DID THE ATLANTIC CLOSE AND THEN RE-OPEN?

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FOR more than a century it has been recognized that an unusual feature of the shallow water marine faunas of Lower Palaeozoic time is their division into two clearly marked geographic regions, which are commonly referred to as faunal realms. "The faunal assemblages are amazingly uniform throughout each realm so that correlation of any Cambrian section with another in the same realm is usually easy; on the other hand, the difference between the faunas in the two separate realms is so great as to make correlation between them very difficult"[1].

Two aspects of the distribution of these realms are remarkable. For one thing, some regions of similar faunas are separated by the whole width of the Atlantic Ocean; then, on the other hand, some regions of dissimilar faunas lie adjacent to one another. This is illustrated by Fig. 1, which is based on work by Cowie[2], Grabau[3] and Hutchinson[4].

Grabau showed that, if Europe and North America had become separated by continental drift, a simple reconstruction could explain the first anomaly in the distribution of the faunal realms in that, before the opening of the Atlantic Ocean, each realm would have been continuous, with no large gaps between outcrops of similar facies (Fig. 2).

It is the object of this article to show that drift can also explain the second anomaly. It is proposed that, in Lower Palaeozoic time, a proto-Atlantic Ocean existed so as to form the boundary between the two realms, and that during Middle and Upper Palaeozoic time the ocean closed by stages, so bringing dissimilar facies together (Fig. 3). The supposed closing of the Tethys Sea by northward movement of India into contact with the rest of Asia, and the partial closing of the Mediterranean by northward movement of Africa, can be regarded as a similar but more recent event. The figures are based on a reconstruction by Bullard, Everett and Smith[5], but because those authors pointed out that no allowance had been made for the construction of post-Jurassic shelves, the continents have been brought more closely together.

Four lines of evidence suggest that this proposal is reasonable. (Unfortunately, so far as I can ascertain, palaeomagnetic evidence which might bear on this problem does not exist.)

First, this reconstruction of geological history is held to provide a unified explanation of the changes in rock types, fossils, mountain building episodes and palaeoclimates represented by the rocks of the Atlantic region.

Second, wherever the junction between contiguous parts of different realms is exposed, it is marked by extensive faulting, thrusting and crushing.

Third, there is evidence that the junction is everywhere along the eastern side of a series of ancient island arcs (Fig. 3).

Fourth, the fit appears to meet the geometric requirement that during a single cycle of closing and

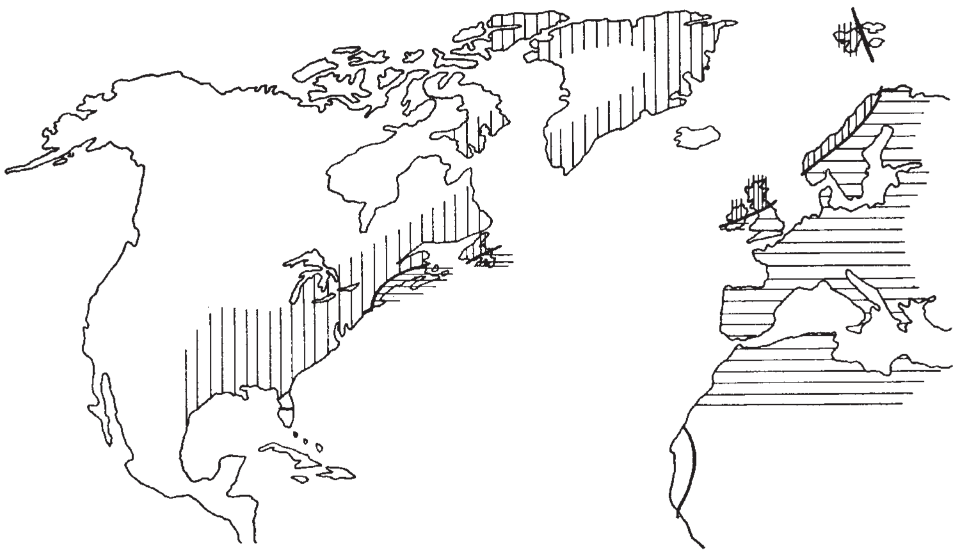

Fig. 1. The North Atlantic region showing the present distributions of the 'Atlantic' faunal realm (horizontal shading) and the 'Pacific' faunal realm (vertical shading). (After J. W. Cowie, A. W. Grabau and R. D. Hutchinson)

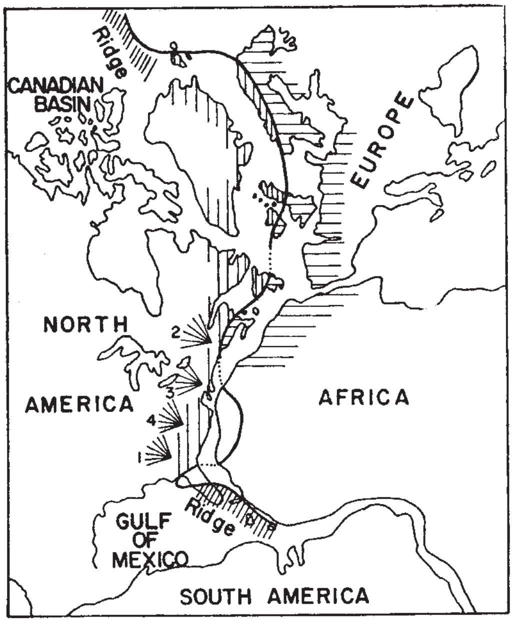

Fig. 2. The North Atlantic region in Upper Palaeozoic and Lower Mesozoic time showing that of the present Atlantic Ocean only the Canadian Basin and the Gulf of Mexico then existed. Four fans are shown which were formed: (1) during Middle Ordovician; (2) during Upper Ordovician; (3) during Upper Devonian; (4) during Pennsylvanian. The heavy line separates 'Pacific' and 'Atlantic' faunal realms. The two ridges are considered to have formed when the modern Atlantic started to open

reopening of an ocean, and in any latitudinal belt of the ocean, only one of the pair of opposing coasts can change sides (Fig. 4).

Recurrent Drift in the North Atlantic

The history proposed for the North Atlantic region can be stated very briefly as follows: (*a*) From the Late Pre-Cambrian to the close of Middle Ordovician time an open ocean existed in approximately, but not precisely, the same location as the present North Atlantic (Fig. 3). (*b*) From the Upper Ordovician to Carboniferous time, this ocean closed by stages. (*c*) From Permian to Jurassic time there was no deep ocean in the North Atlantic region. The only marine deposits of that time are those connected with the Tethys Sea, with a shallow Jurassic invasion of Europe and with deeper Jurassic seas in the Gulf of Mexico and in the western Arctic Basin (Fig. 2). (*d*) Since the beginning of the Cretaceous period the present Atlantic Ocean has been opening, but this reopening did not follow the precise line of junction formed by the closing of the early Palaeozoic Atlantic Ocean; the result is that some coastal regions have been transposed (Fig. 1).

The Lower Palaeozoic continents may have first touched each other at the end of Middle Ordovician time, for thereafter the distinction between 'Atlantic' and 'Pacific' faunal realms ceases to be marked, but the complete closing of the ancient Atlantic may have required several periods.

For each continent, union meant replacing the open ocean by the other continent. This is offered as an explanation of the borderlands of J. Barrell and C. Schuchert for which there is no clear evidence until Upper Ordovician time. As Kay has suggested[6] concerning Eastern North America: "There has been little discussion of the evidence for borderlands in earlier Paleozoic time, though some have expressed scepticism". Kay's own support for island arcs is muted after Lower Palaeozoic time and he accepts the view that the sediments of the "Late Devonian and Early Mississippian came from the land of Appalachia"—a borderland.

This view that extensive upland source areas lay to the east of the Appalachian geosyncline in the sites of the present coastal plain or ocean has been fully supported by recent work[7–9]. Tens of thousands of cubic miles of quartz-rich sediments, derived from the east, were deposited in shallow marine to sub-aerial deltas.

When the continents were pushed together, they would have touched first at one promontory and then at another. It can be expected that high mountains would have been formed locally and that they would have produced alluvial fans on both continents. As the ocean diminished the climate would have become increasingly arid. Such drastic alterations in the physiography would explain the change from predominantly marine and island arc deposition in the Lower Palaeozoic to conspicuous fans of Queenston, Catskill, Old Red Sandstone, and other deltas of Middle and Upper Palaeozoic time (see refs. 10 and 11, and Fig. 2). It can also be expected that the collision of continents would have produced great local uplifts which, if one continent overrode the other, would have migrated inland, perhaps pushing the Taconic and northern Newfoundland klippen[12] before them.

It would seem that by Permian and Triassic times the Atlantic Ocean was completely closed, because only continental beds, such as the Dunkard and Newark series, are found in North America. In Great Britain the New Red Sandstone is also continental as is the Permian of the Oslo district.

No Jurassic beds are known in eastern North America except in the Gulf of Mexico. Those of Europe were formed by a shallow marine invasion of the continent and are said by Hallam[13] to have fossils that "include many neritic forms that could not have crossed a deep ocean. The paleogeography for the Scottish Jurassic gives no hint of increasingly marine conditions to the west" (personal communication). Most of the available geological evidence suggests that the present Atlantic Ocean started to open at the beginning of Cretaceous time[14,15]. Although objections to this view are still being raised, they seem to be minor in comparison with the other evidence, and it is possible that they can be explained in other ways.

Faulted Contact between Faunal Realms

Starting our considerations in the north, the island of West Spitsbergen is underlain by a thick eugeosynclinal section of Lower Palaeozoic rocks named the Hecla Hoek succession. These strata rest on no known basement and were deformed, metamorphosed and intruded by granites during the Caledonian orogeny[16,17]. They contain fossils of the 'Pacific' fauna similar to those of Scotland and North America[18].

In Nordaustland, the adjacent, eastern island of the Spitsbergen group, Kulling[19] and Sandford[20] have mapped a thin section of unmetamorphosed and gently folded strata which a few fossils indicate to be of about the same age. These beds lie uncomformably on a basement which is regarded as part of the Baltic Shield. These strata do not thicken to the west as the much thicker section of West Spitsbergen is approached, nor do the few fossils necessarily belong to the 'Pacific' faunal realm.

Despite the considerable number of attempts to compare the sections in the adjacent islands, the correlation is not good. Changes in thickness, facies, and degree of metamorphism, basement and type of intrusives are all abrupt and striking. Orvin[21] and others have mapped faults in Hinlopen Strait between the islands. Klitin[22] summarizes the situation thus: "Of particular interest is the junction zone of the alleged Caledonian platform and Caledonian fold system. The transition to typical caledonids takes place in a zone not over 15 to 20 km wide, in the Hinlopen

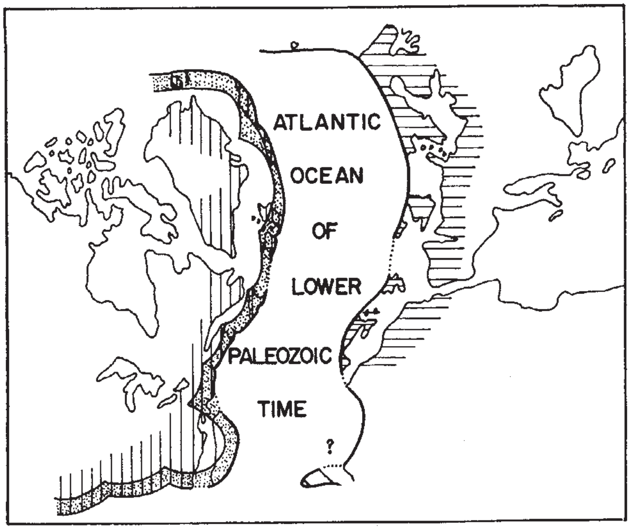

Fig. 3. The North Atlantic region in Lower Palaeozoic time. The proto-Atlantic Ocean would have formed a complete barrier between two faunal realms (shaded). Island arcs (dotted) probably lay along the North American coast. The floor of this ocean could have been absorbed in the trenches associated with these arcs as the ocean closed

Strait area, where the Hecla Hoek section abruptly increases in thickness, by a factor of four, with the appearance of extrusives in its metamorphosed and linearly folded beds. Such radical changes in thickness suggest a fault junction between an ancient platform and the caledonids." Following this interpretation I suggest that the Lower Palaeozoic ocean once separated the two islands and that, whereas Nordaustland formed part of the Baltic shield and shelf, West Spitsbergen was the site of a North American island arc.

In Scandinavia it is well established that the peninsula is divided longitudinally into two different provinces separated by a great zone of nappes and faults overthrust towards the east. According to the descriptions of Holtedahl[23], south-eastern Norway and most of Sweden are underlain by an extension of the Baltic Platform on which lie nearly flat, unfossiliferous rocks and "the eastern facies of the Cambro-Silurian (which) can be classed as miogeosynclinal in the terminology of Stille. The thickness is rather large and there is much terrigeneous material. Caledonian volcanic and intrusive igneous rocks are not found in the deposits of this type. The rocks are unmetamorphosed in the east and are of low metamorphic grade farther to the north-west. The deposits occur in an autochthonous or parautochthonous position above the original Archean basement."

The fossils are repeatedly referred to as being similar to those of the Baltic region, England and Wales. On the other hand, in the Trondheim area of western Norway, a thick succession of pillow lavas, shale and limestone with serpentinites in the lower part of the sequence contains a fauna "of American affinities . . . the limestone of Smøla is similar to the Durness in Scotland and to more or less contemporaneous limestone in Newfoundland, Bear Island and Spitsbergen. The limestone in Smøla thus seems to represent an American-Arctic facies of the Ordovician." In these "mainly pelitic sediments . . . we thus have a eugeosynclinal facies characteristic of the central parts of a geosyncline . . . probably all rocks of the present facies occur in allochthonous positions." An important event in central southern Norway was the close of marine deposition "in Late Ordovician or Early Silurian time brought about by the thrusting of nappes and deposition of the Valdres sparagmite (arkose), which was considered as a deposit of flysch type by Goldschmidt". The zone of nappes is, therefore, held to be the boundary between faunal provinces and the line of closure of the Lower Palaeozoic ocean.

The geological relationship between Spitsbergen, Scandinavia and the British Isles has been discussed by Bailey and Holtedahl[24]. Of the Caledonian structures they state: " . . . in the present land area of Scandinavia we find the eastern part of the orogenetic belt only, while in Great Britain the whole of the orogenetic zone is represented. The Spitsbergen Group seems to lie rather centrally in the zone of deformation." Following Wegener, they consider that Greenland may have been formerly connected with Europe and suggest that, if so, it would have completed the western side of the mountain belt opposite Norway. This relationship has found support in recent years from several authors[14] including Umbgrove[25].

That the boundary between 'Atlantic' and 'Pacific' faunal realms crosses northern England between Scotland and Wales is supported by Walton, who writes of the Scottish occurrences: "The close affinity of the Durness and North America rocks was recognised long ago . . . . The long-recognised affinity of the Girvan Caradocian and Appalachian Mohawkian faunas was re-emphasized by Williams . . . . By contrast the faunas are only remotely connected with the Welsh Ordovician rocks"[26]. George[27] describes the relations thus: "The Salopian geosyncline may thus have extended unbrokenly from conjectural north-western limits in the Highlands to a south-eastern margin or marginal shelf in the English Midlands". It does not require much change to regard this geosyncline as a former ocean.

In Newfoundland the geology of the north-eastern coast has recently been described by Williams[28]. He suggests that in Cambrian time a deep basin or ocean, not underlain by continental crust, crossed the central part of the island and separated two shelves. The north-western shelf underlying the Long Peninsula has a basement of Grenville age overlain by strata with 'Pacific' faunas like those of Scotland, while the south-eastern shelf, which forms the Avalon peninsula, has a younger Pre-Cambrian basement overlain by strata with 'Atlantic' faunas like those of Wales. During Ordovician and subsequent time the intervening sea became filled with eugeosynclinal and volcanic sedimentary rocks, probably representing a former island arc and mountain belt.

Anderson[29] believes that faulting in Hermitage Bay on the south coast of Newfoundland not only separates the rocks of the south-eastern shelf from the central geosyncline, but may also completely divide the two faunas. On the north coast the corresponding fault zone may be in Freshwater Bay, but this point has not been settled as yet[30].

Among those who have recently correlated the Newfoundland and British sections are Dewey and Church[31]. Although Church does not favour continental drift, both he and Dewey make the same correlation as that already given here and extend the Caledonian mobile belt from northern England and central Ireland to central Newfoundland.

South of Newfoundland, the Gulf of St. Lawrence and younger rocks cover the key areas of Lower Palaeozoic formations almost as far as the Maine border. Little can be said except that the faunas of Cape Breton Island and St. John, New Brunswick, have European affinities while those of Gaspé and the Eastern Township of Quebec are typical of Scotland and most of North America[4].

In northern and eastern Maine the older literature is sparse and generalized. Recently a combined group of government and university geologists, including W. B. N. Berry, A. J. Boucot, E. Mencher, R. S. Naylor and L. Pavlides, have discovered new fossil localities there with both European and North American affinities, important Caledonian uplifts and large pre-Silurian faults[32]. Much of the state has been remapped, but for the reason that little of this work has yet been published (R. G. Doyle, personal communication), and because the structure is clearly much more complex than shown on early maps, this is not an opportune time to consider the area in detail.

From the southern part of Maine south across New Hampshire, Massachusetts and Connecticut a major zone can be traced from published accounts. Novotny[33] has described this "major fault zone" where it crosses the New Hampshire–Massachusetts boundary (Fig. 5). To the north it connects with several faults and silicified zones shown on the map of New Hampshire[34,35]. These lie along the line which separates those formations which underlie the greater part of New Hampshire from a suite of completely different formations, underlying south-eastern New Hampshire. This line may be continued northward into south-eastern Maine by the faults which Katz[36] has suggested bound the Berwich gneiss, itself crumpled, "closely folded and overturned". In Massachusetts, Novotny's fault may be exposed in the abandoned Worcester "coal" mine. The description suggests that much of the rock may be carbonaceous mylonite[37]. South of Worcester this fault connects with a major change in formations evident on the geological map of Massachusetts[38].

In Connecticut this boundary appears to join the Honey Hill fault and its northern continuation which bisect the state and separate two major rock sequences. Where best described in the south it "has been mapped for 25 miles eastward from Chester nearly to Preston without apparent repetition of the stratigraphy on either side of the fault. The fault plane dips 10°–35° N parallel to the underlying metasedimentary rocks .... The fault is marked by a zone a mile wide of mylonitized and crushed rocks .... Displacement must have been many miles"[39]. As in Norway, the orogenic belt appears to have been thrust eastwards over the eastern platform. To the south this major fault seems to strike into the Atlantic Ocean and the Appalachian belt, then narrows conspicuously. I have recently learned from L. R. Page and J. W. Peoples that mapping (for the most unpublished) by the federal and state surveys has defined this fault zone more satisfactorily, and that published aeromagnetic maps show a change in the strike of anomalies across it. This evidence suggests that New England is divided by a major fault zone into two provinces underlain by quite different rock formations. Of the few occurrences of the Lower Palaeozoic faunas, all those with European affinities lie to the east of the fault zone; all those typical of North America to the west[40,41].

In the light of this evidence it seems reasonable to suggest that this fault zone marks the line of closure of the Lower Palaeozoic Atlantic Ocean. It may seem strange to propose that a former position of the Atlantic Ocean lies through New England and that its full significance has not been realized, but it must be remembered that throughout the area outcrops are poor and that most of the mapping is old. Surface mapping reveals few faults, but new tunnels have shown that faults abound under the drift-filled valleys and that some of these are major (J. W. Skehan and A. Quinn, personal communications).

Most North American geologists have not accepted the idea of continental drift. Instead they have sought to explain the changes in faunas in terms of different environmental conditions. This has certainly been a factor and no doubt was responsible for the differences between the Durness, Girvan and Moffatt facies in Scotland, although those facies belong to the same faunal realm. In another example, G. Theokritoff (personal communication) has directed my attention to a possible mixing of Atlantic, Pacific and endemic faunas in the Taconic sequence of New York[42]. Christina Lochman[43] has emphasized the difficulties incurred in accepting such an interpretation. She states that the areas of mixed faunas lie in deeply down-warped basins between two shallow shelf deposits containing respectively Atlantic and Pacific faunas. These basins, she remarks, had connexions with the Atlantic Ocean and had a benthonic environment "similar to that of the open ocean .... Few normal benthonic species of the coastal shelf could establish themselves in such an alien environment, although, because of the geographic proximity of the two areas, sporadically drifted individuals might be found." She also refers to deep basins separating different faunas and to the evidence for a "biofacies regime ordinarily found on the floors of the continental shelf beyond the inner islands of the volcanic archipelago". These views would seem to admit the possibility of interpreting the palaeogeography as has been done in this article. It is suggested that one of the deep basins, instead of lying on a shelf, might have been an open ocean in Lower Palaeozoic time and that the mixed fauna may have come from the extreme edge of one continent.

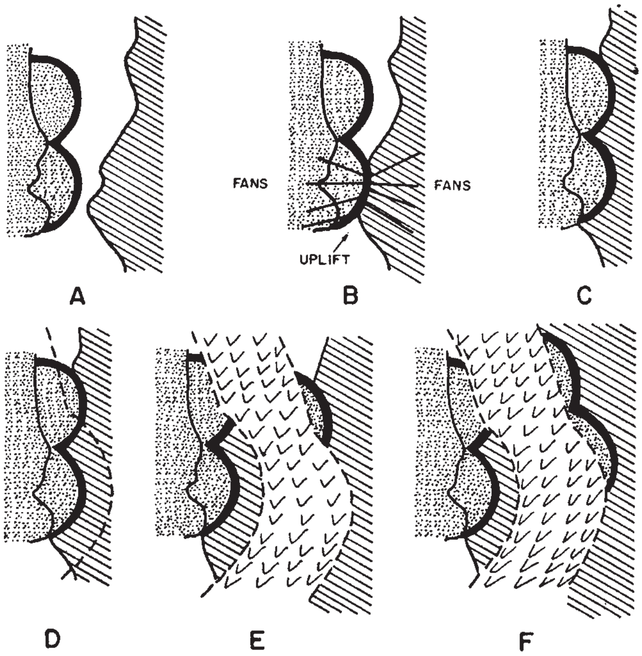

Fig. 4. *A*, A closing ocean, with island arcs on one coast, separating two different faunal realms. *B*, First contact between two opposite sides of a closing ocean. *C*, The ocean closed by overlap of the opposite coasts. *D*, A possible line (dashed) along which a younger ocean could reopen. *E*, A new ocean (checked) opening in an old continent. *F*, A geometrically impossible way for a younger ocean to open. (Note how the arcs overlap.)

The reconstruction (Fig. 2) then leads to Africa. Sougy[44] has described a large plate of metamorphic rocks east of Dakar thrust eastwards over Upper Devonian strata. Farther north in Spanish Morocco there is a folded belt. A large Cretaceous overlap along the coast and lack of diagnostic fossils in the overthrust block make correlation difficult, but Sougy concludes that: "In the future, when geologists study the relationships between America and Africa for evidence bearing on permanence of continents and oceans *versus* continental drift, they will have to consider that the western rim of Africa is made, from Guinea to Morocco, not of a Pre-Cambrian basement but of a mainly Hercynian orogenic belt, in some respects symmetrical to the Appalachian belt." His mention of drift suggests, as do most reconstructions[5], that this West African belt was formerly part of the Appalachians. This view is supported by P. A. Mohr, who writes: "the Cambrian manganese ores of Newfoundland, Wales and Morocco . . . I think were formed in a common geosynclinal trough" (personal communication). The view that these regions were

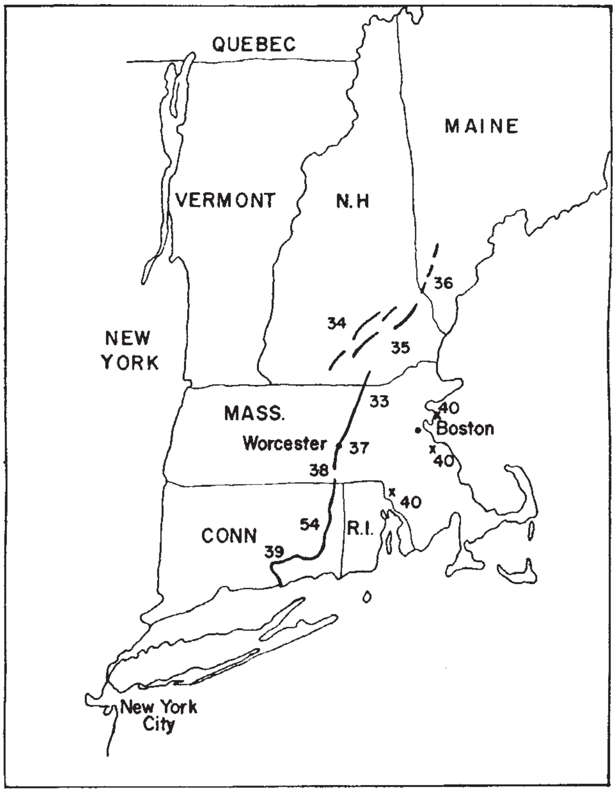

Fig. 5. Sketch map of New England showing location of some major faults and three fossil localities of the 'Atlantic' faunal realm (X). The numbers refer to papers in the list of references from which information was obtained

together until Cretaceous time is supported by the close similarity of Cretaceous fossils from these two regions now on opposite sides of the ocean[45]. Only further investigation, aided by extensive seismic investigations or drilling through the Cretaceous of both continental coasts, can show whether it is possible or likely that West Africa ever fitted into the central east coast of the United States. If so, some rotation of Africa clockwise and a closer fit than that shown by Bullard, Everett and Smith[5] may be indicated.

Although the northern termination of the West African fold belt is covered, its termination to the south is definite; the Pre-Cambrian of the African Shield extends to the Atlantic near Conakry[46]. The reconstruction suggests that this contact might reach Florida. In Florida and Georgia a cross-section of the Appalachians resembles that of Newfoundland in that these are the only parts of the Appalachians with a platform on both sides of the mobile belt. The platform on the south-eastern side of the mobile belt which lies beneath northern Florida and adjacent states is only known from well cores. These consist of Early Ordovician to Middle Devonian sandstones and shales said to have been deposited in shallow water[47]. Published accounts do not correlate the strata or fossils with formations elsewhere. It would seem that the basement has not been penetrated. Thus it is only speculative to suggest that this region was formerly part of Africa.

Island Arcs of Lower Palaeozoic Atlantic

According to a widely adopted hypothesis, island arcs and mountains represent places where the lithosphere is being compressed, while mid-ocean ridges represent places where it is being pulled apart and where new crust is being created. Thus the present Atlantic Ocean is expanding from the Mid-Atlantic Ridge.

For a Lower Palaeozoic Atlantic Ocean to have closed, it must, according to this hypothesis, have been marked not by a central ridge, but by a continuous system of island arcs and mountains. Observation shows that such systems commonly lie at the sides and not in the centre of oceans. Kay's view, that a system of island arcs existed off the eastern and southern coasts of North America in Lower Palaeozoic time, is entirely compatible with this hypothesis. This would have allowed the former Atlantic Ocean to close, and thus to convert the offshore island arcs of Lower Palaeozoic time into the intercontinental Appalachian mountains of Middle and Upper Palaeozoic time. Following Keith, Kay and King, I have sketched the location of seven former arcs in the Appalachians and their south-western continuation past the Ouachita and Marathon Mountains[48]. I see no reason to change this view.

The situation in Scotland has been described by Walton: "It seems likely that both the north-west Highlands and the Appalachians formed part of a very wide stable shelf which also included Greenland and other 'Boreal' regions having very similar Cambrian rock types. . . . it is probable that sedimentation in the area of the southern Highlands during the Cambrian period was mainly of a greywacke, geosynclinal type and contrasted strongly with that in the north-west Highlands . . . it is probable that Cambrian sedimentation stretched unbroken to an unknown distance south of the Highland Boundary fault"[26]. Ordovician volcanism followed and these correlations and descriptions suggest that, during Lower Palaeozoic time, arcs associated with a western land extended across Scotland. That there may have been contemporaneous volcanism and islands along the eastern coast in what is now Wales, merely adds complexity without affecting the history in Scotland. In the Silurian period conditions changed and the marine conditions "gave way to mixed environments . . . at least partly in fluvio-deltaic environments with periods of emergence"[26].

Enough has been described of the conditions in Norway and West Spitsbergen and of their correlations with Scotland to show that they too were the sites of Lower Palaeozoic island arcs associated with a western continent. Thus the Caledonian–Appalachian arcs seem to have formed a continuous system along the western side of the former ocean. It is suggested that it was in the trenches of these arcs that the floor of the Lower Palaeozoic Ocean was swallowed up as that ocean closed.

Geometrical Control of Transposition

If two bodies are brought together so that they unite, and if they are later pulled apart so that they break on a different line from the line of union, then one important geometrical consideration holds. It is that, along any one stretch of the junction, only one fragment can change sides: one cannot transpose pieces from each margin at the same place. This is illustrated in Fig. 4 and a comparison with the other figures shows that our reconstruction obeys this principle. This does not prove that the reconstruction is correct, but the neat fashion in which fragments from either side are alternately transposed meets the geometrical requirements.

Some Possible Extensions

When, as is believed, the present Atlantic Ocean started to open at the beginning of Cretaceous time, it did so by breaking open a continent which was then continuous from West Spitsbergen to Florida (Fig. 2). North of Spitsbergen the coasts of North America and Siberia at that time diverged and the opening ceased to lie wholly within a continent and to have continental blocks on both sides. Following the descriptions of B. C. Heezen and M. Ewing, and Ya. Ya. Hakkel and N. A. Ostenso, I have suggested that the fracture followed the coast of Siberia forming the Lomonosov Ridge on the other side of the opening. Thus the Lomonosov Ridge separates an older Canadian ocean basin from a younger Siberian ocean basin in the Arctic Sea[14].

In the south the situation appears to be similar, but to understand it one must clearly separate the platform of northern Florida from the different geology of southern Florida. South of central Florida a southern Florida–Bahamas Ridge separates a main Atlantic, apparently of Cretaceous age, from a Gulf of Mexico which seems to have been a deep ocean and evaporite basin during the Jurassic period.

Drake, Heirtzler and Hirschman[49] emphasize the importance of the Florida-Bahamas Ridge for sealing off the Gulf of Mexico from the open ocean so that the Jurassic salt deposits could form. They suggest that this ridge is an "extension of the Ouachita system" and that it forms the "foundation for the entire chain of islands and banks". This ignores the earlier interpretations of magnetic and gravity anomaly maps made by Miller and Ewing[50] and by Lee[51]. Both papers suggested that southern Florida and the Bahamas are coral banks built on deeply submerged volcanoes. The Palaeozoic platform-type of sedimentary rocks, described from drill cores in northern Florida, are not like the Ouachita folds. Drilling has revealed no Palaeozoic rocks beneath southern Florida and the Bahamas. The magnetic anomaly map shows a marked change in central Florida. Drake *et al.*, in their Fig. 5, show three trend lines connecting southern Florida with the Bahamas and only one connecting it with northern Florida. It is suggested that the Florida-Bahamas Ridge, like the Lomonosov Ridge, formed when the main Atlantic Ocean started to open at the beginning of Cretaceous time and separated an ocean basin of Cretaceous age from an older ocean basin.

Drake *et al.* hold that the Florida-Bahamas Ridge extends to Navidad Bank, north of Hispaniola. It thus ends at the major zone of faulting which, according to Hess and Maxwell[52], and others, extends from Central America to the northern end of the West Indies arc. The Caribbean Sea and West Indies arc have often been regarded as associated with the Pacific Ocean, and I have discussed elsewhere their possible origin as a tongue, thrust from the Pacific and bounded by transform faults[53].

A complete discussion would require consideration of the Hercynian orogeny and faulting and post-Triassic faulting. This seems feasible but will not be attempted here.

It has been suggested in this article that during Lower Palaeozoic time North America and Europe were approaching each other, that this motion stopped and that it later reversed. If this is true, the onset of the reverse motion and the start of reopening of the Atlantic Ocean must have been an event of very major significance in world geology. The evidence suggests that it occurred at about the close of the Jurassic and the beginning of the Cretaceous periods. It seems reasonable to link it with other major events of that age in the Americas.

McLearn[55] has pointed out that at that time the drainage of much of western North America reversed its direction so that rivers which had been flowing west and building a great shelf along the Pacific coast were interrupted by the rise of the Cordillera and began to follow their present directions. Gilluly[56] has pointed out that "In Cretaceous time plutons probably a thousand times larger than those of all the rest of the Phanerozoic were emplaced". The onset of a relative advance of the Americas over the Pacific Ocean floor might well have caused a crumpling of the shelves along that coast with the creation and rise of extensive batholiths. Gilluly has pointed this out and concluded that the likely cause was that "it is probable that the continent as a whole is moving away from a widening Atlantic".

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