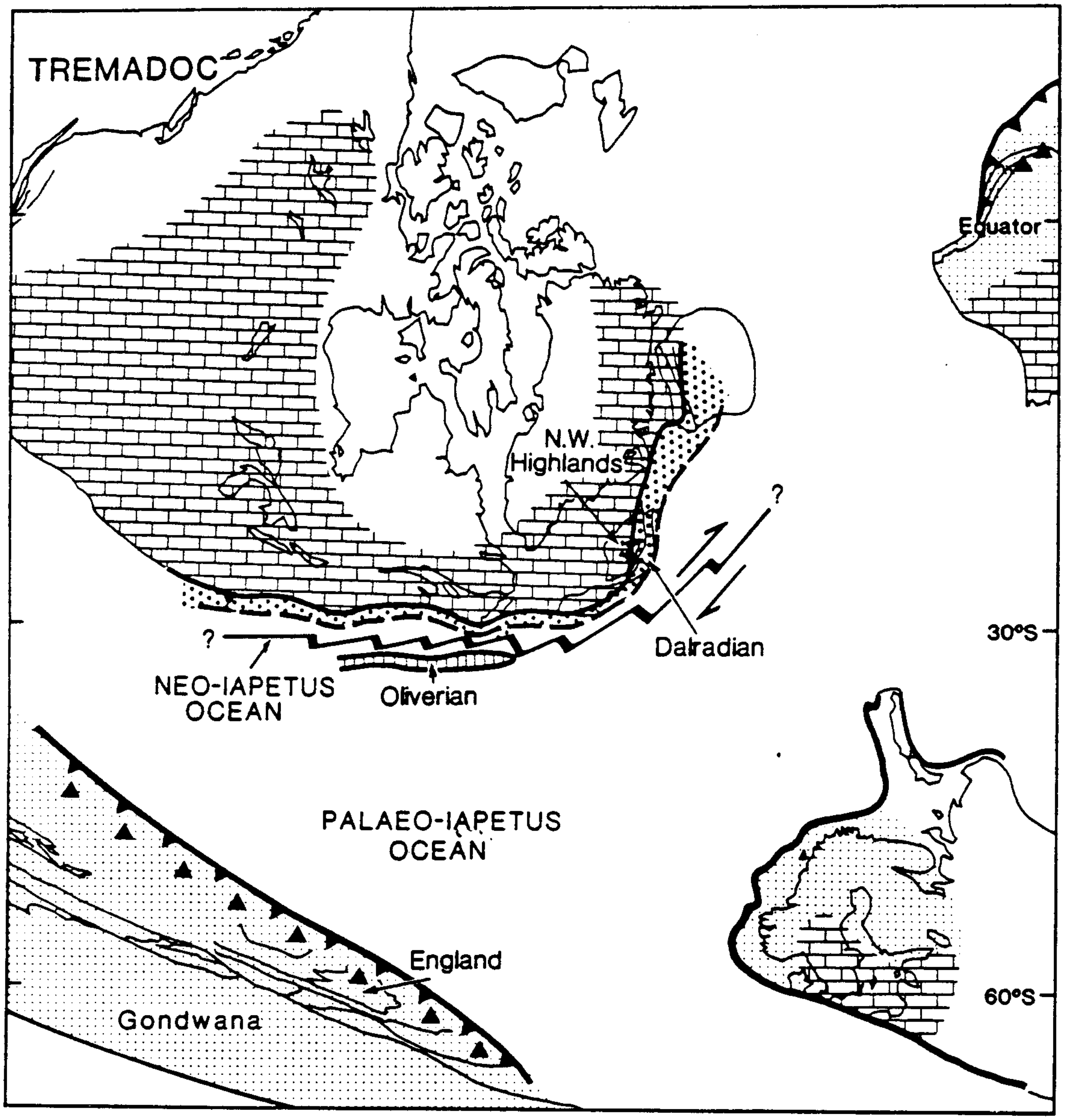


TEXT-FIG. 1. In the Tremadoc Epoch, the long-fracture-zone/short-ridge system in the Neo-Iapetus was separated from Palaeo-Iapetus by the Oliverian/Midland Valley continental sliver. Laurentia was covered by a carbonate platform (brick ornament) but had thick clastic sediments along its eastern margin (coarse dots), which include the Hecla Hoek sequences of Svalbard. Active margins were present in the Mongolian arc, on the north of Siberia, and in Avalonia, on the northern margin of western Gondwana; other margins were passive. Fine dots represent shelf clastic sediments.

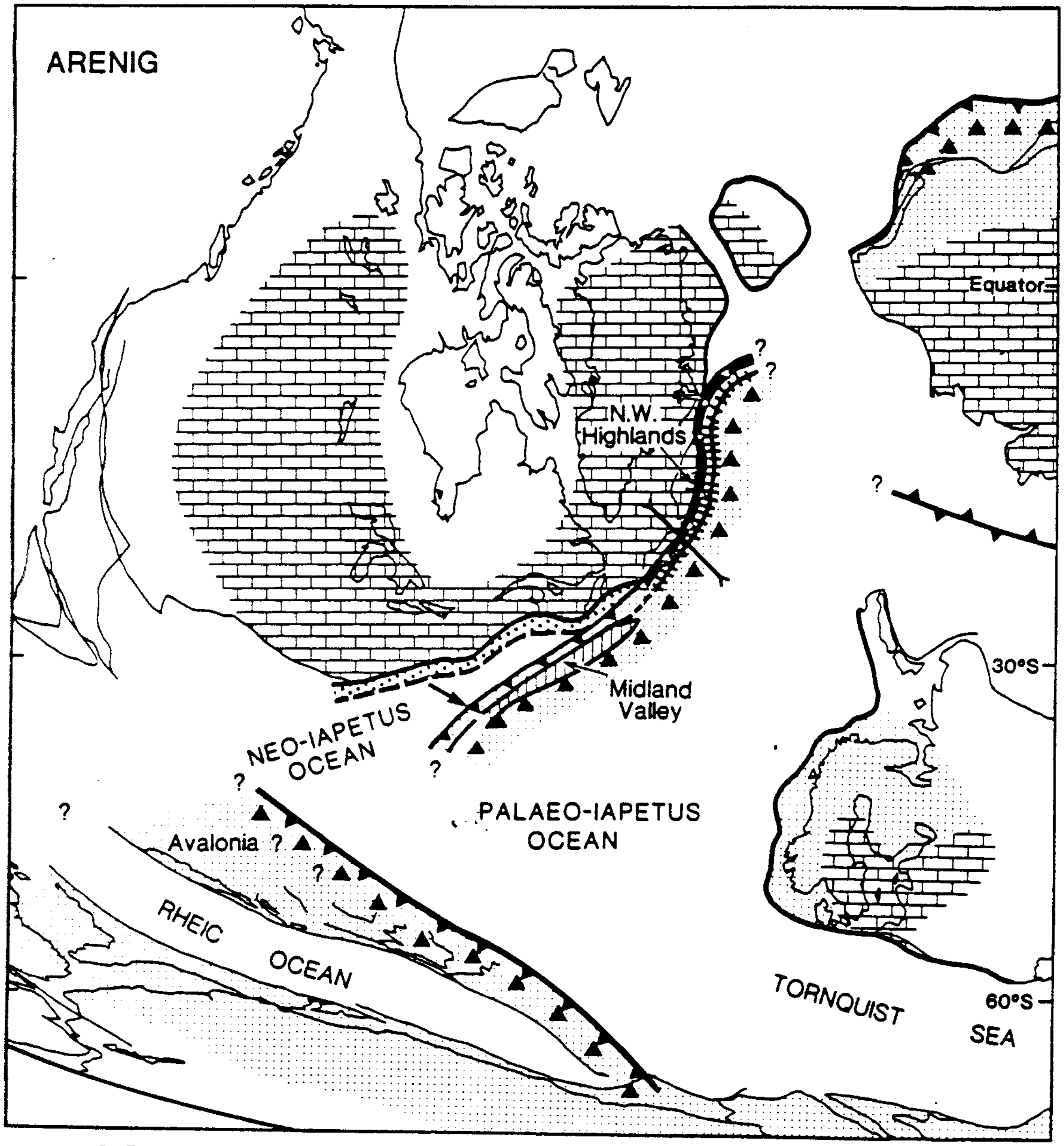
equatorial position. All the early Ordovician continents were bordered by deeper water slope and offshore deposits with a characteristic isograptid graptolite fauna (Fortey and Cocks 1986). Usually, these marginal deposits accumulated slowly but, in the British Isles and East Greenland, the Laurentian margin is marked by very thick late Precambrian sequences: the Dalradian Supergroup in Scotland (Harris *et al.* 1978) and the Eleonore Bay and Tillite groups in East Greenland (Henriksen 1985). The Hecla Hoek sequences of Svalbard (Harland 1985), and the typically laurentian early Palaeozoic biofacies, suggest that the thick deposits of the Laurentian margin continued along eastern Svalbard prior to the mid Ordovician, and perhaps underlie much of Barentsia (the Svalbard–Barents Sea continent).

The Palaeo-Iapetus Ocean did not develop until well after most of the Dalradian and equivalent sequences had been deposited. Its opening, at about 600 Ma, was marked by the eruption of the Lighthouse Cove and Tayvallich volcanics in western Newfoundland and Scotland (Strong 1974; Graham 1976). This opening was due perhaps to the rifting of a continent (?Baltica or Siberia) from Laurentia. The thick sedimentary sequences, which later marked the early Palaeozoic margin of Laurentia, appear to have developed during a pre-rifting extensional stage prior to 600 Ma; both the high stratigraphical position of the 600 Ma Tayvallich Volcanics in the Dalradian sequence (Harris *et al.* 1978) and the 590 Ma age for the Ben Vuirich granite (Rogers *et al.* 1989) suggest that the Dalradian sequence had a prolonged pre-rifting history. We accept the suggestion of Rogers *et al.* that the term Grampian Orogeny be restricted to the earlier (590 Ma) event, and that the term Athollian Orogeny be applied to the Tremadoc (c. 500 Ma) deformation of the Dalradian.

The Athollian Orogeny was the result of closure of the Neo-Iapetus Ocean, which developed long after the 600 Ma Palaeo-Iapetus. During Late Cambrian or earliest Ordovician times (?530–510 Ma), a thin strip of continental crust rifted from the edge of Laurentia and generated a narrow ocean by dextral motion along the Palaeo-Iapetus margin (Karson and Dewey 1978). This Neo-Iapetus Ocean developed an east-dipping subduction zone on its western margin which built the Oliverian–Midland Valley island arc (Text-fig. 1). This arc is exposed in New England (Bronson Hill), New Brunswick (Tetagouche) and Newfoundland (Lushs Bight) (McKerrow 1988*a*), but its presence in the Midland Valley is surmized only from large boulders in a shallow water conglomerate near Girvan (Bluck 1984). It may have extended northward to the east of East Greenland, and may then have been emplaced on Norway in the Scandian Orogeny (Gale and Roberts 1974; Stephens and Gee 1985; Roberts 1988). This subduction zone was nucleated partly along the western margin of a thin slice of continental crust, but was developed largely by the growth of a subduction complex along the margin of the Neo-Iapetus oceanic long-fracture-zone/short-ridge system (Karson and Dewey 1978; Casey and Dewey 1984; Dewey and Shackleton 1984).

Avalonia consisted of continental crust, which includes part of the late Precambrian Cadomian arc. It extends from coastal New England, through coastal New Brunswick, Nova Scotia and the Avalon Peninsula of eastern Newfoundland to south-east Ireland, Wales, England and the Ardennes. Prior to the Ordovician period, Avalonia formed part of the northern margin of Gondwana (Cocks and Fortey 1982), perhaps adjacent to the present north-west African coast (Text-fig. 1). At some time during late Cambrian or earliest Ordovician times, Avalonia rifted off Gondwana, opening a back arc basin that developed into the Rheic Ocean (Text-fig. 2). The earliest calc-alkaline volcanics (Rhobell Volcanic Complex) in eastern Avalonia appear in the late Tremadoc of Wales (Kokelaar *et al.* 1984). In Avalonia, Ordovician arc rocks are present only in the north-east, from Ireland to the Ardennes (Stillman 1988; Andre' *et al.* 1986); their absence in the Avalonian parts of the Canadian Maritime Provinces and New England may possibly be explained by subduction of continental crust during the Silurian and early Devonian (see p. 000).

Our maps (Text-figs 1–6) differ from many previous reconstructions in that they show Siberia close to the north-east margin of Iapetus; we now consider that the tectonic development of Siberia affected the development of the Caledonides. Palaeomagnetic (Khramov *et al.* 1981) and faunal (McKerrow and Scotese 1990) evidence suggests that the present day Mongolian margin was facing north and that its Ordovician and Silurian latitudes were similar to those of the Canadian Arctic archipeligo. During the late Precambrian and early Palaeozoic the Mongolian margin was an Andean-type arc (Mossakovsky and Dergunov 1985). It is possible that the Hecla Hoek, Eleonore Bay and Dalradian sequences were derived from Siberia as, in the Vendian, Laurentia had no obvious mountain range to provide such a copious supply of clastic sediment. However, the



TEXT-FIG. 2. By the Arenig Epoch, the Oliverian/Midland Valley terrane had collided with Laurentia in Scotland (Athollian Orogeny), but not yet farther south-west. Westward subduction of Neo-Iapetus produced an arc in the Oliverian/Midland Valley terrane. Avalonia had rifted from western Gondwana with the formation of the Rheic Ocean.

evidence that the Mongolian arc supplied clastics to the margins of Laurentia in the late Precambrian is not as strong as it is in the Ordovician and Silurian (see p. 000).

In the Arenig Epoch, Baltica moved north, closer to Siberia, presumably with subduction of the intervening ocean. The margins of these continents which bordered this ocean appear to have been passive, so we show a possible oceanic arc (Text-fig. 2).

During the early Arenig, the transform/ridge boundary that generated the Neo-Iapetus Ocean converted to a south-east dipping subduction zone bounding a north-west facing arc (Karson and Dewey 1978), and the Neo-Iapetus Ocean was closed progressively from north to south (Dewey and Shackleton 1984; McKerrow 1988*a*) by the Athollian Orogeny (and perhaps also the Finnmarkian) in the early Ordovician (Text-fig. 2) and the Humberian and Taconian Orogenies in the Llandeilo and Caradoc (Text-fig. 3). In places, e.g. Newfoundland (Karson and Dewey 1978), an ophiolitic fore-arc was obducted across the Laurentian margin and caused the deformation and metamorphism of continental margin sediments of late Precambrian to early Ordovician age. In the British Isles, the relationships between the arc collision and the deformation and metamorphism is less clear. In some areas, like South Mayo Trough, thick fore-arc sequences are preserved and in others, ophiolite obduction is less obvious, although it can be well dated at Ballantrae, where several Arenig events are now recognized (Stone and Rushton 1983). In the Dalradian, further uncertainty exists as some of the deformation appears to predate collision.

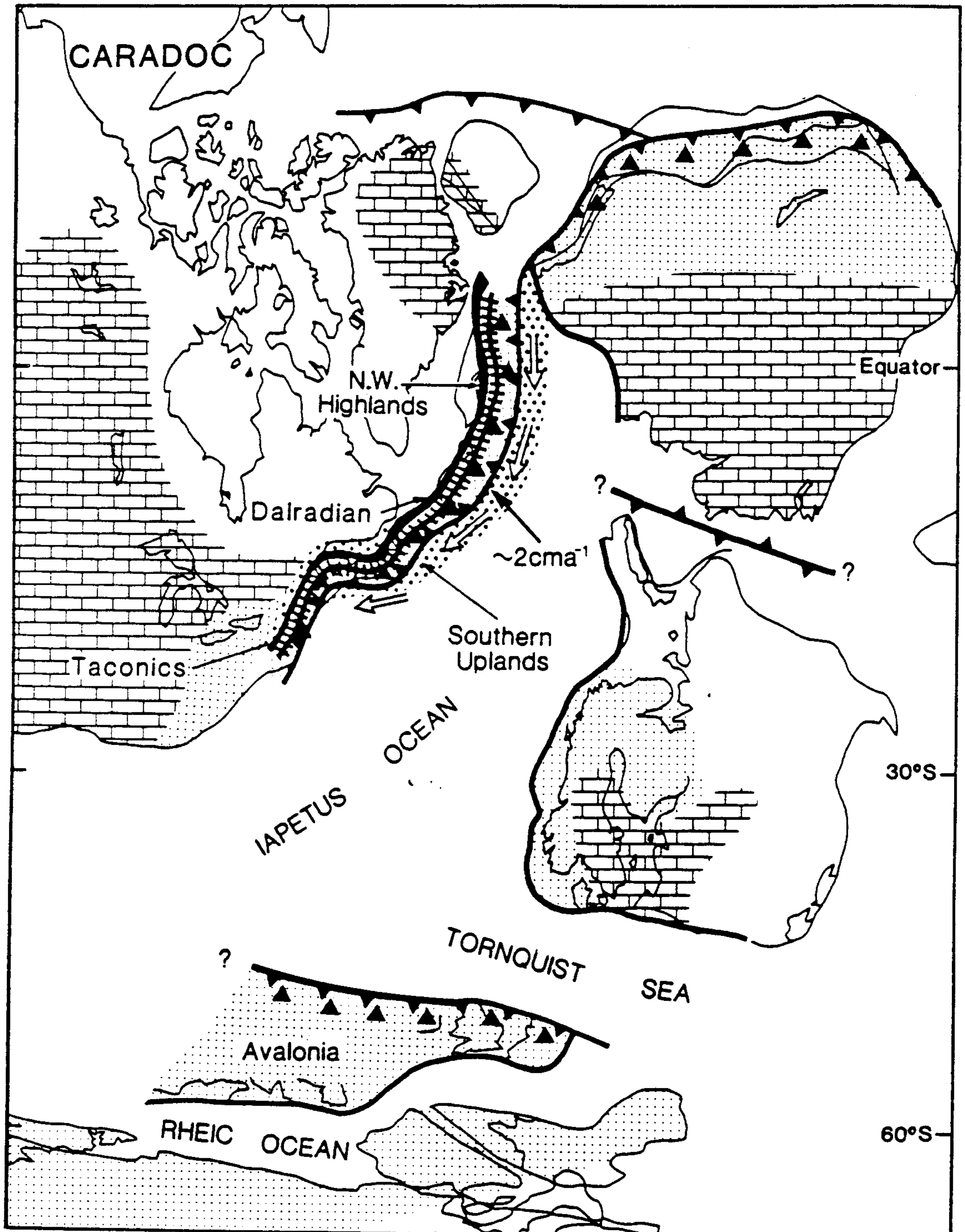
LATE ORDOVICIAN

After the mid to late Ordovician Humberian and Taconian orogenies, when the Oliverian terrane collided with Laurentia and the Neo-Iapetus Ocean closed, north-west subduction commenced along the east margin of Laurentia and a south-east-facing arc was established. At first, this is recognized only by the accretion of the Southern Uplands trench deposits, where accretion commenced in early Caradoc times (Leggett *et al.* 1982). Most of these trench sediments show longitudinal current directions from the north-east, but some were derived from Laurentia to the north-west (and were transported down the inner trench wall), and a few appear to been derived from an offshore igneous source (Kelling *et al.* 1987; Stone *et al.* 1987; Styles *et al.* 1989).

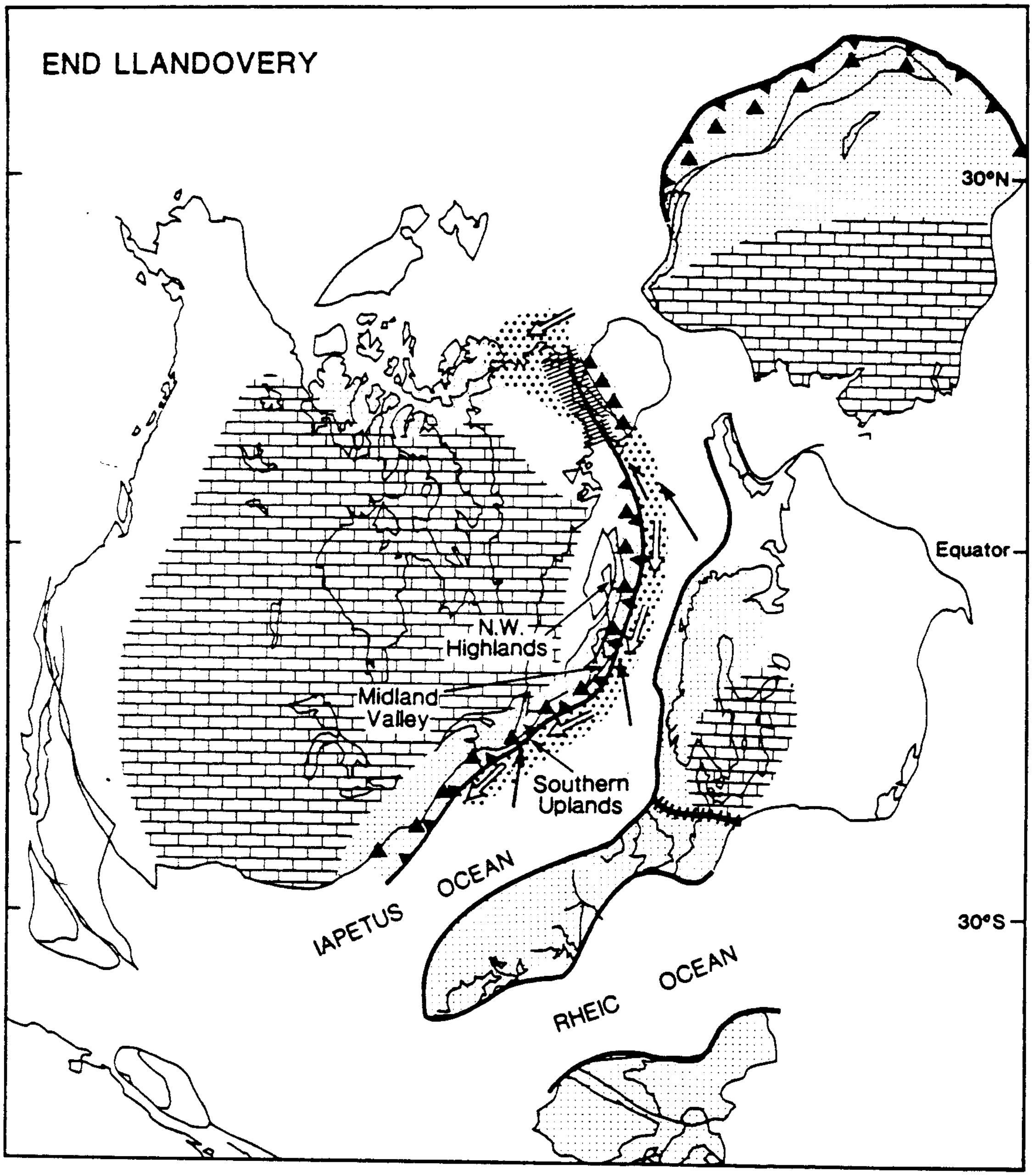
Sm/Nd analyses of those sediments derived from the north-east show that they are unlikely to have had a provenance area in Laurentia (Miller and Onions 1984). This is not surprising because Laurentia was covered by a carbonate platform during the Ordovician period and thus has no obvious sediment source. Miller and Onions (1984) suggested Baltica as a possible source, but our map (Text-fig. 3) shows that, in the Caradoc, Baltica lies too far to the south to contribute sediments into the Southern Upland trench from the north-east. The Mongolian arc of Siberia appears to fit much better. Volcanic activity in this arc was at a maximum from the late Precambrian to the early Ordovician (Mossakovsky and Dergunov 1985), so it is compatible with the 560–530 Ma cooling ages of detrital volcanic clasts (Kelly and Bluck 1989). The igneous rocks of the Mongolian arc were intruded into metamorphic terranes, some parts of which were deformed in late Cambrian and late Ordovician times, which are intervals compatible with the 502–458 Ma detrital mica ages from the Southern Uplands (Kelley and Bluck 1989). The Mongolian arc may have fed sediments directly into the north-eastern end of the Southern Uplands trench or by Amazon or Orinoco-type rivers that flowed south-west across the Siberian continent to the north edge of Iapetus.

The Mongolian arc may also have supplied an early Silurian turbidite fan along the north edge of Greenland (Text-fig. 4) which was derived from the east (Surlyk and Hurst 1983). It, too, could not have come from Laurentia as North Greenland was covered by carbonates through most of the Llandovery Epoch.

The large sinistral displacements on many strike slip faults in Scotland were related to oblique subduction of the Iapetus Ocean along this margin of Laurentia. In the United States, the clastic wedges derived from both the Taconian and Acadian Orogenies lie adjacent to the corresponding orogens, suggesting that large scale movements (with hundreds of kilometres' displacement) were absent south-west of Newfoundland.



TEXT-FIG. 3. In the Caradoc Epoch, after collision of the Oliverian terrane (Humberian and Taconian Orogenies), subduction flipped; the Southern Upland trench originated with longitudinal sediment coming from the Mongolian arc (white arrows show dominant current directions; black arrow shows relative motion between Laurentia and Iapetus of 2 cma^{-1}). Subduction below Wales was related to consumption of the Tornquist Sea, while the Rheic Ocean opened.



TEXT-FIG. 4. The slip vector of the Iapetus and Laurentian plates had changed by the Llandovery Epoch (black arrows). Avalonia collided with Baltica in early Ashgill times and Barentsia with north-east Greenland in the late Llandovery (close hatching indicates mountains), but deposition in the Southern Uplands trench was uninterrupted. The sediments may have crossed Siberia along an Amazon-like river (not shown). Turbidite fans off North Greenland also may have come from Siberia.

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The Scottish faults moved at different times. Soper *et al.* (1989) introduced a thematic set of papers on British Palaeozoic terranes which provide a recent summary. Late Ordovician movements can be inferred on the Highland Boundary Fault (Curry *et al.* 1984) and, with more certainty, on the Southern Upland Fault, where boulders in middle and upper Ordovician conglomerates from the Southern Uplands (which were derived from the north-west) show changes in composition through time (McKerrow and Elders 1989). It would seem that the development of the Southern Upland trench in the Llandeilo/early Caradoc *gracilis* Biozone also heralded the initiation of large sinistral strike slip movements in Scotland.

By early Caradoc time, the shallow shelf faunas of Avalonia changed from resembling those of Gondwana to become more like Baltica, and by the late Caradoc they were identical, showing that the Tornquist Sea was very narrow, probably less than 1,000 km wide (McKerrow and Cocks 1986).

An unconformity is present in the early Ashgill of eastern Wales and western England (Woodcock 1990), and probably also (though the age is less definite) in south-west Norway (Roberts 1980) and may mark the time of collision. By the Silurian period, the ostracodes are identical in Avalonia and Baltica (Berdan 1990); this is significant because ostracodes could not cross even narrow seas of oceanic depths (Cocks and Fortey 1982). The early Ashgill also marks the end of calc-alkaline igneous activity in Wales (Kokelaar *et al.* 1984), which supports our hypothesis that the Welsh arc is related to the south-westward subduction of Tornquist Sea oceanic crust.

SILURIAN

At the end of the Llandovery Epoch, nappe emplacement took place in north-east Greenland, suggesting collision with an island arc or continent. There are no arc rocks in North Greenland, so the subduction leading to this collision was probably eastward dipping; this polarity would be in accord with the direction of emplacement of the west-verging nappes (Hurst *et al.* 1983; McKerrow 1988*a*). The colliding continent may have been Barentsia. If this is the case, then Barentsia may have been separated from Greenland by a small back-arc basin during later Ordovician and earliest Silurian times (see Text-figs 1–4).

Accretion in the Southern Uplands probably continued without a break from the early Caradoc until the late Wenlock, but the accreted record has an unusually long time gap (three graptolite biozones) between the successions in the Northern Belt (which extend up to the Ashgill) and those in the Central Belt (where trench turbidite deposition did not commence until the *gregarius* Biozone) (Leggett *et al.* 1982, figs 3 and 4). This time gap coincides with the emergence of the fore-arc prism (Cockburnland) above sea level, which separated the Midland Valley from the open ocean (Cocks *et al.* 1980).

Another major change in sedimentary regime occurred in the *turriculatus* Biozone. Prior to this time, most longitudinal current directions in the trench turbidites show little variation, but subsequent, more variable, current directions appear to be related to the spread of the turbidite fans over the outer trench high on to the adjacent ocean floor (Leggett *et al.* 1982).

The Llandovery turbidites of south-west Scotland have yielded several transported corals. Most of these are geographically wide ranging forms, but one belongs to the genus *Ceriaster*, which previously was only known from Tadzhikistan (a province of the USSR north of Afghanistan) and China (Scrutton and McCurry 1987). This biogeographical link strongly supports our hypothesis that the longitudinal trench-fill deposits of the Southern Uplands continued to be derived from the Mongolian arc through the Silurian period.

The Scandian Orogeny, marking the collision of Baltica with Laurentia, has been considered to have started in the late Llandovery Epoch from the appearance of coarse sediment in south Norway and Sweden derived from the west (Bassett 1985). Though some minor tectonism may have developed to produce the coarse sediment, we consider that any continental collision was improbable until after the late Wenlock, when sedimentation ceased in the Southern Uplands trench. If continental collision had occurred before this time, some considerable change would be expected in the provenance of the south-east-derived Southern Uplands sediments. We thus consider that the Scandian collision did not occur until latest Wenlock or Ludlow times (Text-fig. 5).

Most of the east-verging nappes in Scandinavia developed at this time, in conjunction with a westerly-dipping subduction zone below Scotland and adjacent parts of Laurentia. However, these may have been also some backthrusting, as the west-verging Moine Thrust (Text-fig. 5) is dated at 430–425 Ma (Johnson *et al.* 1985), which is perhaps late Llandovery to Wenlock (McKerrow *et al.* 1985), although some considerable errors may be involved. The Moine Thrust might yet be shown to be synchronous with the (late Wenlock–Ludlow: ?422–414 Ma) Scandian Orogeny. However, the 460–450 Ma (Llandeilo) Caledonian deformation events of the Northern Highlands of Scotland (for summary, see Harte 1988; Soper 1988) are distinctly earlier than any Scandian event.

EARLY DEVONIAN

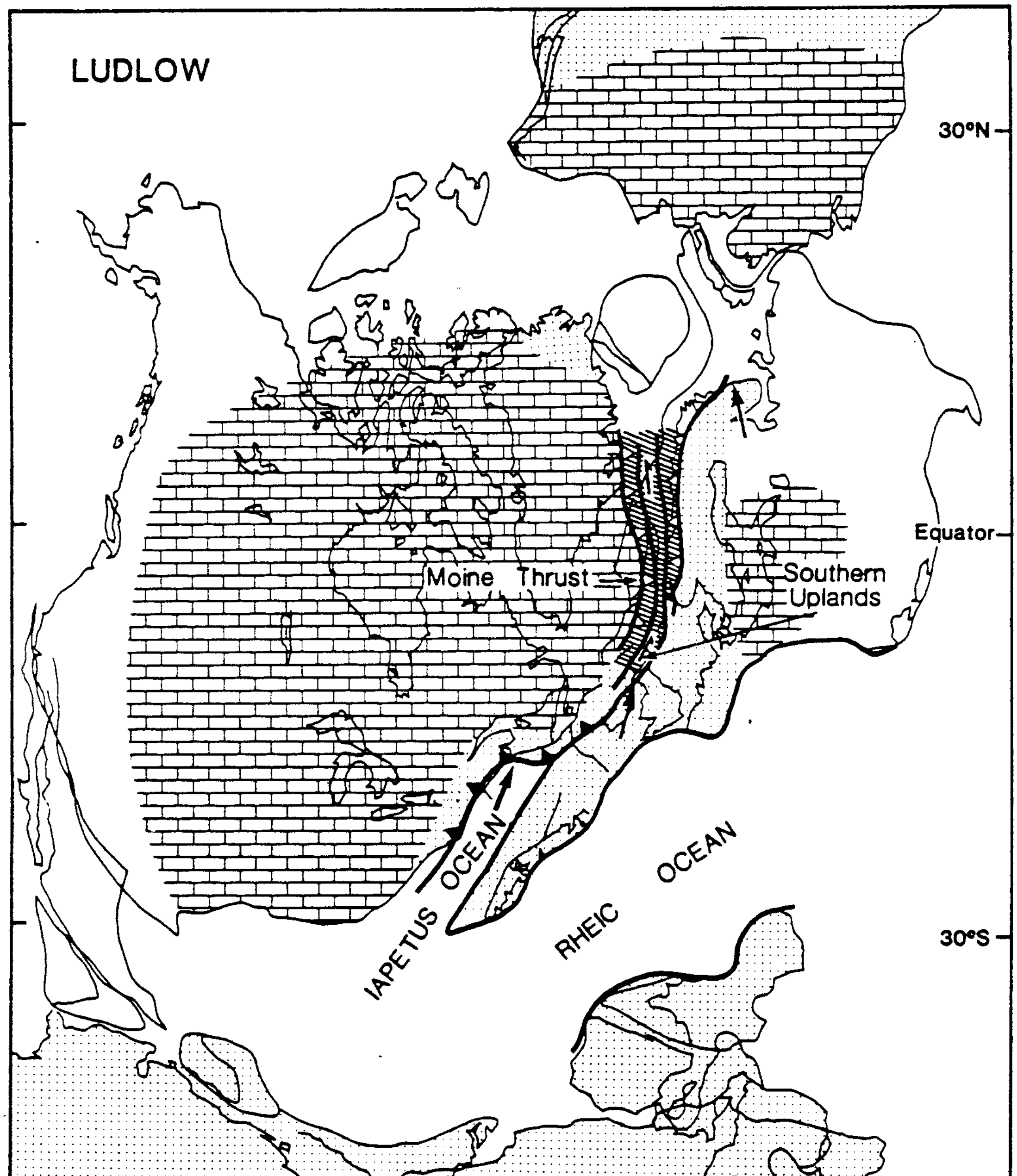
In the Pentland Hills inlier in the Midland Valley of Scotland near Edinburgh, there are two distinct unconformities: one below and one above the Lower Old Red Sandstone. This part of south-east Scotland is an area where the effects of both the Scandian Orogeny (Ludlow) and the Acadian Orogeny (Emsian/Eifelian) can be distinguished clearly in the field. The Scandian orogen extends north from the Pentlands (Text-fig. 5), whilst the Acadian orogen extends to the south-west (Text-fig. 6). Much of the early Devonian detritus of the Scottish Lower Old Red Sandstone might be expected to come from the newly formed Scandian Mountains (Text-fig. 5). Could some of the exotic clasts (Bluck 1984; Haughton 1988) in the upper Silurian and lower Devonian successions of the Midland Valley have been derived from Norway?

From Edinburgh to Connecticut, subduction below Laurentia continued after the Silurian (Thirlwall 1988*a*, *b*), as Avalonia (which had collided with Baltica in the Ashgill) swung towards Laurentia; pivoting near the Tornquist Sea suture (Text-fig. 5), perhaps accompanied by rifting and/or faulting on the suture or on the Tornquist Line (Ziegler 1984; Soper 1986), which lies near, but not on, the suture (Pegrum 1984).

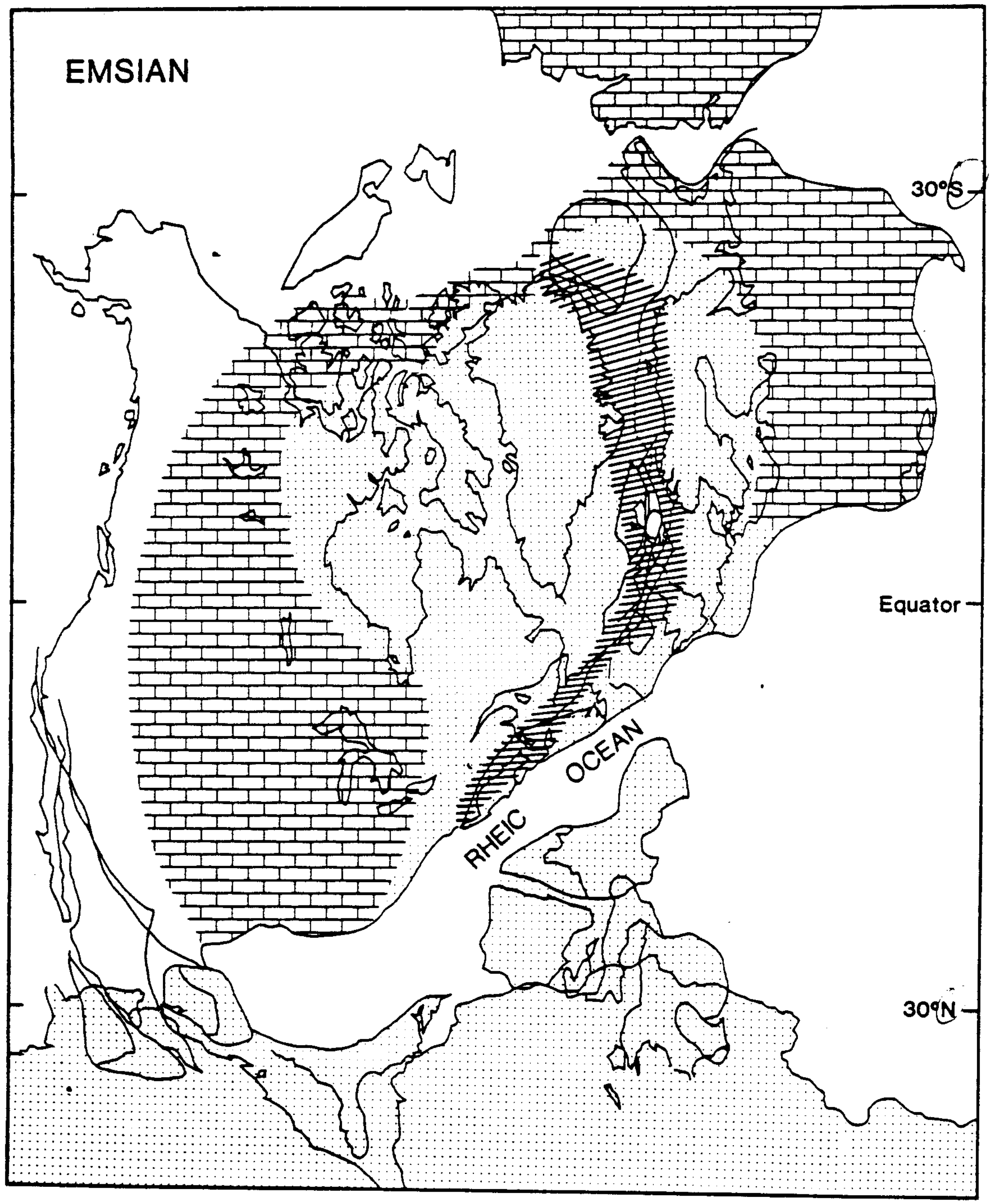
Seismic refraction studies (Bamford *et al.* 1977) show that basement with a velocity of 6·3 km/s extends north from the Lake District of northern England below the Southern Uplands. This is confirmed by BIRPS deep seismic reflection profiling (Klemperer and Matthews 1987) and is supported by magnetotelluric deep sounding measurements in southern Scotland (Beamish and Smythe 1986). It has been concluded (Leggett *et al.* 1983) that, when Avalonian continental crust reached the Southern Upland trench in the late Wenlock Epoch, sedimentation in the trench ceased, and that continued subduction of continental crust caused uplift of the Southern Uplands and depression of northern England, and hence the deposition of over 5 km of Ludlow and Přídolí sediments in the Lake District which were derived mainly from the north. Similar subduction of continental crust in Ireland is suggested by the presence of turbidite fans from the north crossing the suture (Navan-Silvermines Fault) onto subsiding Avalonian crust in the Wenlock (McKerrow and Soper 1989). The subduction of a large amount of Avalonian crust farther to the south-west might explain the absence of any exposed Ordovician arc rocks in south-west Avalonia (Text-fig. 2). Certainly, the last remnants of oceanic crust may have been subducted long before subduction ceased in early Devonian times.

Our maps (Text-figs 5 and 6) show many of the major strike-slip faults in Scotland still offset in the Ludlow and Emsian, but after the Scandian Orogeny only the Southern Upland Fault is likely to have seen much strike-slip movement and this may have been completed by the end of the Middle Devonian (Bluck 1983; McKerrow and Elders 1989; Thirlwall 1989; McKerrow and Soper 1989).

The Acadian Orogeny in Britain and the Canadian Maritime Provinces appears to be largely of Emsian age (McKerrow 1988*b*), but, in New England, the time of major deformation extended into the Eifelian (Boucot 1968). The end of subduction-related igneous activity north of the Iapetus suture in Scotland appears to occur in the Gedinnian (408 Ma), but younger igneous rocks, as yet uninterpreted, are present in the Southern Uplands (Thirlwall 1988*a*). In the Northern Appalachians



TEXT-FIG. 5. Baltica collided with Laurentia in the Ludlow Epoch (Scandian Orogeny), after sedimentation in the Southern Upland trench had ceased. Subduction of Avalonian continental crust in the northern British Isles makes it uncertain how much Iapetus Ocean floor was still exposed. The Rheic Ocean was wide.



TEXT-FIG. 6. Subduction related to the closing of Iapetus ceased with the Emsian/Eifelian Acadian Orogeny. The Old Red Sandstone and other clastic facies bordered the Caledonides and Northern Appalachians. The Rheic Ocean was narrow.

subduction continued until the Middle Devonian (Thirlwall 1988*b*), immediately prior to the Acadian Orogeny.

CONCLUDING REMARKS

We realize that this scenario will be much improved when more geological data become available. We wish to stress that our models have been constructed using actualistic plate tectonic constraints. We also wish to emphasize that we have used data from many different branches of the Earth Sciences; reliable palaeogeographical reconstructions cannot be produced without assessment of all available types of evidence.

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