FLAWS IN THE CONTINENTAL CRUST

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by

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Summary

The Precambrian portions of the continental crust commonly retain structural patterns formed in response to early global tectonic regimes which bear no relationship to the plate tectonic regime of Mesozoic and Tertiary times. Some large shear zones that were built into the European and North American continents at an early stage have persisted as deep flaws extending into the lithospheric mantle and have influenced crustal movements, magmatism and hydrothermal circulations throughout later geological events. On a larger scale, the architecture of the continents has tended to pre-determine the positions of rift systems formed during the preliminary stages of continental break-up. These relationships raise general problems concerning the functioning of the plate tectonic regime.

The antiquity of continental structures

Among the most remarkable geological findings of the past two decades has been the discovery that the crustal layer which underlies the oceanic basins differs from the continental crust not only in composition and thickness but also in age - the oceanic crust is almost everywhere less than two hundred million years in age, whereas much of the continental crust dates back to at least two thousand million years ago. The characteristic structure of the oceanic crust established by marine geophysical studies has turned out to bear a direct relationship to the process of sea-floor spreading which is responsible for the formation of new oceanic crust (Vine & Matthews, 1963, see Oxburgh, 1974, for a general synthesis). The growth of the crust is achieved by magmatic activity at the mid-oceanic ridges which are sites of abnormally high heat flow; parallel strips of igneous rock added symmetrically on either side of the ridge define a broad striping of the crust which is readily detected by magnetometer surveys. The short life-span of the oceanic crust is a consequence of the fact that the generation of new crust at the mid-oceanic ridges is balanced by the removal of the excess material at destructive plate boundaries where old oceanic crust is forced down into the mantle and largely destroyed. The integrated movements of crustal plates under the present-day tectonic regime of the Earth (the plate tectonic regime) are to a large extent controlled by the effects of sea-floor spreading and the attention of geologists and geophysicists has consequently tended to concentrate on the oceanic parts of the cycle.

The continental crust, on the other hand, is made largely of Precambrian rocks formed under tectonic regimes that have long since ceased to operate. Granitic rocks of low relative

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density which form much of the continental crust impart a buoyancy that has rendered the continents almost unsinkable, thereby preserving them as geological entities from a very early stage of the Earth's history. Older portions of the continents may therefore preserve structural patterns which are very much older than the framework of constructive and destructive plate boundaries that control the workings of the plate tectonic system. Given this discrepancy in age, one might expect the early structural features of a continent such as North America to bear little relationship to the tectonic system controlled by sea-floor spreading in the adjacent ocean basins. A closer look at the structural evolution of the continents, however, reveals some unexpected relationships and raises interesting questions concerning the mechanisms by which place movements are initiated. I hope to explore these relationships by reference to early structures of two kinds in the continental crust. In this context, it is convenient to take up the story at about the end of the Archaean era (~2700 Ma) when, for the first times, masses of continental crust several hundred kilometres in diameter and at least 30 kms in thickness began to behave as cratons - that is, as stable and mechanically strong structural units.

Shields and platforms

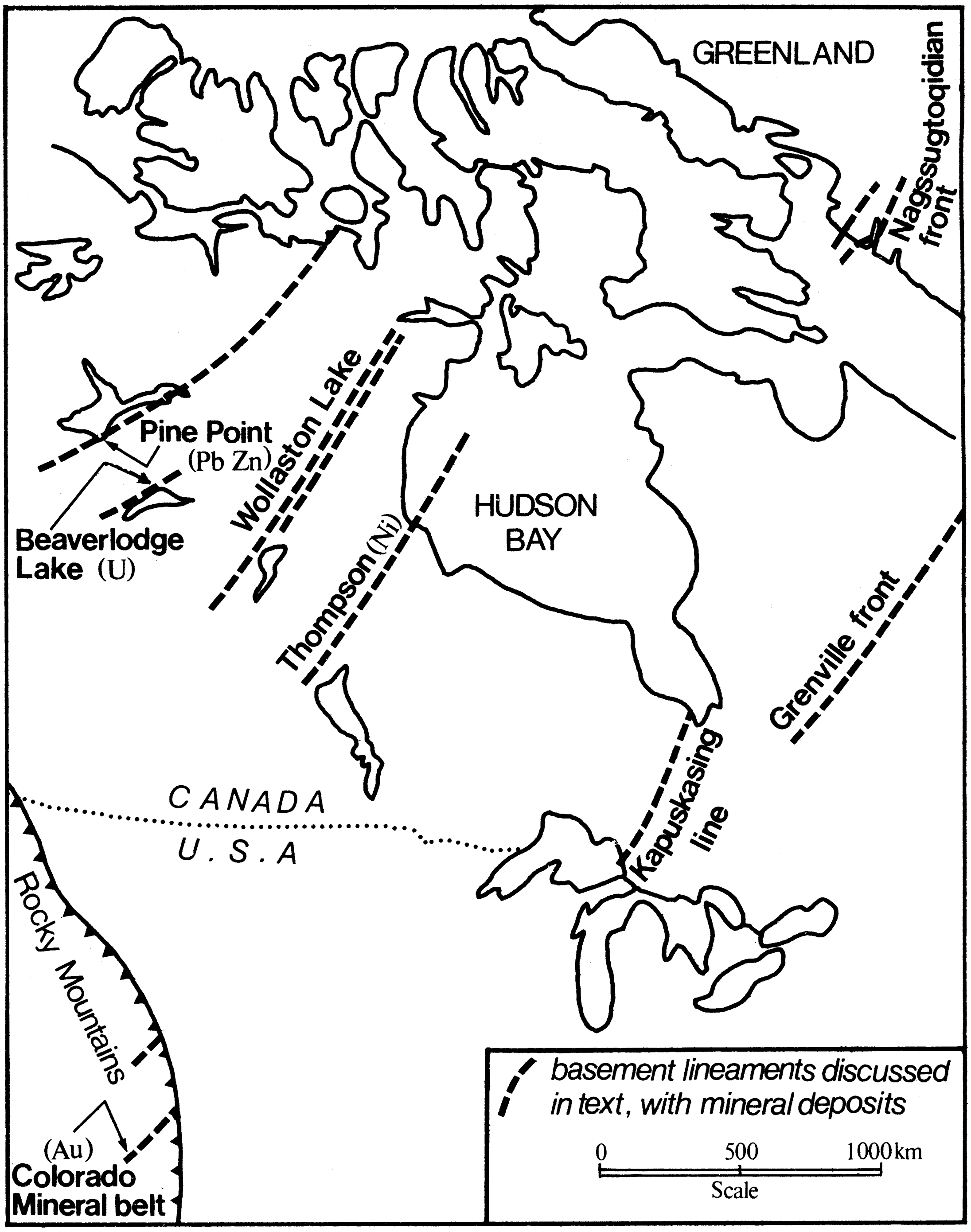
Archaean and early Proterozoic rocks in which early structural patterns remain are exposed today in most of the large Precambrian shields and in a number of smaller shield fragments such as southern Greenland and north-west Scotland. Similar rocks are also found at depth in platform regions, such as those of central USA and the plains of western USSR, where they form a basement lying unconformably beneath a cover of undisturbed younger strata. The structural patterns which were developed during Archaean or early Proterozoic periods of deformation and metamorphism can, of course, be established in the shield areas by the ordinary techniques of geological mapping. In addition, geophysical techniques which can "see through" the undisturbed sedimentary cover may enable one to trace the main structural elements through the platform areas. By these means, one can obtain structural pictures of very large areas in which the small scale complexities that take the eye of the field geologist fall into place as components of a pattern measurable in hundreds or even thousands of kilometres.

When considered on this scale, most ancient basement complexes are found to be traversed by linear zones along which regionally developed structures are distorted or truncated. Such zones evidently mark faults or dislocations on which adjacent masses of the continental crust have moved relative to one another. Examined at close quarters, they reveal a variety of signs of disturbance. Where the basement has not been deeply eroded, a mesh of clearcut faults and shatter zones may be seen, but where deeper sections are exposed, the fracture systems are replaced by steep tracts of mylonites or schists in which a strong metamorphic planar fabric is developed. These shear zones are characterised by distortion rather than disruption of pre-existing structures and are the common products of fault movements in deep crustal environments where high temperatures facilitate metamorphic recrystallisation.

From my present viewpoint, interest centres on large dislocations which were built into the continental crust in Precambrian times, long before the present-day plate tectonic regime came into existence. I shall refer firstly to examples from North America and south-west Greenland and secondly to examples from northern and north-western Europe.

Deep dislocations in North America

A look at the 1:5 million Aeromagnetic Map of Canada (Geological Survey of Canada, 1973) shows that in the area south of Hudson Bay, an irregular pattern of roughly east-west trend is interrupted and distorted by several linear zones of north-easterly trend which have the structural effects of faults. By making use of other lines of evidence, these north-easterly dislocations can be seen to be members of a set extending from south-west Greenland to the Rocky Mountains (text-fig. 1). The distortion of the east-west structures south of Hudson Bay (which are known to be of Archaean age) indicates that they were formed after the Archaean era and a number of lines of evidence suggest that they came into existence very early in the succeeding Proterozoic



Text-fig. 1: Sketch map of the basement of North America showing the shear zones discussed in the text.

era, perhaps about 2500 Ma (Escher *et al.*, 1976; Watson, 1980). Although offsets on individual dislocations seldom seem to be greater than 100-200 km, the scale of the set as a whole is so large as to suggest that they were formed in response to tectonic forces operating on a global scale (Sutton & Watson, 1974; Piper, 1976).

Two aspects of the north-easterly structures are of immediate interest - their vertical extent and their persistence through time. As regards the former, the large horizontal distances over which individual structures extend implies that they must continue down at least to the base of the crust, an implication which is supported by the available geophysical evidence (Innes *et al.*, 1967). An indirect argument based on the occurrence of suites of igneous rocks along certain lineaments suggests that they continue down through the Moho Discontinuity for distances of at least several tens of kilometres into the underlying mantle. Along the Kapuskasing line, for example (text-fig. 1), are scattered small alkaline and carbonatite plugs which are rare in the regions on either side of the line. These plugs (mostly emplaced long after the formation of the dislocation during the period 1700-1200 Ma) are derived from magmas probably originating well below the base of the crust, which appear to have used the old dislocation as a passageway in their upward migration. A more striking illustration of the connection between crustal flaws and magmas generated at depth is provided by the Nagssugtoqidian front of south-west Greenland which is penetrated by many small kimberlitic intrusion of Phanerozoic age. The parent magma of kimberlites, even those which carry no diamonds, are usually considered to have originated at depths of 100-150 km below the surface, an inference which suggests that the Nagssugtoqidian front extends deep into the mantle as an anomalous structure of some sort. Since the kimberlites are 1000-2000 million years younger than the dislocation, it follows that the lithospheric mantle has remained attached to the base of the Greenland continent for this period of time.

The presence of the igneous bodies mentioned above in association with crustal structures orginally formed in early Proterozoic times is, in itself, enough to show that the dislocations have not entirely healed up during the long period since they came into existence. Other lines of evidence point to the same conclusion - for example, a belt of Devonian reef limestones in the undisturbed platform cover of western Canada is lined up along a NE-SW Devonian topographical feature coinciding with the trace of an ancient dislocation in the basement (text-fig. 1). Watterson (1975) has concluded that deep shear zones characterised by strong parallel mineral fabrics constitute permanent flaws in the crust because there are no effective mechanisms for destroying these fabrics. The persistence of the North American dislocations is well illustrated by their relationship to mineralization. Several of Canada's principal concentrations of uranium, deposited from circulating waters of meteoric or juvenile origin, are located in north-easterly basement shear zones in Saskatchewan and Manitoba (text-fig. 1). Far to the south-west, the abundant gold deposits which drew so many nineteenth century prospectors to Colorado are strung out along a north-easterly basement shear zone. The shear zone itself is of Precambrian age (Tweto & Sims, 1963) but the deposits of the Colorado mineral belt are late Mesozoic to Tertiary. The old shear zone appears to have provided a passage for the circulation of hot mineralising solutions and, perhaps, for the uprise of magma from depth.

Deep dislocations in northern Europe

In the European continent, the exposed basement terrain of the Baltic shield is relatively small and if the crust is traversed by old dislocations like those of North America, one would expect only one or two members of the set to be exposed. There is, in fact, a major lineament of NW-SE trend which extends from the head of the Gulf of Bothnia to Lake Ladoga as a zone of structural disturbance containing a variety of mineral deposits (Kahma, 1973). This lineament played an important structural role during the early Proterozoic (Svecofennide) tectonic cycle and is therefore of much the same age as the Canadian dislocations. Although, on the principle that one swallow does not make a summer, too much cannot be read into this structure, the possibility that it originated as one of a set of parallel dislocations is enhanced by the occurrence of several anomalous NW-SE lineaments in the platform area south-west of the Baltic shield.
Chief of these structures is the Tornquist line which extends for some 1200 km from northern Denmark to southern Poland. The Tornquist line is thought to coincide with the boundary between

two tectonic provinces in the basement (e.g. Khain, 1977) and although its history cannot be carried back beyond about 1000 Ma it evidently originated in Proterozoic times. Variations of sedimentary facies and thickness in the overlying formations show that it was the site of repeated vertical movements from late Precambrian to Mesozoic times.

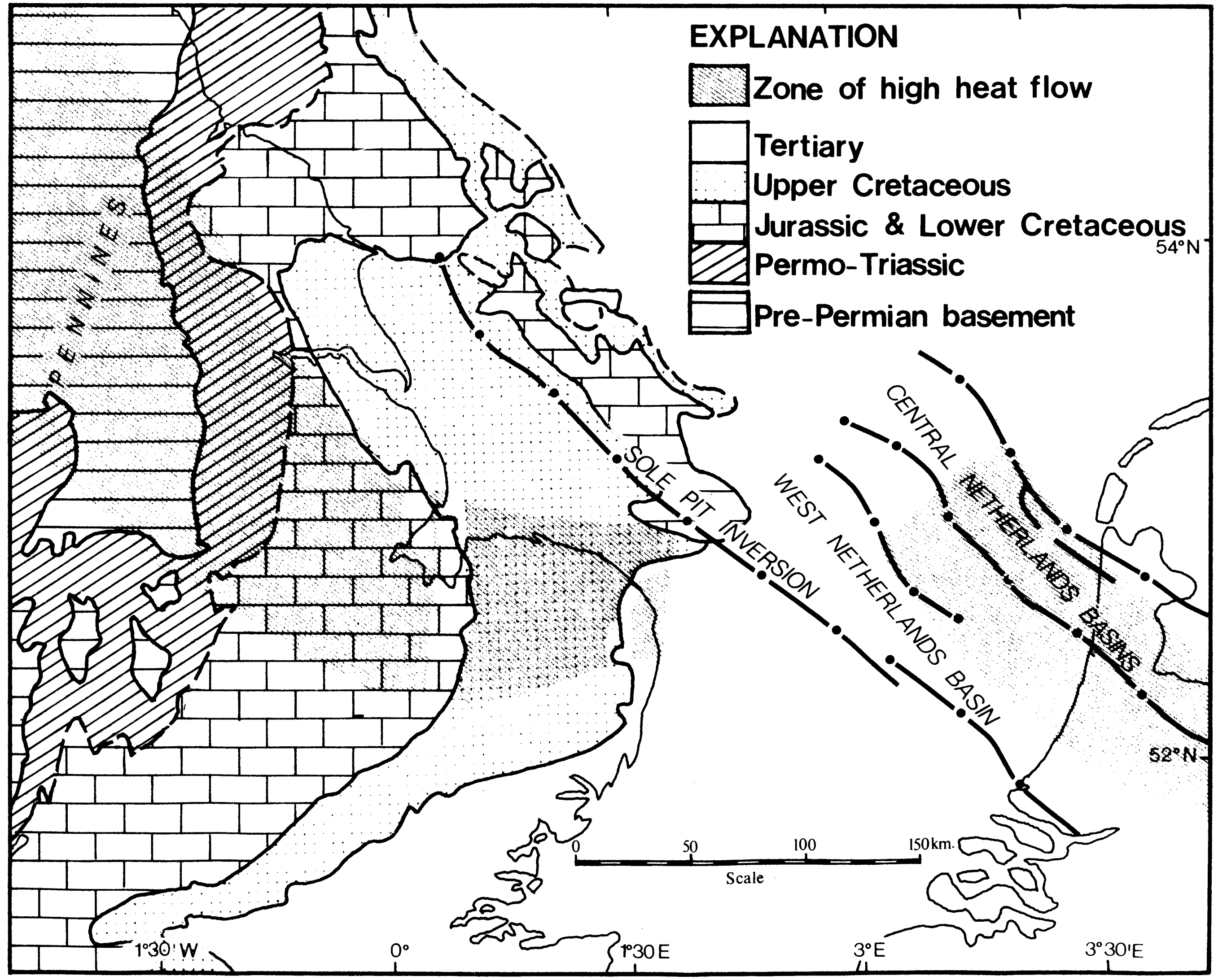
To the west of the Tornquist line, the basement of northern Europe is traversed by a system of branching rift and horst structures developed in early Mesozoic times as a result of the stretching of the continental crust immediately before the severance of Europe from North America that led to the opening of the Atlantic Ocean. Although the development of these rifts and associated structures appears to have been directly controlled by the plate tectonic regime responsible for the widening of the Atlantic and Indian Oceans by the process of sea floor spreading, it is worth enquiring whether the location and alignment of the faults themselves had any connection with the pattern of pre-existing dislocations in the basement. Evidence on this topic comes not only from Britain and the Low Countries but also from the North Sea where the principal Mesozoic rifts have attracted considerable attention on account of their influence on the distribution of oil and gas fields (e.g. Kent, 1975; Ziegler, 1978).

In eastern and northern England, where Carboniferous and Mesozoic rocks form most of the surface outcrops, an idea of the basement structure can be gained from aeromagnetic maps (Institute of Geological Sciences, 1965, 1972). Three "noisy" tracts of strong anomalies are seen on these maps running north-westward from East Anglia and the south Midlands for distances of up to 350 km (text-fig. 3). Comparison with the geological map shows that they are unrelated both to the distribution of Mesozoic strata and to the Pennine axis which controls the structure of the more disturbed Carboniferous. Hence, it seems certain that the north-westerly anomalies have their origin in pre-Carboniferous structures of some kind. It is unlikely that these anomalies relate directly to the distribution of individual pre-Carboniferous stratigraphical divisions because a single anomaly - for example, that running north-westward from the Wash - appears, from the palaeogeological map (Wills, 1978) to pass through regions underlain by basement units of several different ages.

Two alternative interpretations of these observations can be envisaged. One is to attribute the north-westerly zones of "noisy" aeromagnetic patterns to the occurrence of Caledonian (roughly end-Silurian) or pre-Caledonian igneous intrusions. The granitic plutons known to underlie the Trias near Leicester do, in fact, lie near the southern end of a lineament which continues north-westward through Derbyshire. Evans & Maroof (1976) have suggested that basement (Caledonian?) granites also underlie the Derbyshire section of the lineament and that these granites acted posthumously as a heat source which facilitated the formation of the famous lead-fluorite mineral deposits in the unconformable Carboniferous cover. A spatial connection between lead-zinc fluorite deposits in Carboniferous rocks and an underlying pre-Carboniferous granite has already been demonstrated in the north Pennine orefield where the buried Weardale granite, predicted from gravity surveys, has been encountered in the Rookhope borehole (Dunham *et al.*, 1961). The hypothetic Market Weighton granite (Bott *et. al.*, 1978) lies close to the long anomalous zone passing through the Wash; and the central Pennine orefield is also located on this zone.

An alternative possibility, which I myself favour, is that the north-westerly anomalies mark a mesh of old faults in the basement which locally acted as conduits for rising bodies of magma and which also served to focus hydrothermal convection systems in the Carboniferous and post-Carboniferous cover. Such a fault mesh would have to date back at least to Lower Palaeozoic and more probably to Precambrian times.

The picture of a heavily fractured basement underlying Carboniferous and younger strata is reinforced by recent studies of the Brabant massif which extends at depth from East Anglia south-eastward to the Netherlands (text-fig. 3). The Brabant massif has long been known to have formed a stable block during the Hercynian orogeny. Bless, Bouckaert and Paproth (1980) consider that it also escaped severe deformation during the Caledonian cycle and that it consists essentially of a mosaic of NW-SE horst blocks separated by linear basins which subsided to receive sequences of early Palaeozoic sediments. Combining the evidence from England and the



Text-fig. 2: The geology of eastern England and the south-western North Sea.

Netherlands, we arrive at the possibility that extensional fault systems with a predominant north-westerly trend had been built into the crust by late Precambrian or earliest Palaeozoic times. This possibility is in keeping with Evans' (1979) view of the principal basement structure of the Midlands as an aulacogen or fault-trough branching from the Iapetus Ocean rather than with the alternative favoured by some authors that the Midlands are underlain by a branch of the Caledonian orogen itself.

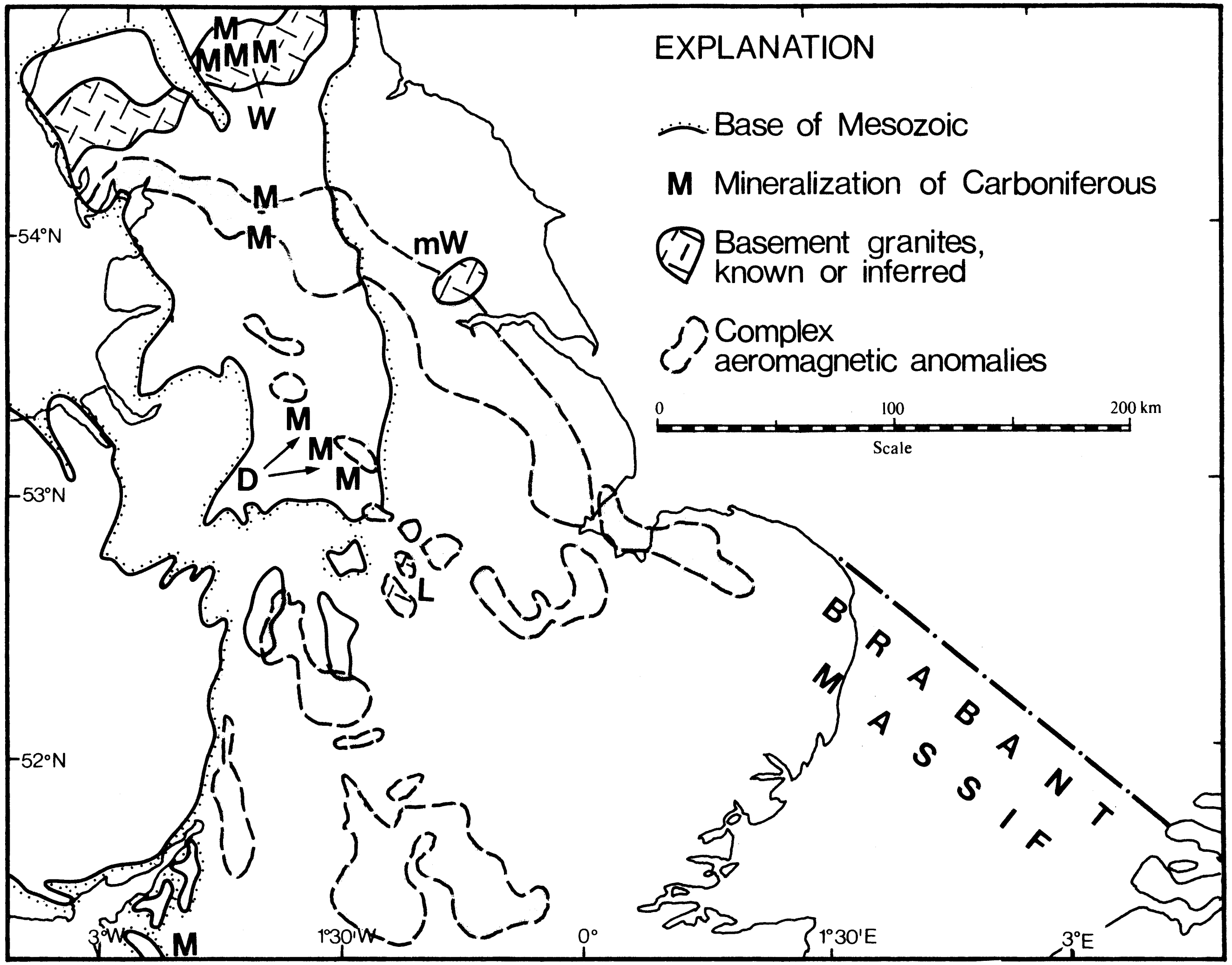
In the light of the evidence discussed above, the NW-SE orientation of the principal rifts and horsts in the southern North Sea which were formed under extensional early Mesozoic tectonic regime acquires a new significance (text-fig. 2). Bless *et al.* (1980) emphasise the parallelism between the sedimentation trends for the Carboniferous and for the Jurassic and Lower Cretaceous of the West Netherlands basin, and remark that other NW-SE fault systems in the Netherlands may also turn out to be formed by rejuvenation of Palaeozoic structures. The Sole Pit trough which skirts East Anglia and the Yorkshire coast with a SE-NW orientation developed as a subsiding trough in early Jurassic times and was subsequently uparched during a late Cretaceous phase of mild compression (Sole Pit "inversion", text-fig. 2). The Dowsing fault which marks the western boundary of the trough parallels the linear magnetic anomaly extending north-westward from the Wash and lines up closely with the eastern margin of the Brabant massif (text-fig. 3). There is thus a good case for supposing that the deformation of the north-west European crust caused by the initial stages of Atlantic opening was achieved largely by the reactivation of fractures built into the basement under a different and much earlier tectonic regime. Evidence for the persistent influence of north-westerly basement structures down to the present day is supplied by Richardson and Oxburgh's discovery (1979) of a NW-SE province of above average heat flow in northern and central England (text-fig. 2).

The disruption of continents

Although the crustal structures discussed in the last sections are not of the first order of magnitude when considered in terms of global tectonic regimes, the roles which they appear to have played in modifying the responses of the old continental cratons are of interest in several respects. In the first place, we have noted a few instances in which fractures developed under the extensional tectonic regime controlling the opening of the Atlantic Ocean are sited on older basement dislocations independent of this regime: thus, the pattern of fractures bore no direct relationship to the controlling stress system. In the second place, distinctive igneous activity originating in the mantle has been localised with respect to the siting of much older structures in the crust.

To see these relationships in context, it is helpful to look at the global pattern of structures related to the plate tectonic regime. At the present day, the arrangement of continents and oceans is the end product of a series of plate movements involving the widening of the Atlantic and Indian Oceans by sea floor spreading and the consequent dispersal of the continental masses adjacent to these oceans. At the start of this period, the continents were massed together in the supercontinents of Laurasia and Gondwanaland and the crucial event that set the Mesozoic-Tertiary cycle of continental drift in motion was the opening-up *within the super-continents* of connected fracture systems at which the continents parted company. In Europe, as we have seen, the preliminary fracturing was associated with the development of rift structures such as those which traverse the North Sea. Investigation of the borders of the Atlantic and Indian Oceans, stimulated by the search for oil, has shown that a similar phase of rifting of the continental crust preceded the opening of the oceans almost everywhere. The newly formed mid-oceanic ridges which were to be responsible for the growth of the oceans therefore made their appearance along predetermined lines in the crust of the supercontinents.

As early as 1965, Kennedy realised that the marginal rifts which define the fracture coast-lines of Africa were not haphazardly placed with respect to the structure of the continent. He showed that the sediment-filled marginal Mesozoic fault basins had been developed in regions where the basement had been strongly deformed and metamorphosed during a late Proterozoic to early Palaeozoic (Pan-African) cycle of crustal mobility. As a result of this selective placing



Text-fig. 3: Inferred basement structures in England.
D: Derbyshire L: Leicestershire
mW: Market Weighton W: Weardale

of the marginal fracture systems, the large tectonic provinces in which the basement had remained stable since Archaean or early Proterozoic times lie intact in the interior of the continent and only occasionally emerge at the coastline.

The fundamental relationship between the history of the continental crust and the siting of fractures destined to give rise to new oceans which Kennedy established in Africa (1965) has turned out to be of worldwide significance. In North America and Europe, for example, the Atlantic coasts follow the early Palaeozoic Caledonian-Appalachian orogenic belt for very long distances, only occasionally (as in north-western Scotland) trespassing into tectonic provinces where the basement has remained undisturbed since earlier Precambrian times. It seems to follow that the positions at which the new oceans began to form were determined very largely by reference to the structural history of the continental crust, together with the attached lithospheric mantle.

These inferences suggest that there may need to be a shift of emphasis, in the interpretation of plate tectonic systems, from sea floor spreading which is now rather well understood to the processes which precede the development of a new mid-oceanic ridge. The association of the ridges with magmatism originating in the mantle and the high heat flows characteristic of ridges have led many people to think in terms of a control involving mantle upwelling and/or the activity of mantle hot spots. Such mechanisms, however, leave unexplained the selectivity of the continental fracture systems whose development pre-determines the sites of the new oceans. Perhaps the time has come to look more closely at crustal and mantle processes in the continents.

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