PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Introductory Remarks

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Introductory remarks

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Palaeomagnetic measurements show that horizontal displacements of the crust occurred throughout the Proterozoic at rates comparable to those recorded from the Mesozoic to the present day. However, examination of Proterozoic continental crust reveals some structures which cannot be matched precisely at the present time. Proterozoic stable blocks are smaller and more numerous than the plates of the present day. Those blocks were surrounded by belts in which deformation and igneous activity occurred during times when the blocks behaved as rigid masses. When the apparent polar wander paths of these stable blocks are compared, they are seen to follow rather similar tracks implying that a number of isolated blocks followed approximately the same course. Bearing in mind the uncertainties in establishing pole positions and in dating the rocks concerned, Precambrian apparent polar wander paths are still not precisely located. Despite these uncertainties it would appear that a genuine phenomenon has been revealed which can be described in these terms. During Proterozoic times rates of divergence between stable blocks within a continental mass were an order of magnitude smaller than the overall rate of horizontal displacement of that mass. This suggests that we may be seeing the effects of two distinct phenomena. The major horizontal movement of a Proterozoic continent was probably connected with sea floor spreading and with destruction of oceanic crust. Paul Hoffman (1973) has recorded phenomena including extensive acid volcanicity in the north-west of the Canadian Shield which suggest that about 1700 million years ago continental crust in that region was overriding subducted oceanic floor. He was investigating what occurred at one Proterozoic continent-ocean boundary. However, a rather different type of deformation appears to have occurred in the interior of Proterozoic continental bodies. It is this motion which is reflected in the breadth of the polar wander track of continental crust of those times. Such tracks have the form of a broad swathe 1000 or 1500 km wide, a distance very much smaller than that of the 10000 km or more over which such a track may extend during several hundred million years of Proterozoic time. These smaller movements reflect the jostling as it were of individual plates within the continental block.

The relative movements of individual plates are reflected in the nature of the structures preserved in continental crust of Proterozoic age. These structures indicate transcurrent, convergent and divergent movements within continental blocks. One feature well seen in North America and probably also in western Europe and in Africa are systems of parallel transcurrent faults, which show a consistent movement in any one region and which can be seen to follow small circles (Watson 1973; Sutton & Watson 1974). In some areas such a system of transcurrent faults is accompanied by structures suggesting opening or closing of crust which lie at a large angle to the transcurrent system. The Labrador trough in eastern Canada could be quoted as such a structure. It runs virtually at right angles to the transcurrent fault system of the Central Canadian Shield. Basic rock within this trough could have formed at a time of tension within the crust; subsequent folding within the trough indicates compression. However, these movements were never so great as to separate the stable blocks on either side of the

Labrador trough by more than a few hundred kilometres. The evidence for this statement is found in the demonstration of Irving & McGlynn (this volume, p. 433), that isolated stable masses within the Canadian Shield followed closely similar polar wander curves while these internal movements were taking place in intervening areas between the blocks.

Essentially the difference between Phanerozoic and Proterozoic tectonics appears to be that in Proterozoic times continental crust behaved as a non-rigid body over a much greater proportion of its mass. Small rigid blocks a few hundred kilometres or less in extent remained enveloped in a network of mobile belts within which continental crust was deformed though the continent remained a coherent mass which did not break up to form major oceans. Small intra-continental seas may have opened and closed as relative movements of a few hundred kilometres occurred between blocks. The essential point is that these movements were small compared with the displacement of continental crust as a whole.

In contrast to the present day situation where most continental crust forms a few large plates undeformed except near the leading edges, Proterozoic continental crust was everywhere deformed outside the relatively small rigid bodies scattered through its mass. How many major continents existed in Proterozoic times is still uncertain but it is known already that Proterozoic continents were very much larger than the largest preserved rigid plates of that time, whereas at the present day the largest contemporary plates are larger than some continents.

During the Proterozoic the number of rigid blocks decreased, as further stabilization occurred linking previously isolated blocks and increasing the proportion of stable rigid to non-stable mobile continental crust. By one billion years ago there were fewer but larger stable masses than at the start of the Proterozoic and by that time the process of continental break up and collision which characterizes the present day Earth had certainly begun. On the other hand the non-rigid behaviour of continental crust appears to have continued in parts of Gondwanaland to the very end of the Precambrian. The Pan-African belts of Africa, Western Australia, Antarctica and eastern South America resemble in many features middle Proterozoic structures formed about a billion years earlier in Canada and northern Europe; the change seems to have been diachronous.

It is uncertain when major fracturing may have begun. There is evidence indicating that Australia moved as an independent mass from at least as far back as 1.8 billion years. One question we could consider at this meeting is whether the available facts support the hypothesis of a diachronous change in global tectonics over the latter part of the Proterozoic or whether plate tectonics as we know it today was in fact established much earlier, say at the end of Archaean times.

Holmes (1929) recognized nearly half a century ago at a time when the nature of horizontal movements of the crust was less well understood, that convection in the mantle could separate continental blocks, so opening new oceans. This expansion, he saw, could be balanced by the contraction of other oceans around which mountain chains and active volcanoes would develop. Holmes recognized most of the essentials of what has since been termed plate tectonics though he did not understand correctly the manner in which new oceans are formed. It is this understanding which has been the great development of the last decade particularly through the elegant way in which it makes possible quantitative estimates of the speed and direction of plate movements. Holmes however foresaw more correctly than some of his successors that horizontal movements would be accompanied by extensive deformation of the crust.

When considering the early history of the Earth there is some virtue in going back to Holmes' more generalized view of global tectonics, though clearly we must take into account the great advances which have followed the successive concepts, continental drift, seafloor spreading, plate tectonics. When considering the Precambrian we can have no direct knowledge of the behaviour of oceans of those times. However, we should not minimize what can be achieved without such knowledge. Holmes' original hypothesis was arrived at at a time when very little was understood about ocean formation. By 1961 Miyashiro had appreciated that metamorphic belts from Japan and other circum-Pacific areas overlie Benioff zones down which ocean floor is being subducted. He had also made the important observation that metamorphic belts around the Pacific may occur in pairs with a blue schist belt on the oceanic side and a high temperature metamorphic belt further from the Pacific. It is inherent in Holmes' hypothesis that mountain chains evolve at and travel with the leading edges of continents as they move outwards from new oceans to encroach on end. In 1956 Clegg and colleagues demonstrated that the northward movement of India led to the construction of the Himalayas in precisely this fashion. As India travelled into the northern hemisphere so closing a section of the Tethys ocean, and throwing up the Himalayas, a newly formed portion of the Indian Ocean opened as India separated from Africa. I applied Holmes' concepts (Sutton 1963) to suggest a possible explanation for the succession of major structural provinces recorded in each of the continents. I suggested that these could be explained by periodic disruption of continents followed by reassembly to form new continental groups. I suggested that some such movements could account for the successive Precambrian tectonic provinces recognized in many continents, the three youngest of which began their developments in one or other of the following three periods

2900–2700 million years (Ma),

1900–1700 Ma,

1200–1000 Ma.

Since that time it has become increasingly clear that such changes are superimposed on a still longer change in global tectonics which takes one from an Archaean system to the system of the present day. Perhaps the most important advance has been the recognition that apparent polar wander curves for individual continental blocks show major inflexions or hairpins (Spall 1971; Donaldson, McGlynn, Irving & Park 1973), some of which correspond to the times when new structural provinces developed as Irving and his colleagues have shown. This work suggested a link between structures developed in continental crust and movements in the mantle. Runcorn (1962) had already taken the step of suggesting how developments in the core and mantle might be related to such long term changes in the behaviour of the crust. In particular he drew attention to a possible link between changes in the core and mantle and the appearance of granitic rocks in unusually large quantities at certain periods in the Earth's history as first recorded by Gordon Gastil (1960). Three of Gastil's peaks occur between 2750 and 2450 Ma, between 1900 and 1600 Ma and between 1150 and 900 Ma, and thus coincide with the onset of new structural provinces and in some instances with abrupt changes in the polar wander path of Precambrian continents.

In trying to understand Precambrian tectonics we have at least some advantages; we deal with a long period of time and may therefore be able to detect long term changes in the behaviour of the Earth and we are concerned with continental crust which over at least part of Precambrian time responded by internal deformation more extensively than at the present day, to movements of the underlying mantle. We have the advantage therefore of being able to study igneous activity, metamorphism and deformation, not only in the vicinity of the leading edges of moving continents but throughout an extensive network of mobile belts covering continental lithosphere.

In making comparisons with the Phanerozoic it may be preferable to look at the Phanerozoic as a whole rather than to concentrate on the opening and closing of individual Phanerozoic oceans. For example as we learn more about the history of what is now the North Atlantic we find a record of repeated closing and opening which can be traced as far back in time as the period when Late Precambrian sediments accumulated close to what are now the eastern and western sea boards of the Atlantic. It could be argued that there is a distinction between the history of such a region lying as it does between blocks of continental crust and the history of an area such as the western United States lying at the margins of a continent close to the Pacific. If we look at global tectonics through the Early Phanerozoic we may also be struck by the remarkable contrast between deformation in the central parts of Gondwanal where what Kennedy (1965) called the Pan-African belts developed, and deformation in other areas where oceans opened and closed. Could it be that this contrast between two contemporary regimes represents the closing phases of a scheme of global tectonics dominated by non-rigid behaviour of the continental crust and the emergence of the plate tectonic mode. This essentially is the problem we are going to examine in the next two days.

The symposium is so arranged that the early contributors deal with palaeomagnetic phenomena. These contributions are followed by papers concerned with structural geology and questions of heat flow as indicated by metamorphism and igneous activity. I am conscious that there are many other aspects of these questions, in particular the considerable contribution of geochemistry especially through the study of the occurrences of unstable isotopes through geological time, which may not be adequately covered in the papers as set out in the programme. I hope therefore that speakers who can contribute in fields not so covered will take part in the discussion.

In introducing a symposium on continental drift almost exactly eleven years ago P. M. S. Blackett, P.R.S., made the following comments:

'Now if, as I think this Symposium may show, the consensus of opinion is moving towards the assumption that drift has occurred, then it seems likely that the ultimate explanation of why it occurs will be much more complicated than the arguments used by both sides in the earlier controversies. Here perhaps one can derive a warning against possible mistakes in the methodology of subjects like the earth sciences, where the observational facts are highly complex and difficult to reduce to quantitative terms. In such subjects, a highly simplified model which can explain a large number of observed facts is invaluable, especially when it suggests new observations. When the observations are made, it is generally found necessary to make the model more complicated. However, highly simplified models which prove that some supposed phenomenon cannot have occurred, must be treated with caution, for they may discourage new observations' (Blackett, 1965).

This might serve as a text for the next two days in our consideration of global tectonics in the Proterozoic. How far back in time can the plate tectonic model take us? What if anything preceded it? Was there a rather different system of tectonics in Proterozoic times or did plate movements as we experience them today take place in early Precambrian times?

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