Discussion

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Phil. Trans. R. Soc. Lond. A 1965 **258**, 52-75
doi: 10.1098/rsta.1965.0021

V. Discussion

Professor J. H. Taylor, F.R.S. (King's College, London) opened the discussion:

The foregoing contributions prompt two major questions. Is evidence for movement of the continents now sufficiently convincing to compel us to consider drift at least as a working hypothesis? If the answer to that is 'yes', then what was the most probable form of the continents before disruption?

Let me say at once that, of all the evidence for former union of the continents, I have always found what one might call the classic geological arguments—the arguments based on stratigraphy and lithologies and faunas—the least convincing. They were deemed inconclusive in the 1920's and 1930's when admittedly they suffered grievously at the hands of their own enthusiastic advocates. Are they any more convincing today? A phrase used by Professor Runcorn—'Individually indecisive yet collectively suggestive'—sums up the situation very fairly.

This comment could be applied with equal force to a lot of the palaeoclimatic data. Permo-Carboniferous glaciation was one of the corner stones of the drift edifice but, like the ancient distributions of corals or of evaporites, could it not be explained simply in terms of polar wandering, taking into account the local climatic effects of land masses, mountains and seas, and bearing in mind the imperfections of the geological record? In any case are we entitled to explain the Permo-Carboniferous glaciation when we still have not succeeded in explaining the Pleistocene ice age?

Small wonder that, thirty years ago, these uncertainties produced a position of stalemate. Palaeomagnetism more than anything else has been responsible for the changed outlook of today. If one can accept the proposition that it is justifiable to extrapolate the known behaviour of the Earth's field in geologically recent times back into the more remote past—and this comes relatively easily to geologists brought up in the school of uniformitarianism—then one is faced with a formidable weight of evidence for drift. The fact that the pole positions calculated for ancient rocks of the same age in different continents don't agree makes it impossible any longer to consider polar wandering by itself as adequate. The evidence presented this morning by Professor Runcorn and Dr Creer is impressive even though there are still uncertainties to be resolved and discrepancies to be explained.

Perhaps the most cogent of reasons for retaining the drift hypothesis is the number of observed phenomena for which it offers a reasonable explanation. One obvious example is the distribution of the recent orogenic belts round the peripheries of the northern and southern groups of continents while, as emphasized by Professor Westoll, on their inner margins facing the Atlantic, Arctic and Indian Oceans, the structures are truncated. Continental drift is compatible with the disappearance of the great oceanic trans-current faults at (or beneath) the continental margins. It contributes to a possible explanation of the remarkable fact disclosed by radiometric data that the inception of major structural provinces seem to have been confined to a few relatively short periods of geological time.

For such reasons, rather than because of fully authenticated resemblances in the geology of the severed continents, I suggest that drift has to be retained as a working hypothesis until either its existence can be confirmed or it makes way for a more acceptable theory.

In this case my second question—what is the best fit of the continents?—should be the main subject for our discussion. The reconstructions arrived at by computation and presented by Sir Edward Bullard are stimulating, and geologists must search for criteria whereby their validity may be tested. The mere juxtaposition of Palaeozoic fold belts, for example in Norway, eastern Greenland and Spitzbergen, is not by itself necessarily proof of original spatial connexion. In 1958 A. H. Voisey illustrated how, by citing fortuitous simularities, a case could be built up for fitting the (inverted) eastern coast of Australia to eastern North America. Both the Tasman and Appalachian geosynclines have folds which can be broadly classed as Taxonic, Acadian and Appalachian in age. The 'Taconic sequence' can be matched with the Brisbane schists. Both fold belts have Silurian volcanism and thick continental clastics in the upper part of the Devonian. Both have marine Lower Carboniferous, continental Upper Carboniferous and what appear to be Permo-Carboniferous tillites.

Some of the evidence for du Toit's Samfrau geosyncline which linked the Tasman geosyncline through western Antarctica with the Cape folds and the Bahia Blanca (Sierra de la Ventana) belt of Argentina, was little better. The last two do contain similar rocks and have somewhat comparable styles of folding but their postulated links with the Tasman trough through the metamorphics of the Edsel Ford Range were quite unconvincing and have been abandoned in modern reconstructions.

Because of the very much longer time span involved, Precambrian fold belts may prove more useful in intercontinental correlation than the later ones. Structural analysis allied to radiometric age determinations—surely one of the most exciting combinations in geological research today—is already providing some of the evidence. In the northern group of continents there is now a fair amount of information for the comparison of Labrador with western Greenland. In the southern continents we know that there is reasonable agreement of ages from the Mozambique belt, Madagascar and the Seychelles but geochronological data from India and Antarctica are still very inadequate. What information have we for comparing the Brazilian shield with west and equatorial Africa?

It would be helpful to see the latest structural and radiometric data plotted on the various units of Gondwanaland for it is only by a synthesis of this kind that we can assess the validity of our continental reconstructions.

Professor M. G. Rutten (University of Utrecht) described some recent palaeomagnetic work carried out in the Netherlands:

Apart from the data presented by palaeomagnetism on the drift of continents as a whole, we have at the moment some indications as to how these were assembled during successive orogenetic cycles. The data available admittedly are scarce. Moreover, most of them come from the Alpine fold belt of Europe. But it seems probable that earlier orogenics behaved in a similar way.

In Europe van Hilten (1962*b*) first noted the consistent discrepancy between the poles found for the Permian in that part of Europe not mobilized by the Alpine orogeny—that is for the Meso-Europe of Stille—and in the Alpine fold belt. This discrepancy has since been repeatedly confirmed, both for the Pyrennees, for the western Alps (Estérel) and for the Alps of northern Italy (figures 1, 2).

The deviations from the Permian pole for Meso-Europe are, however, not the same for all of these areas. If large scale extra crustal movements are responsible for this discrepancy, which seems to be the most plausible hypothesis, the Alpine fold belt consequently

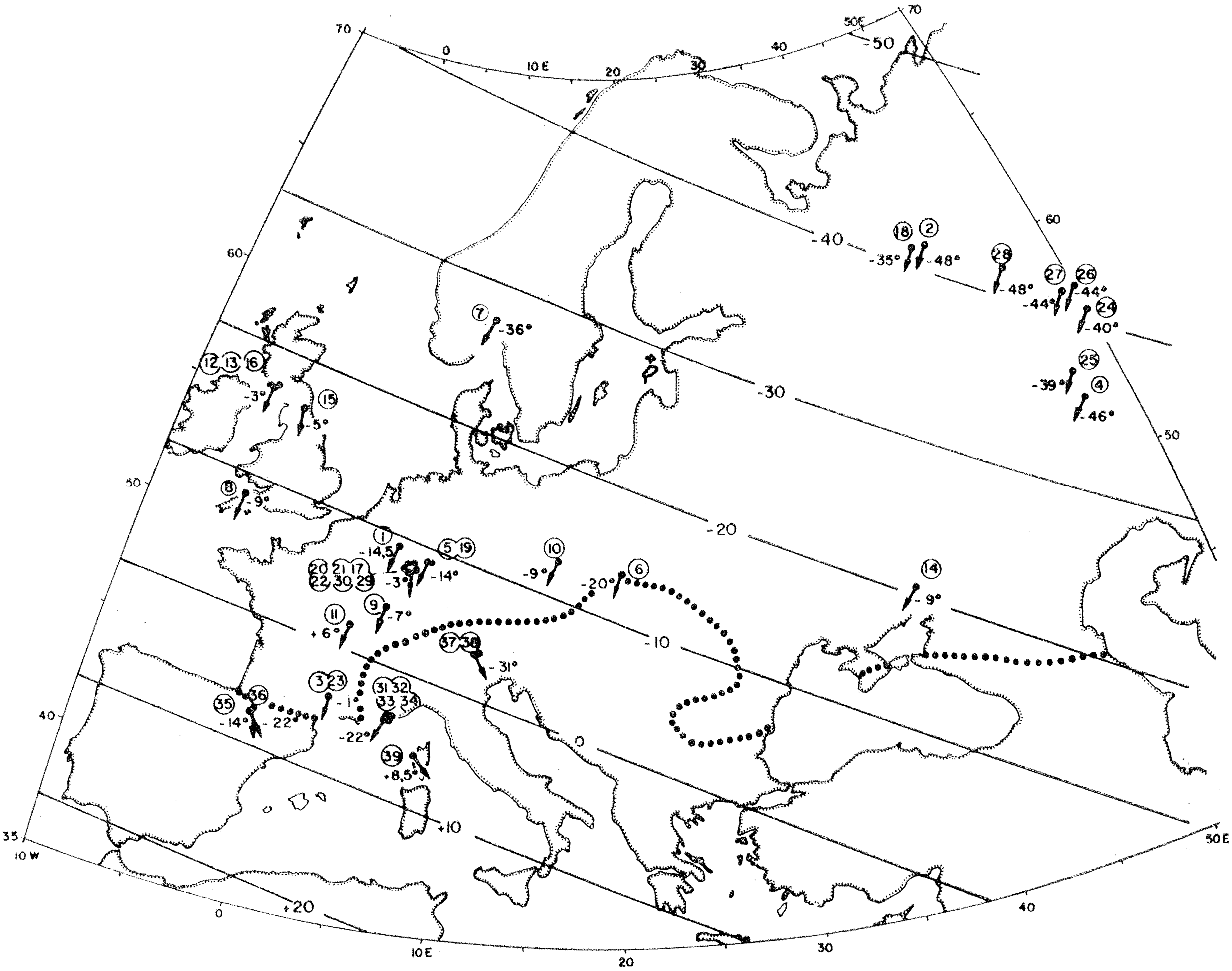

Figure 1. Permian directions of magnetization in Europe. Data compiled by van Hilten up to March 1963. Isoclines drawn around mean pole position for Meso-Europe: 170° E, 42° N. Note aberrant declinations and inclinations for all localities within Alpine fold belt. Numbers correspond to figure 2. •••, Southern border of Meso-Europe. (From Rutten & Veldkamp 1964.)

forms a mosaic of various crustal blocks. These must have drifted together during Mesozoic and early Tertiary in a rather complicated pattern.

An idea of the possible size of these extra crustal movements has recently been supplied by de Boer (1963), who, like van Hilten, is a student of van Bemmelen. de Boer found an average inclination of $-20°$ for the Permian of the Alps of northern Italy. During the Permian the $-20°$ isocline lay a considerable distance to the north, in central Europe (van Hilten 1962*a*). This is a stable area, which cannot possibly have served as the origin of parts of the southern Alps. The nearest area of origin is where the $-20°$ isocline for the

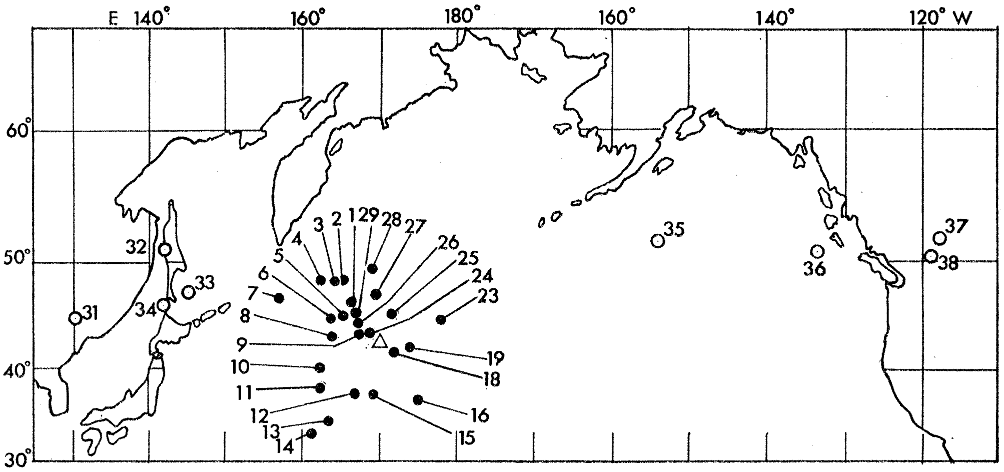

Figure 2. Permian pole positions for European sampling sites. Data compiled by van Hilten up to March 1963 (but samples 17, 20–22 have since been omitted). Samples from Meso-Europe cluster well around mean Permian pole for Meso-Europe (particularly as it was before elimination of above mentioned samples). But samples from the Alpine fold belt are consistently divergent. ●, Meso-Europe; △, mean position; ○, Mediterranean area. (From Rutten & Veldkamp 1964.)

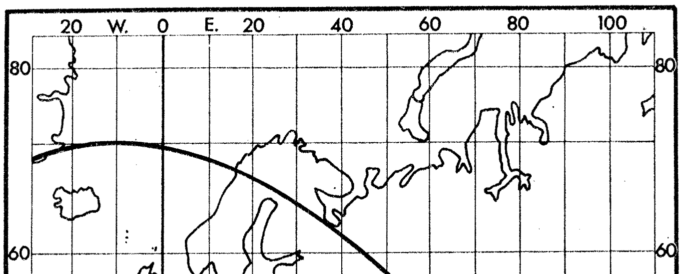

Figure 3. Postulated position of north Italian Alps during the Permian, derived from the position of the Permian isoclines for Meso-Europe. Position *A* refers to the $-30°$ inclination found by van Hilten and by de Boer, position *B* to the $-10°$ inclination found by Findhammer & Guicherit in the same general area of northern Italy (from de Boer 1963).

Permian crosses southward from the stable core of Eurasia into the mobile belt of the Alpine orogeny. That is somewhere at the site of the present Himalayas, some 5000 km east of the present position of the Permian studied by de Boer (figures 3 and 4).

An extra east–west crustal movement of 5000 km, since the Permian, and superimposed upon the continental drift known from the stable part of Europe, is therefore postulated by de Boer.

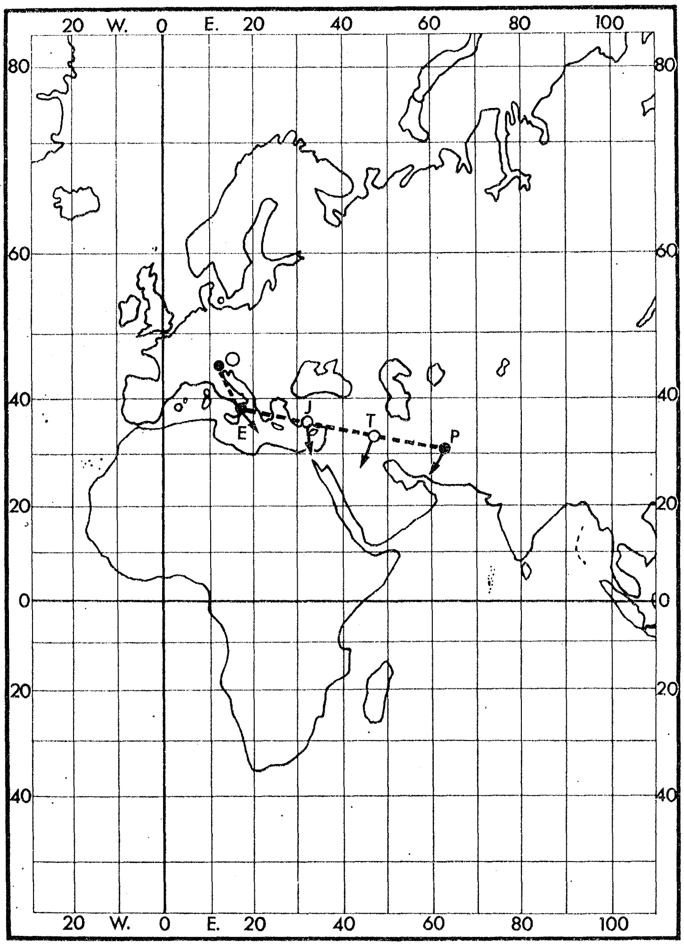

Figure 4. Wandering path of the Alps of northern Italy relative to Meso-Europe. Position of Africa is unknown. Positions *A* and *B* of figure 3 have been averaged to a mean Permian position for the Vicentinian Alps. Open circles indicate less reliable measurements. Wandering was apparently completed by Oligocene time. (From de Boer 1963.) *P*, Permian; *T*, Triassic; *J*, Jurassic; *E*, Eocene; *O*, Oligocene. ↓ direction of Permian palaeomagnetic declination.

This is a first indication only, and much research is at present going on around the Mediterranean, to check this spectacular assumption. But even if the size of these extra crustal movements will ultimately be found to be somewhat smaller than postulated by de Boer, the existence of such extra movements is already most strongly indicated by the discrepancies in pole positions found consistently for various parts of the Alpine fold belt. Incidentally this throws quite a new light on geotectonics, for such tremendous crustal movements within the Alpine fold belt are of a much larger size than those required by the most nappist of tectonicians (Rutten 1964*a*).

Following this further back in the history of our continents, one must always be careful to distinguish between what was at a certain time the stable core of a continent, and what was the mobile belt of a contemporaneous or younger orogenetic cycle. For instance, for the Hercynian orogenetic cycle in Europe the stable core coincides approximately with the Palaeo-Europe of Stille, whilst for the Caledonian orogenetic cycle the stable core of Europe is only Stille's 'Ur-Europa'.

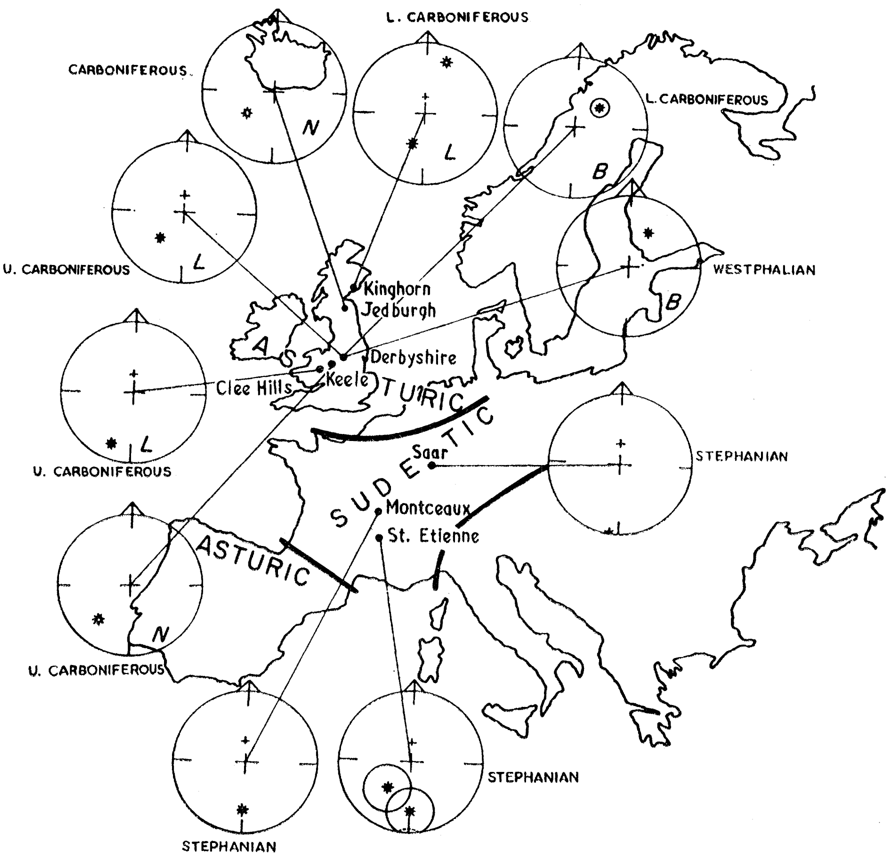

FIGURE 5. Difference in direction of magnetization of Carboniferous rocks from Britain and from continental Europe (Nairn 1960). The British rocks lie in the Asturian part of the Hercynian fold belt, where the folding is post-Westphalian. These rocks are pre-orogenetic, and were laid down in the mobile part of the fold belt. The rocks from continental Europe belong to the Sudetic part of the Hercynian orogeny, which is pre-Stephanian. They are post-orogenetic and were laid down on the stable part of Europe. (The difference in inclination in the British rocks, as studied by Belshé (*B*), by the London (*L*) and Newcastle (*N*) groups, might be due to an error in sign made by one of them—Zijderveld, personal communication.)

We have at present three indications that comparable extra crustal movements also took place during earlier orogenetic cycles. One is for the Hercynian orogeny of Europe, the second for the Hercynian orogeny in Eurasia, and the third for the late Precambrian orogeny in North America.

For the Hercynian orogeny in Europe there seems to be a consistent difference in declination between pre-orogenetic rocks of the Carboniferous of Britain and post-orogenetic rocks of the uppermost Carboniferous in continental Europe (figure 5). The rocks of Britain would in this case belong to the mobile belt of the Hercynian orogeny.

In Russia Kalashnikov (1961) found different pole positions for European and Asiatic rocks of the Silurian and earlier. This too can be interpreted to mean that palaeo Europe and palaeo Asia, which are separated by the Hercynian fold belt of the Oural Mountains, only form one stable continent since post-Hercynian times (Rutten 1964*b*).

In North America Runcorn has cited a consistent difference in pole positions for the late Precambrian from the west and from the northeast of this continent. This indicates that, here also, the present continent is formed from at least two older cores which were separate at that early time.

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Professor A. L. Hales (Southwest Center for Advanced Studies, Dallas, Texas) in a discussion with Professor P. M. S. Blackett said:

It has been remarked that the palaeomagnetic data can only be used to test hypothetical reconstructions, but cannot be used to find the relative positions of the continents, i.e. to make rather than test reconstructions. This is only true if the palaeomagnetic data refer to one period of time only. If, however, data for more than one period of time are available then unique reconstructions can be made as has been suggested in a paper by Graham, Helsley & Hales (*J. Geophys. Res.* **69**, 3875 (1964)). In this paper we pointed out that the relative positions of the continents can be determined uniquely from palaeomagnetic data provided that the continents did not move relative to one another for some considerable interval of time during which appreciable polar wandering occurred. Of course, if this procedure is applied to data from continents moving relative to one another it will not be possible to superpose more than one set of poles, and an assumption will then be needed to assign relative positions.

We have used this procedure to compare the palaeomagnetic data from Australia and Africa and have shown that there is a unique position of Africa relative to Australia (not that given by du Toit or Wilson) for which all the available poles between Silurian and late Mesozoic coincide within the limits of experimental error.

Our reconstruction may conceivably be in error but if so it is because of inadequate data rather than a failure of the method.

Professor R. M. Shackleton (University of Leeds) drew attention to the problems of changes of shape and size of continental masses. The Cambridge work described by Sir Edward Bullard showed only minute changes in the pieces that fitted so perfectly together and this was of great geological significance, but it could not be generally true far into the geological past. A major uncertainty about the structure of the crust is that we lack reliable data on crustal shortening in orogenic belts. Estimates for the Alps have ranged from 0 to 1500 km. If we accept the general opinion that the shortening is of the order of 30 to 50% in many orogenic belts, we must suppose that the crust has been reduced by folding to a mere fraction of its original area and that it may originally have covered the whole surface. About half of the continental crust has been involved in orogenic deformation in the last 600 My. A main result of recent work in Africa has been to show that a large part of that continent has been involved in a late Precambrian or early Palaeozoic orogeny. Through geological time all parts of the crust have been repeatedly deformed, on an average at least four times. No process but convectional sweeping appears competent to account for such deformation.

A possible method for measuring the total shortening in an orogenic belt is the method of offset. If one orogenic belt is crossed obliquely by a second, the earlier one will be offset. It seems possible that this method may be applicable to the crossing of the Ubendian by the Kibaran in Central Africa. Preliminary inspection of maps suggests little or no offset. If confirmed, this would imply no shortening.

An independent estimate of the total area of the continents through time would be possible if the relative rates of change of the volumes of oceans and continental crust were known and if one could assume that the hypographic curve has been maintained in approximately its present form.

Dr A. E. Nairn (University of Newcastle) pointed out that measurements on Cretaceous volcanic rocks from Madagascar and on a few poorly consolidated sediments from south-west Tanganyika suggest that since mid-Cretaceous at least there can have been no relative displacement of these two land masses. Tentative pole positions from Permian measurements on samples from the Série rouge inférieur at Sakoa are significantly different from the Tanganyika Permian pole and hence relative movement of Madagascar appears to have occurred between Permian and mid-Cretaceous times.

Mr W. B. Harland (University of Cambridge) discussed the tectonic evolution of the Arctic–North Atlantic Region:

It is sometimes supposed that Wegener developed his idea of continental drift from watching pack ice splitting and drifting off the Greenland coast. It is certain that much of his thinking about this hypothesis derived from his knowledge of the position and shape of Greenland. To a large extent the postulated past positions and subsequent movements of Greenland provide a clue to, and a critical test of, the history of the whole of the North Atlantic and Arctic region.

My own research bearing on this problem has centred on the relation between Spitsbergen and Greenland (Harland 1959, 1961). In the past various authors have placed these two lands differently. Some of the variety in these positions has arisen because of the differing degrees of precision in plotting according to appropriate projections. But of the more careful reconstructions it is possible to recognize two distinct positions for Spitsbergen in relation to Greenland:

(i) With Spitsbergen to the northeast of Greenland and adjoining its east coast. This position (figure 2) was first used by Wegener in 1912 (see Wegener 1924), also by Bailey & Holtedahl (1938), Carey (1959), and by Wilson (1963).

(ii) Others fitted Spitsbergen on the north coast round the Peary Land corner, as did du Toit (1937) and this position (figure 1) was considered (and rejected) by Wegmann (1948). Bullard, Everett & Smith (1965, this Symposium) found this position the best fit.

These different hypotheses may involve various centres of rotation and transcurrent sheer zones (cf. Harland 1961, p. 124; Wilson 1963, p. 100).

If the Caledonian interpretation of northeast Greenland be accepted with structural trends not smoothing round the corner of Peary Land but passing out in a northeasterly direction (figure 6), then it is difficult to compromise between these two positions—e.g. by arranging Spitsbergen across the corner.

I will outline a new hypothesis relating the history of crustal movements in the North Atlantic and Arctic regions. It is a preliminary attempt to produce a special theory of continental drift, for a limited area, so as to be consistent with available stratigraphical, structural, palaeomagnetic and geophysical evidence. Too little is known of some of the areas under consideration, and some degree of extrapolation to unknown structures has been used. The evidence employed has been considered in its stratigraphical context, and since any palaeogeological reconstruction of a period depends on a satisfactory solution to the arrangement in the succeeding period, an outline of the evidence is taken in order backwards through time.

North, south, east and west will be used as the continents are at present oriented, although it is realized that polar wandering requires different palaeocompass directions.

Two kinds of maps are shown. Four maps with approximately present distribution of the continents (a hybrid projection), emphasize some features of successively earlier periods. The other four attempt to make continental reconstructions and begin with two possible geometrical fits representing different (not extreme) positions of Spitsbergen, rigidity being assumed within three landmasses, namely North America, Greenland and Europe, these being defined by the 500 fm. contour. The first of these was recently computed by Bullard *et al.* (this Symposium). I sketch only two other reconstructions, each representing an earlier long span of time. I intend to draft a series of reconstructions for successive phases to show the palaeogeological situation in each. This will be in conjunction with a geological comparison of the Arctic areas, a project in collaboration with Dr P. F. Friend.

An outline is presented here.

Recent events (figure 1)

Many of the varied methods employed recently give information about relatively late geological circumstances. Thus detailed topographical and bathymetric knowledge, geodetic and gravity studies, evidence for the elastic properties, strength and density distribution within the Earth, estimates of thermal loss, and marine magnetic surveys, as well as surveys of the deep oceans, give data which belong only to the present state of the Earth. Whereas the continental margins once provided the principal evidence concerning continental drift, the ocean floors now yield their share.

All this combines to suggest that the North Atlantic ocean opened out with the formation of new basaltic sea floor. The argument that the line of fission, where the Atlantic floor has recently grown, passes through Iceland and by Jan Mayen and continues into the sea between Greenland and Spitsbergen is accepted here. By analogy, the ridge northeast of Jan Mayen suggests late dextral shear along the west coast of Spitsbergen.

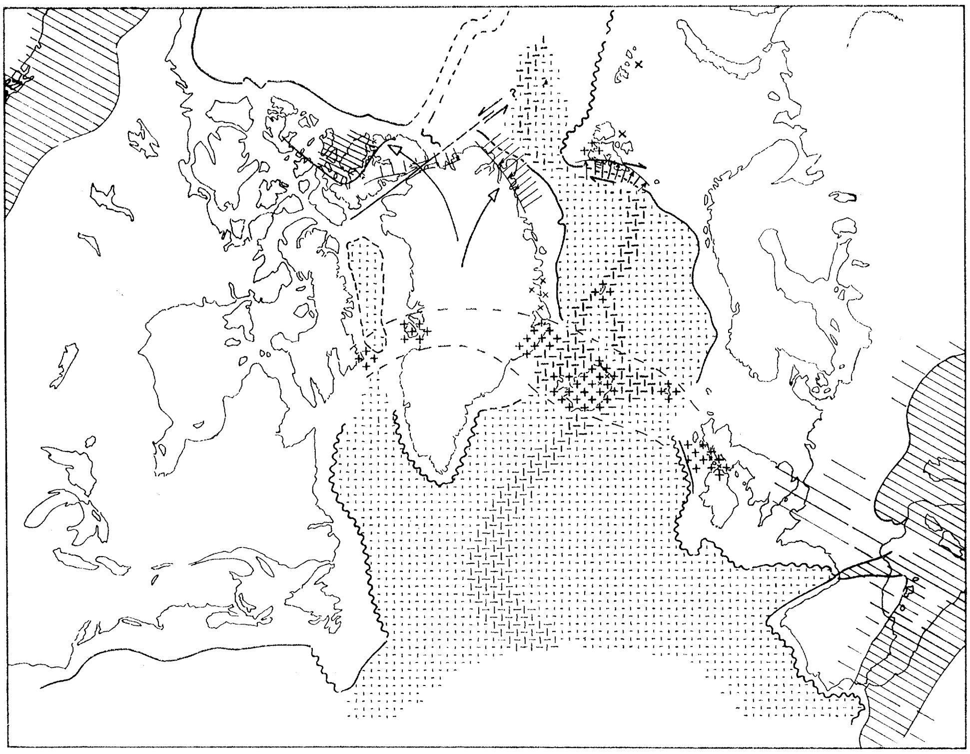

FIGURE 1. Schematic interpretation of Alpine features according to present arrangement of continents. *Heavy lines* indicate continental shelf; where *smooth* it is concordant (Pacific type coastline), where *wavy* it is it discordant (Atlantic type coastline). *Parallel lines*, parallel to general direction of compression; *arrows*, direction of over-thrust movement; *vertical crosses*, volcanic activity; *oblique crosses*, intrusive activity; *cross dashing*, presumed new ocean floor (heavier over Mid-Atlantic Ridge).

This Arctic opening is the thin end of a wedge which widens towards the South Atlantic. It is possible that the whole opened simultaneously with slower movement in the north, but in view of the evidence for northward movement of Greenland and compression in Spitsbergen in Lower Tertiary time it seems that the main opening was interrupted then or more probably began later. Recent volcanic activity in Spitsbergen (Gjelsvik 1963) as well as Iceland is evidence of continued opening.

Early Tertiary events (figures 1 and 2)

Early Tertiary history (figures 1 and 2) in the north does not fit this simple pattern. The volcanic activity of the Brito–Arctic igneous province lies in an approximately transverse belt extending from Scotland and Ireland through the Faroes, Iceland, east Greenland and west Greenland (Disco Island) to east Baffin Island. This suggests north–south extension. It is indicated as an east–west line on Wilson's map (1963, p. 88). We now know that most of the other basic rocks in the Arctic region, e.g. of Spitsbergen (intrusive dolerites) and probably also Franz Josef Land, etc. are of earlier date and therefore not relevant to this phase.

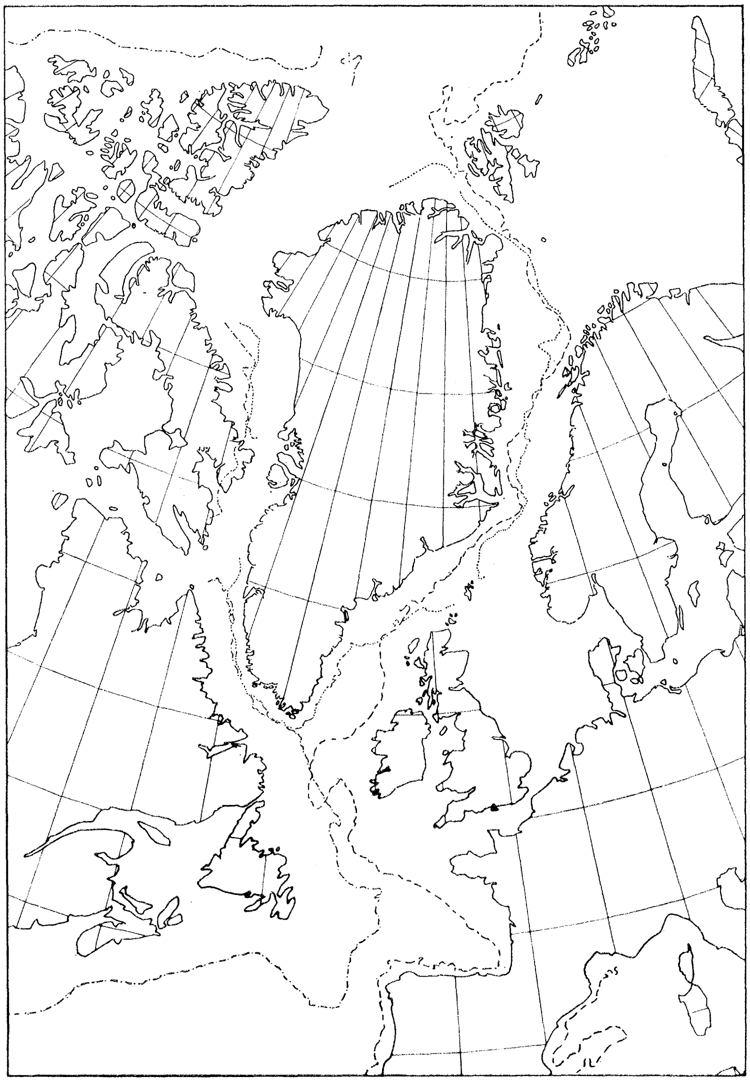

Figure 2. Rearrangement of position of Greenland according to present continental shelves: type (ii) of text. This particular map is taken from a larger plot by Dr A. G. Smith (see Bullard *et al.*, this Symposium) in which the 500 fm. contour is fitted. Europe including Spitsbergen, and North America including Ellesmere Island, are taken as units from present charts without internal distortion. Thus Ellesmere and Baffin Islands have not been adjusted to fit Greenland.

Not so widely appreciated is the evidence of a considerable fold and thrust belt in western Spitsbergen (Orvin 1940, p. 42), part of which has been recently elucidated in great detail (A. Challinor, personal communication). Still less known are belts in north and in northeast Greenland, about which very little has been published (Haller & Kulp 1962). Finally, since Operation Franklin (Fortier *et al.* 1963) there has been intensive investigation of the Tertiary fold structures in the Canadian Arctic. These are largely mapped with north–south axes, and appear to be discordant to the main Parry Islands fold belt of the Arctic islands. These three early Tertiary structures can be interpreted if it be assumed that Greenland pushed north at that time, producing mutual compression structures in west Spitsbergen and northeast Greenland on the one hand, and on the other turning the Ellesmere Island fold belt anticlockwise and so causing east–west compression in the Sverdrup basin.

It is noteworthy that the Tertiary folding was preceded by subsidence with clastic sedimentation in both Vestspitsbergen and the Queen Elizabeth Islands (Sverdrup Basin, Eureka Sound Formation). These short-lived basins of sedimentation may be interpreted as the preliminary stages of the movements which eventually folded them. The Sverdrup basin was probably largely supplied towards the end of its sedimentation history from the Ellesmere Island side, and folding appears also to have been most intense on that side. In Spitsbergen, Tertiary clastic sediments seem to derive from the west and, in addition to thrust and fold structures, faulting parallel to the west coast has long been suspected. A recent analysis of the Alpine structures of west Spitsbergen (A. Challinor, private communication), suggests a general transcurrent faulting in a dextral sense. This also confirms the northward push of Greenland between Spitsbergen and Ellesmere Island. The narrow strait between northwest Greenland and Ellesmere Island was one of the first major transcurrent faults to be claimed. This was suggested by Wegener (1920) on the basis of the map by Dr Lauge Koch. It is only fair to say that Dr Koch, who discussed the matter with Wegener, did not at that time interpret his map in the same way (private communication). However, such a shear movement if only on a small scale would fit the same northward transport of Greenland: the striking photograph reproduced in Wilson (1963, p. 87) suggests at least some movement of this kind. A total movement of not more than 200 km is permissible, but probably far less if most of the crust less than 1000 m below sea level in the Baffin Basin area is of sialic composition.

Palaeomagnetic evidence also supports northward movement of Greenland in so far as pole positions calculated from Triassic, Permian, Infracambrian and late Precambrian rocks (which were among the stable rocks collected in east Greenland in 1957) show a systematic displacement with regard to pole positions derived from North America (Bidgood & Harland 1961). To fit the Greenland results to those from North America requires a closing of the gap between south Greenland and Labrador. This palaeomagnetic evidence for change of latitude is consistent with the excellent fit of present continental shelves and coastline (figure 2). It is assumed that Greenland moved northwards from Labrador, probably in late Cretaceous and/or early Tertiary time, certainly since Triassic time. Wilson (1963) postulated another mid-oceanic rise branching from the mid-Atlantic between Greenland and Labrador.

It is possible that the northward movement of Greenland allowed the east–west Brito-Arctic belt of volcanic activity to be displaced northwards in Greenland.

Mesozoic and late Palaeozoic events

The above assumptions facilitate the stratigraphical interpretation of Mesozoic and late Palaeozoic successions, which are remarkably similar in Spitsbergen, north Greenland,

and the Canadian Arctic. Much work has recently been published by the Geological Survey of Canada, and our own unpublished studies in Spitsbergen serve to confirm what is already known in this respect.

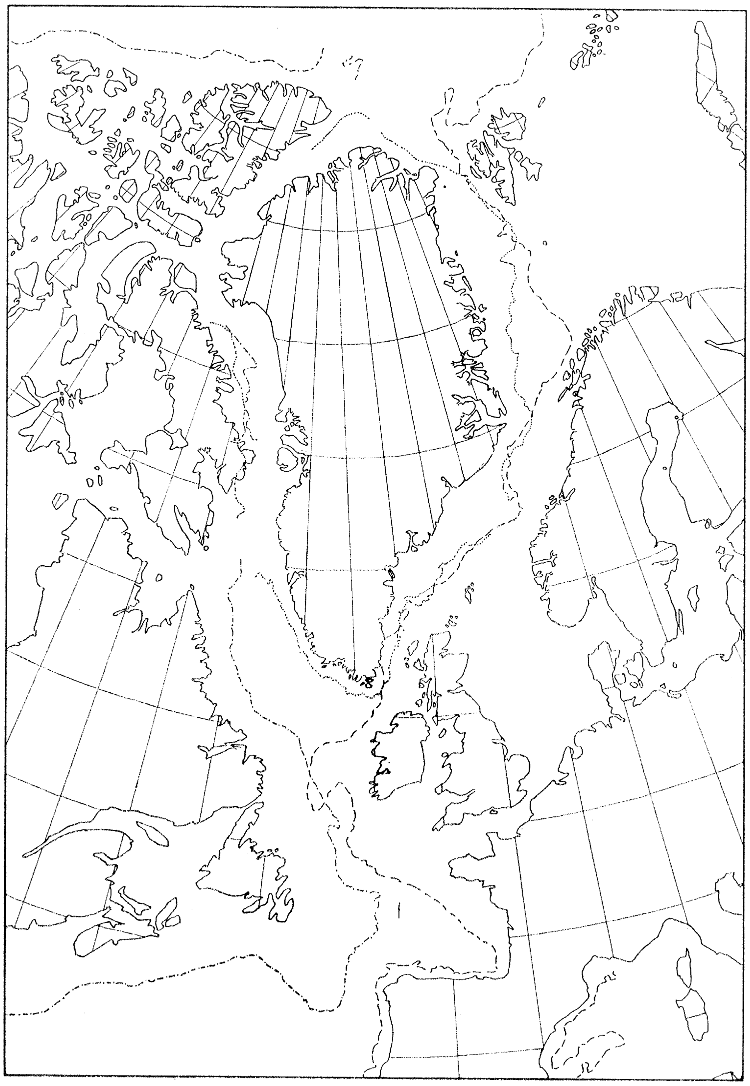

Figure 3. Rearrangement of position of Greenland according to present continental shelves: type (i) of text. Adapted from figure 2; to show an alternative position which best fits the Caledonian geological relations.

A contrast can be made here between central east Greenland and northeast Greenland. Thus Trümpy (1961, p. 248) wrote [the Peary Land] 'Triassic sequence shows affinities with those of Arctic and Cordilleran North America, Spitsbergen and Siberia. It is quite different from that of central east Greenland, where strata of the same age are either missing or (more probably) represented by part of the poorly fossiliferous Mount Nordenskiøld formation.' Indeed, whereas the east Greenland Lower Triassic rocks include red beds indistinguishable from some Keuper siltstones, no red beds are known from the northern localities. The conclusions are that Carboniferous to Lower Tertiary rocks show a striking similarity around the Arctic basin and a marked contrast as one passes south to central east Greenland. This is surprising when the present distribution of structures is considered, for Greenland now cuts across the obvious connexions between Spitsbergen and Ellesmere Island, and Spitsbergen is now nearer to east Greenland. I therefore accept a position with Greenland further south, and joined to Labrador, for late Palaeozoic and Mesozoic time and at least until mid-Cretaceous time. In Spitsbergen, for instance, the Cretaceous succession begins with fine shales and passes upwards into coarse sandstone and conglomerates and Upper Cretaceous strata are missing.

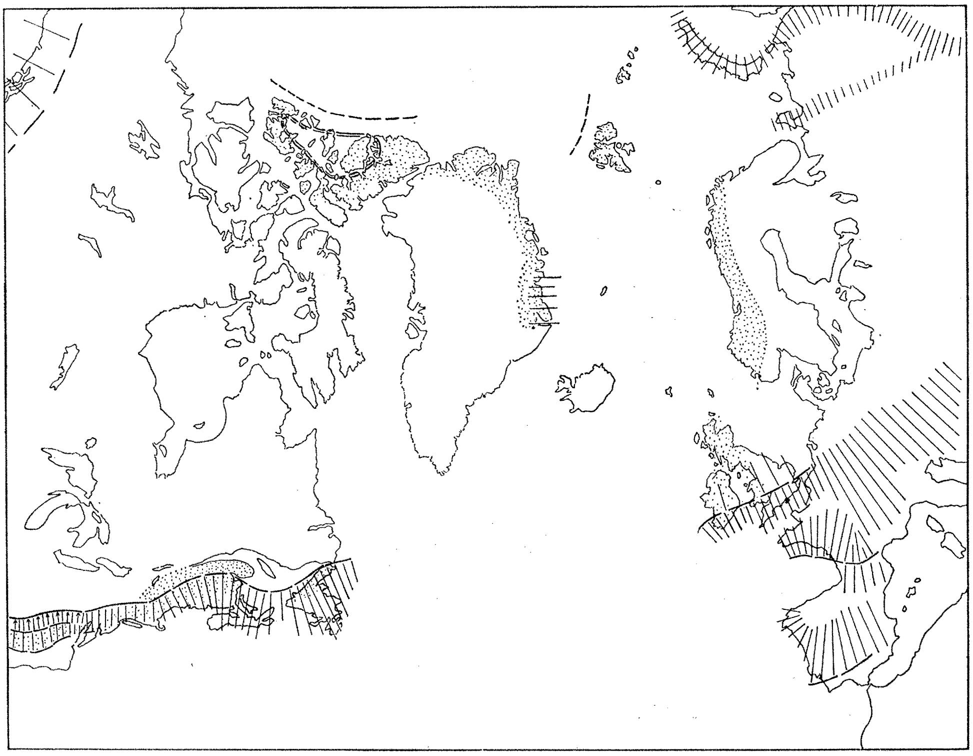

FIGURE 4. Present distribution of some exposed late Palaeozoic features. *Stipple* indicates relics of previous orogenic belt; *linear* shading is parallel to general direction of compression; *the Sverdrup Basin* is marked.

The same contrast is found by considering the distribution of Earth movements between upper Carboniferous and lower Tertiary time. Around the Arctic Basin there was very little diastrophism. In the Canadian Arctic archipelago the Sverdrup Basin received a relatively undisturbed miogeosynclinal sequence from middle Pennsylvanian until the Lower Tertiary Eureka Sound Formation which foreshadowed the orogeny. In Spitsbergen a similar, but less thick, succession is found. Those who seek to recognize Stille's phases of folding throughout the world have tended to emphasize slight breaks in the successions and, once so labelled in the literature, these breaks have given the impression of considerable Hercynian disturbances. Recent Soviet tectonic maps of the Arctic, for instance, colour the northern fold belts of Canada and Greenland as Hercynian structures. This is misleading, for severe diastrophism of either late Carboniferous or Permian age is conspicuously absent in the north.

The later Palaeozoic (Hercynian-Appalachian) tectogene stretched in a belt from the Appalachians, through southern Britain and central and southern Europe, to Suess's massive Altaids in the heart of Asia (figure 4). At this time, Greenland was part of North America and was welded by the Caledonian belt to the Fenno-Scandian Shield; the Caledonides, being still an unstable area, allowed marine extension, and responded to late Palaeozoic north-south stresses in a more gentle way (as evidenced in east Greenland, where, after much Devonian diastrophic and igneous activity, some Lower Carboniferous folding and very extensive north-south faulting took place in Carboniferous and Lower Permian times. To emphasize the posthumous nature of these late Palaeozoic movements Koch (1961, p. 153) included all Upper Ordovician to Lower Permian structures in the term Caledonian *sensu lato*. The role of Hercynian in relation to Caledonian movements will be considered after this stratigraphical review.

Devonian–Lower Carboniferous events: (figures 5 and 6)

The Caledonian diastrophism (*sensu lato*) is taken here to include Ordovician to Devonian movements in the Caledonian province and this section mainly concerns the *Late Caledonian events*. The relics of the Caledonides in Spitsbergen, Scandinavia, and the British Isles on the one side, and east Greenland, Newfoundland and right through the Appalachians on the other, represent one of the greatest tectonic features on Earth. Little is known of the fold system of north Greenland but the Innuitian fold systems of the Canadian Arctic had a similar Palaeozoic history except that diastrophism appears to have extended well into Lower Carboniferous time. However, it is an essential feature of the Caledonian–Appalachian system that the geosynclinal development which preceded the folding began long before Cambrian times, and indeed in all cases accumulated great thicknesses of Precambrian sediment.

In east Greenland movements probably continued, with faulting, folding, and igneous activity in small, well established phases in Middle and Upper Devonian time (continuing onwards). In Scandinavia and Britain Old Red Sandstone facies also reflect uplift and local subsidence with some deformation at different times in different places. Similar Old Red facies are found across the Atlantic, and the clastic wedges along the western flank of the Appalachians are related to the Acadian orogeny along the geosynclinal axis.

This late Caledonian diastrophism seems to reflect a change from the east-west compression of the main Caledonian phase to the north-south compression of the Armorican belt in the North Atlantic region. It is postulated here that whereas some east-west compression continued, a north-south component was beginning and early became most evident in the east-west Innuitian fold belt where it was the main orogeny, and also in the Acadian system. Otherwise graben and basin structures were developed by this changing situation, as posthumous movements of the main Caledonides. Where the Caledonian belt runs with the main north-south component the tectogenic events were minor. There is a marked similarity in the scale and tectonic position of the graben in the late Caledonian movements of the Midland Valley of Scotland, east Greenland and north Spitsbergen.

The Franklinian geosyncline was divided by Thorsteinsson & Tozer (1961) into an inner or southern miogeosyncline and an outer or northern eugeosyncline. Less is known of the latter but it is characterized by some volcanics, much clastic sediment and few fossils, and is in any case much obscured by Pennsylvanian and later rocks. This whole fold belt trends east–west and curves round in Ellesmere and Axel Heiberg Islands to northeast–southwest. It is generally dated pre-Pennsylvanian and in places post-Devonian, but Devonian rocks are of limited extent and where found are commonly clastic, suggesting northerly provenance. Thus it seems reasonable to suppose that some compression and uplift began in Devonian time even if it extended into Lower Carboniferous time.

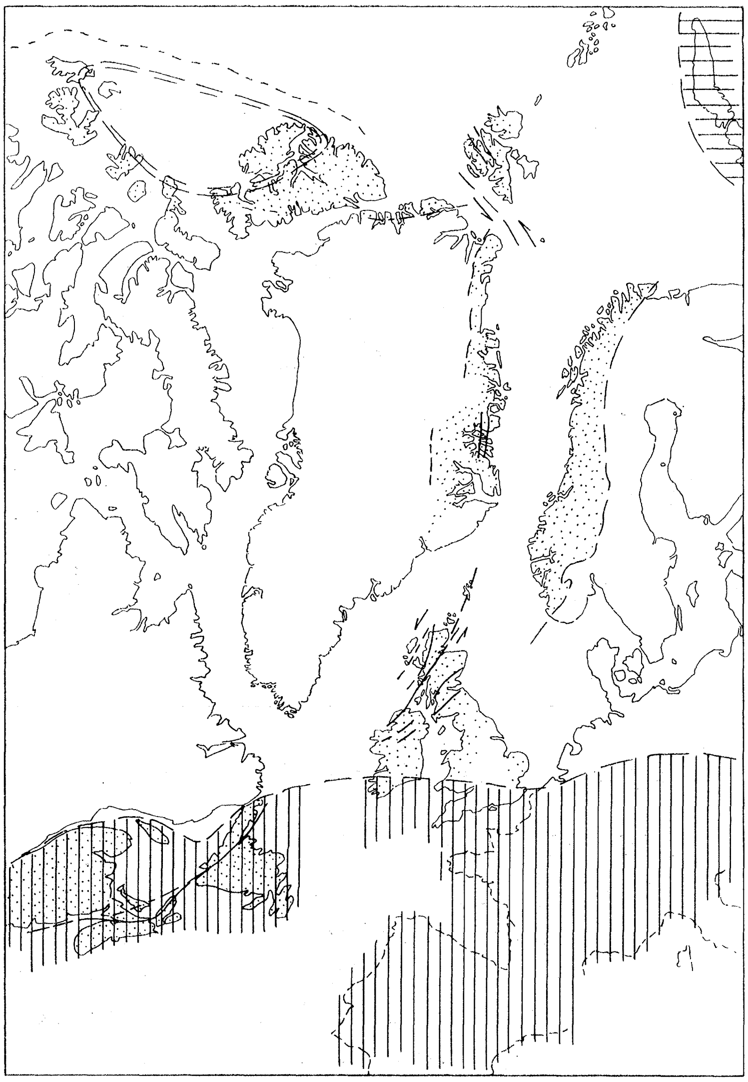

Figure 5. Mid-Palaeozoic reconstruction. *Stipple* indicates area of newly formed mountains; *ruling* covers mobile area to be compressed in late Palaeozoic compression and the coastlines thereunder are not palinspatic.

Throughout the Arctic Basin in Permian time conditions were uniformly marine with distinctive facies (e.g. 'Svalbardian stage'). Before that, in Spitsbergen and northeast Greenland the Carboniferous succession was more disturbed and Lower Carboniferous and uppermost Devonian facies were entirely continental. These followed the Svalbardian folding of late Middle to early Upper Devonian. This folding is demonstrably pre-Tournaisian and probably pre-Famennian and most probably began in late Givetian. The north–south graben formation is associated with this phase of folding and thrusting and was preceded by typical Old Red Sandstone facies with freshwater connexions throughout the Caledonides and with marine incursions from the north and the south.

The suggested change in compression direction may be responsible for some of the later and weaker cross-folding characteristic of some late Caledonian structures.

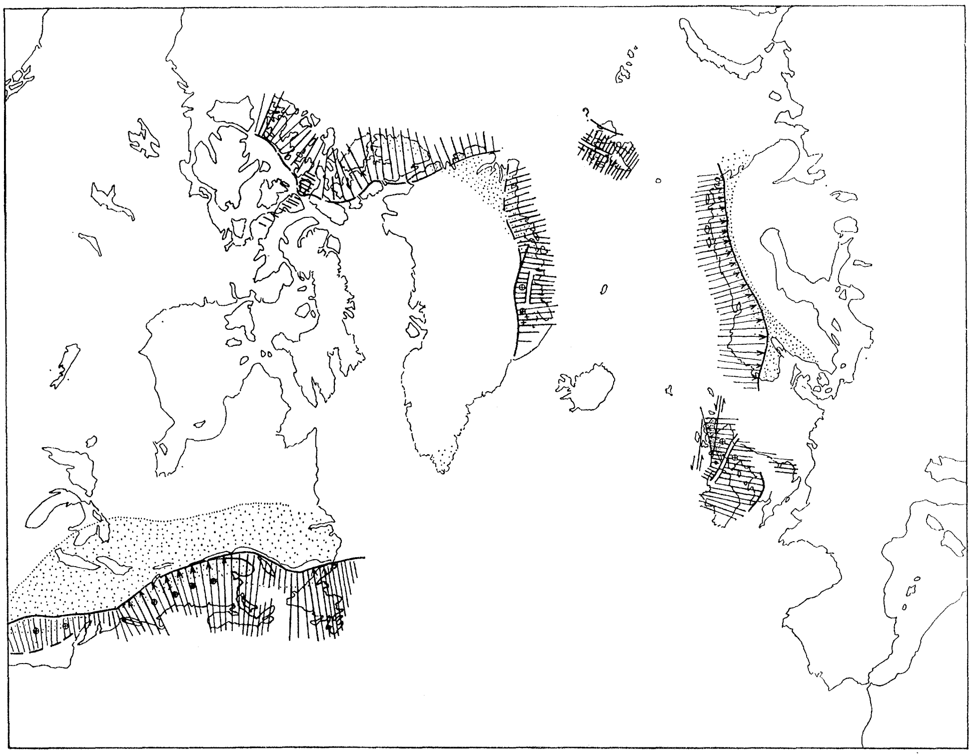

Figure 6. The present distribution of Ordovician to Lower Carboniferous compression structures. *Stipple* indicates remains of earlier mobile belt.

Main Caledonian compression (figures 5 and 6)

Throughout the Caledonides (Spitsbergen, Greenland, Scandinavia and Britain) there seems little doubt that the main tectogenic phase was centred in Silurian time. In some cases it may have begun earlier, from late Ordovician to early Silurian; in others it continued later, from late Silurian to early Devonian. Generally the date cannot be fixed precisely and the diastrophism may have had a long and complex history.

Extreme deformation and metamorphism resulted, and where the metamorphism was less intense (and the tectonic facies of low intensity), i.e. by the forelands, extensive overthrusting is manifest. Considerable crustal shortening in a generally east–west direction must have resulted. Thus any reconstructions of pre-Silurian events must allow for an extension throughout the Caledonian geosyncline of not less than 200 km and possibly much more.

The generally east–west direction of this compression is emphasized because it distinguishes the early phase of the Canadian Arctic. At this time relatively minor folding, trending north–south, in Cornwallis Island, West Devon Island, and south in the Boothia arch, interrupts the later east–west fold system of the main miogeosyncline. It took place between Upper Silurian and Middle Devonian and may thus be later than the main phase elsewhere. On this interpretation it is only a partial explanation of the Cornwallis fold belt to attribute its discordance to basement control. To this may be added the explanation that folding was a marginal effect of the main Caledonian east–west compression, and resulting uplift yielded thicker later deposits on either side where the later folding was accentuated. This change of strike in the Canadian Arctic would appear to pinpoint one of the major changes in the pattern of convection currents of the mantle.

Another conclusion is that the Caledonides need not wrap around the north coast of Greenland and join the Franklinian fold belt. Rather these are distinct, often discordant, but related systems. The temptation to join up the ends of fold belts need not be indulged. Assuming that there was an Arctic Ocean basin at that time, the Caledonides would run north from east Greenland through Spitsbergen and stop at the margin of the Arctic basin. For, if a general compression belt in a downward convecting zone crossed from a geosynclinal area to a basaltic ocean basin, the former would compress to form an orogenic system which would continue to rise, and the basalt with thin ocean sediments would roll down without leaving obvious trace. There might be some tendency to squeeze the folds out axially into the ocean basin; this may be a partial explanation of the axial extension in the north–south Ny Friesland belt in Spitsbergen (Harland 1959). There is great variety of structure within the Caledonides; but there is also marked similarity as between one region and the next resulting from an overall tectonic regime possibly due to a particular convection pattern developing and changing under a wide area of the crust.

Areas of extension corresponding to the Caledonian compression may have been at a considerable distance but, in the evolution of the Urals, the beginning of the Upper Palaeozoic geosyncline has been regarded by some Soviet geologists as a period of extension in Lower Palaeozoic time. It is even possible that between the Fenno–Scandian Shield and the Siberian Platform an oceanic belt extended which was closed in later Palaeozoic time.

Mid-Palaeozoic transcurrent movements (figure 5)

The transcurrent fault system of the Great Glen in Scotland with its sinistral shear may well be repeated between the mainland and the outer Hebrides (Dearnley 1962). If two, and indeed more, such faults are recognizable in such a small sector of the crust it is not unreasonable to suppose that others in a similar sense existed, and therefore that the total displacement was greater. The Cabot fault system may also be analogous (Wilson 1962).

It is postulated, then, that a megashear system extended at least to the latitude of Spitsbergen, and the net effect was to bring Greenland south with respect to Europe and Spitsbergen by 200 to 300 km. There is other indirect evidence for this: the north–south compression evident in Arctic Canada is not so marked in the Caledonides proper, and thus a consistent differential on either side of the Caledonian belt is demonstrable. More striking is the effect this has of bringing about an earlier change in the position of Spitsbergen in relation to Greenland.

After this supposed transcurrent faulting, Spitsbergen lay northeast of Greenland throughout at least Permian to Jurassic time, and until Greenland reversed and moved north differentially Spitsbergen was connected with the then uniformly east–west Sverdrup basin on the ruins of the Innuitian system. Before this the whole of the older history of Spitsbergen connects intimately with that of east Greenland, not only in Caledonian deformation but even more in the facies of the Caledonian geosyncline. Figure 7 shows the postulated Lower Palaeozoic relative positions with a minimum opening of the Caledonian compression and with an arbitrary amount of transcurrent movement replaced.

Once formed, such a fracture zone would be a permanent weakness in the crust and this may have selected the particular line of later shear in the opposite sense and finally of separation.

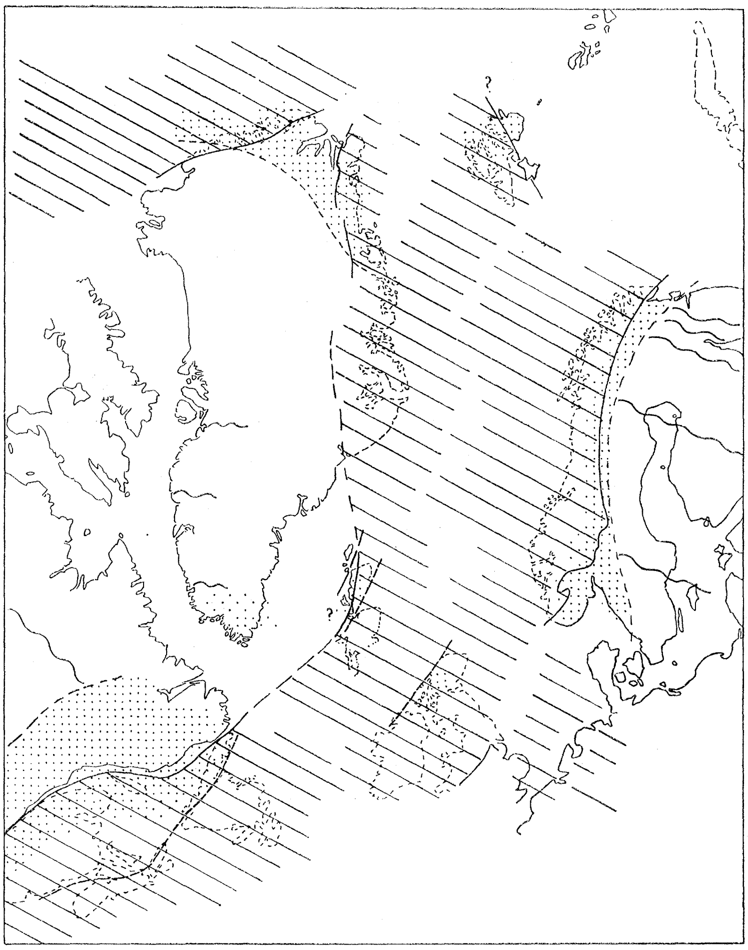

FIGURE 7. Late Precambrian–early Palaeozoic reconstruction. *Stipple* marks relics of latest Precambrian orogenies; *ruling* marks mobile area to be compressed in Mid-Palaeozoic time.

The Caledonian geosyncline (figure 7)

Within the axis of the geosyncline, sediments to a thickness of 10 to 15 km of late Precambrian age were capped by a distinctive double tillite horizon, then fossiliferous Lower Cambrian, and a carbonate sequence in which Lower Cambrian faunas were followed, after a somewhat barren succession, by Canadian faunas. This facies, familiar in the Durness Limestone, occurs throughout much of the geosyncline (which was then in equatorial latitudes). Below the double tillite horizon there is also a widespread carbonate facies which can be matched in many respects between north Norway, Greenland and Spitsbergen. The Precambrian succession still lower becomes more variable, and farther south the lower Palaeozoic succession is more variable and is commonly transgressive, with facies evidently responding to other disturbances in the neighbouring geosyncline. This suggests that the Lower Palaeozoic geosyncline in Britain, for instance, has migrated southeastwards from an older geosyncline which was in part uplifted. Somewhat analogous situations occur in Newfoundland in the Appalachians.

For a Precambrian time span long enough to accumulate 10 to 15 km of fine sediment over a wide area, with little disturbance, the Caledonian geosyncline was developing, and the Lower Palaeozoic part of it is to some extent the final and/or semi-final chapter. The comparable carbonate facies which are found in some thickness above and below the tillite horizon in the Caledonian Arctic make it reasonable to suggest a minimum time interval for this Precambrian sedimentation. Such an estimate was made graphically (Harland 1961, p. 116) on the basis of the Hecla Hoek succession. It would seem to require at least 300 My and probably more. Thus, while orogeny was slow and tectonic events gradual, nevertheless the preceding subsidence was far more slow and gradual. This has implications for the convection current theory discussed below. Igneous activity seems to be characteristic of the early and late stages.

The Pre-Caledonian orogenies (figure 8)

Throughout the area of the Caledonian geosyncline, and intimately mixed with its subsequent deformation, there is the following evidence of earlier orogeny or orogenies.

1. The well established Grenville belt parallel to and overlapping the west of the Appalachian belt (say 850 to 1050 My).
2. The southern tip of Greenland, which is presumed to have been joined to Labrador at that time, shows some similar ages amongst others.
3. The Carolinidian belt of northeast Greenland preceded, underlies, and extends west of the main Caledonian belt. It has not been dated radiometrically and may or may not correspond to the Grenville orogeny.
4. Similarly, the Moine Series, but with the possible relic radiometric dates of about 720 My, may belong to the same belt.
5. Possibilities of relatively concordant yet older structures with some radiometric evidence are emerging from the Caledonides of Spitsbergen.
6. The Scandinavian part of the Caledonides probably contains much of the earlier metamorphosed material, often difficult to distinguish. The main evidence, however, for a Pre-Caledonian orogeny arises in a parallel belt just to the east of the thrust margin, which widens at the south and north. This belt has been called the Ripheides in Soviet literature, e.g. Polkanov & Gerling 1960, and recently the Sveconorwegian by Magnusson (1965).

Whether or not these all belong to one earlier belt analogous to the Caledonian-Appalachian system, or represent separate orogenic epochs, they clearly may be classified together as being generally concordant with the Caledonian, in contrast with the still earlier (Pre-Grenville) structures and some later (post-Caledonian) structures.

The duration of the Caledonian geosyncline and orogeny might extend from 800 ± 100 to 350 My; the Grenville and contemporary sequences, allowing a similar if shorter period of prior sedimentation (but younger than the previous metamorphic events), would range from say 1300±100 to 800±100 My. Indeed, the combined Grenville-Caledonian history represents a time interval (in two broad chapters of nearly equal span), of about 1000 My.

This suggests that a convection system was similarly oriented for a very long part of geological history, yet not actively turning except at two widely separated periods. It is possible the early Caledonian sequence was the longer if Gastil's radiometric curves are representative. However, the view that here was a unique interval and change in the course of the evolution of the Earth, as held, for example, by some Soviet geologists, does not seem to be warranted if the evidence of still earlier tectonic events be considered.

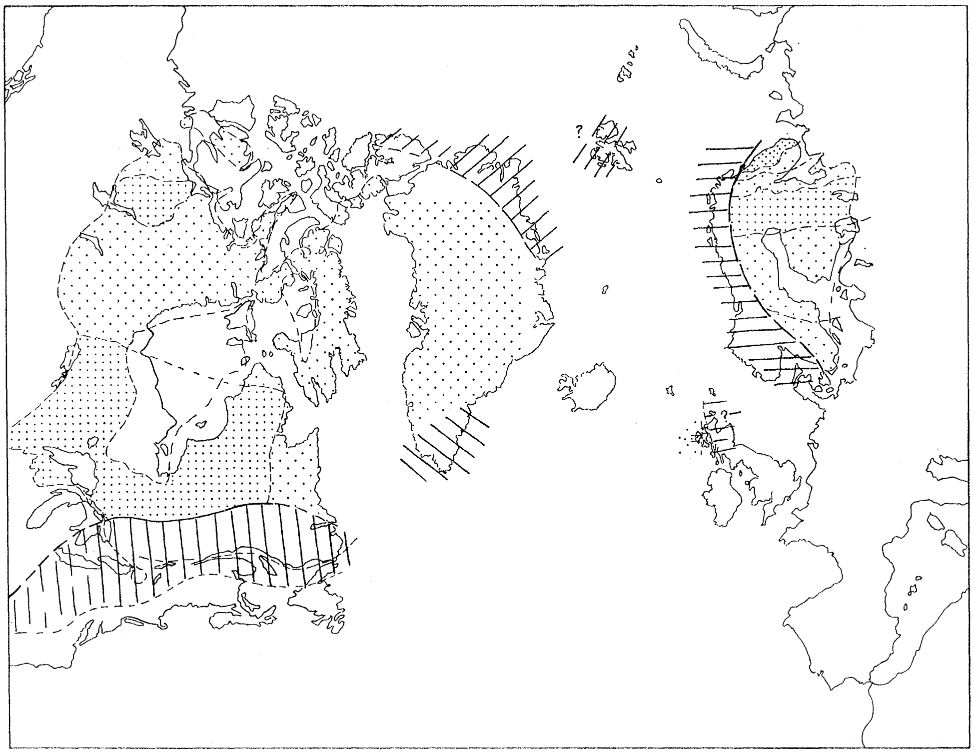

FIGURE 8. Present distribution of exposed Precambrian tectogenesis. Areas of Grenville-Riphean mobility are *ruled*. Areas of earlier tectogenesis are *stippled*, with increasing intensity for the older metamorphism.

Pre-Grenville history (figure 8)

Structures earlier than say 1300 My are mostly discordant to the Caledonian-Grenville pattern, and if they are to be interpreted by palaeo-jigsaw methods this must be done by first joining the Canadian, Greenland and Fenno–Scandian Shields, with the Atlantic closed (to restore Alpine movements) and then sheared and reopened in stages (to restore Caledonian and Grenville movements). Palaeogeological maps and palaeomagnetic interpretations must take account of these drifts. The older structures are somewhat fragmented but there is a tendency to a similar arrangement in the Canadian shield and the eastern part of the Fenno–Scandian Shield (figure 8).

The Arctic basin (figure 1)

Any hypothesis of the Arctic should account for the principal features of arctic bathymetry. The Lomonosov and other ridges cannot easily be dated, and so, depending on their age, alternative hypotheses are open. Because these hypotheses are so speculative they are more likely to derive from the kind of hypothesis outlined above, rather than to support or refute it. It may be surmized that the latest drift which opened the space between Greenland and Spitsbergen also opened the basin between the Lomonosov ridge and Spitsbergen (the Siberian basin; cf. Wilson 1963) so that the more ancient basin would largely be inherited at present by the Canadian basin. In this way (as suggested by Wilson) the Lomonosov ridge could have been a strip of the continental margin north of the Barents Shelf and Greenland, split off by this latest drift.

Sequence of convection currents

It would seem that, viewed from the standpoint of the Arctic–North Atlantic region, the sequence of patterns of convection currents may be summarized broadly to account for a complex succession of dominantly north–south compression structures recorded in the pre-Grenville shields. Combined with similar studies elsewhere, a global sequence may in due course be derived.

Some time after 1300 My a new sedimentary pattern developed which resulted in the Grenville-Caledonian belt. We cannot say from available evidence whether any extension took place during the period 1350 to 350 My but at least two major periods of compression must be accounted for and this would be consistent with two turns of a major convection system with long pauses for preparation.

Some reorientation—particularly in the eastern part of the area under consideration—took place about mid-Palaeozoic time, and Hercynian-Alpine events reflect a north–south compression. The Alpine compression was accompanied and outlasted by the Atlantic extension. Whereas in general the opening may have been localized by the combined Palaeozoic fold belts, a stronger upwelling was located (actively or passively) by the junction of the Appalachian, Caledonian and Armorican belts, to allow some subsidiary north–south extension as well.

Discussion

Some general considerations from this regional analysis include:

(1) Compression structures indicate the relative movement of different parts of the crust. Conservative compression (shortening) estimates have been used, and these give only minimum figures for local crustal shortening, which may also take place with little folding preserved and exposed. Economy of hypothesis would attribute most compression structures to convection currents, if convection currents are to be invoked to drift continents.

(2) Although some geosynclines may not be explained in terms of simple convection hypothesis, it is suggested here that the typical development is a long period of gentle subsidence, possibly due to cooling and contraction of the mantle until it is dense enough to subside actively and thus localize a downward convection. If subsidence, due to a change of volume, creates a space which is filled by sediment this will accentuate the process for a time. Convection will bring in the consequent horizontal transport which will close up the crust and compress the geosyncline or whatever else is above the downwardly convecting belt. If this takes place in the ocean with virtually no sediment, there will be no evident record of it except in general subsidence at the time. It is thus possible

for a mobile belt to pass directly into an ocean (as already discussed in the case of north Spitsbergen).

(3) Sufficient cases are known where relatively quiet conditions appear to have obtained at no great distance from 'violent' diastrophism, so that undisturbed marine successions do not necessarily rule out synchronous tectogenesis of a neighbouring region. This fits the idea of passive conveyor-belt type transport of crust on mantle, with deformation mainly at the rollers and edges. This is supported by the extraordinary geomorphological 'fit' of continental shelves. Some parts of the Earth's crust may thus retain their shape for long periods while other neighbouring parts undergo considerable plastic distortion. Moreover, the extraordinary fit using the 500 fm. line suggests that continents have retained their isostatic level as well as their undistorted plan in spite of drift. The parallelism of the Labrador and south Greenland coasts to each other and to their continental shelves suggest in this case more or less equal marine erosion with or without equal warping.

(4) Runcorn (1962) set up a hypothesis that continental drift on the scale of the late Cretaceous-Tertiary opening of the Atlantic and Indian Oceans was a unique or exceptional event in geological history. This he related to the growing diameter of the Earth's core and consequent effect on the size and number of convection cells possible in a mantle of reducing thickness. According to this postulate the 'Alpine' drift would be preceded by a very long period of no convection, before which was a convection of a larger order.

It is suggested here that geological history as seen throughout the surface of the Earth is punctuated by orogenic epochs, and the simplest explanation is to treat these structures as compression belts related to downward convection currents. If so, there must have been convection currents intermittently throughout geological time. However, it is reasonable to assume that the development of the core (which seems inevitable) had some effect on the convection currents, and the long pause before the Caledonian geosyncline was squeezed (and possibly also the Grenville one) may represent a time of relative stability in the mantle. At least the same pattern persisted for a long time in the North Atlantic.

(5) Palaeoclimatological and palaeomagnetic considerations suggest that this could also have been a time of stability with regard to polar wandering. Late Precambrian data may be fitted to Ordovician and Devonian reconstructions of palaeolatitudes without obvious inconsistency.

(6) Polar wandering in addition to continental drift must have taken place, and the great Caledonian-Grenville belt could have been near-equatorial. It is thus possible that this belt resulted from a symmetrical circulation with downward movement approximately about the equator or swung to that position on formation.

(7) Following Holmes's original suggestion (1933) it seems reasonable to postulate that the later opening up of the Atlantic Ocean was due to the concentration of [Grenville-] Caledonian-Appalachian mountain systems. For the typical North Atlantic coastlines are largely of Pacific type, i.e. concordant (parallel to the great orogenic belts of Greenland, Spitsbergen and Scandinavia and then the Appalachians). Whether convection currents are generated in the lower part of the mantle or not, the pattern must be affected somewhat by the ability to lose heat at the surface. Thus a thick sialic crustal welt might be capable eventually of localizing an upward current.

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