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

# Architecture of the Continental Lithosphere

J. Sutton and Janet V. Watson

*Phil. Trans. R. Soc. Lond. A* 1986 **317**, 5-12
doi: 10.1098/rsta.1986.0020

*Phil. Trans. R. Soc. Lond.* A **317**, 5–12 (1986) [ 5 ]
*Printed in Great Britain*

# Architecture of the continental lithosphere

By J. Sutton, F.R.S., and Janet V. Watson, F.R.S.†
*Centre for Environmental Technology, Imperial College,*
*48 Prince's Gardens, London SW7 1LU, U.K.*

The continental lithospheric plates are traversed by numerous large-scale dislocations, many of which date back to late Archean or Proterozoic times. These major dislocations, often extending for 1000 km or more, are commonly characterized not only by the presence of fault rocks and by significant misfits between the adjacent crustal blocks, but also by the presence of localized basins of deposition, or by anomalous igneous suites, or mineral deposits. Although to a first approximation they may be regarded as narrow linear features, most consist of complex arrays of faults, ductile shear zones and fractures; some with associated deformation spread over tens and hundreds of kilometres. Lineaments that originated as within-plate transcurrent shear zones or rift systems are generally steep and many of these probably extend down through the base of the crust into lithospheric mantle. Lineaments that originated as sutures along which formerly separated crustal blocks have been welded together are, on the other hand, sometimes expressions of low-angle dislocations not continuous with mantle structures directly beneath the lineament observed at the surface.

Geological records show that displacements or magmatic activity (or both) along many lineaments were repeated over long periods spanning successive changes in the global tectonic régime. Modern lineament movements can be fitted to plate tectonic hypotheses. However pre-Phanerozoic movements are more conjectural: for example, early Proterozoic lineaments appear to be associated with more extensive internal deformation within large crustal blocks. The siting of fracture systems activated in response to regional plate motions has, on occasion, been determined by the occurrence of pre-existing deep dislocations. The scale and longevity of the deep dislocations raise many interesting general questions with respect to the coordination of mantle and crustal activities and to the evolution of the continental lithosphere.

When considered on a grand scale, the architecture of the continental lithospheric plates can be seen to reflect their antiquity. Whereas the structural patterns of the oceanic crust can usually be attributed to the effects of a few comparatively recent events, those of the continental crust are composites developed stage by stage over periods of as much as 2000–3000 Ma. Most of the continental rifts contain a high proportion of Precambrian rock and most incorporate two or more tectonic provinces which, together with some smaller crustal blocks, have been assembled to form a present-day continent, welded into a single mass of various mechanisms. All the continental rifts have lived through and responded to many changes in the global plate tectonic régime. Their geological diversity, attested to by large-scale lateral variations in composition, in structural 'grain', in density, and in other physical properties, reflects their long geological history. Ancient dislocations, some marking the lines at which incipient or complete separation of continental fragments has taken place and others marking the sutures at which formerly separate blocks have been welded together, appear as linear zones of

† Died 29 March 1985.

anomalous structures that traverse the continent for distances up to at least 1000 km. These are the lineaments with which this Meeting is concerned.

At every stage from the Archaean to the present day, the responses of the continental crust to the external stresses generated by changes in the motions of the mantle and plates have been influenced by the pre-existing anisotropy and inhomogeneity of the crust. The patterns of distribution of sedimentary basins, of magmatic activity, and of ore deposits as well as the structural patterns resulting from crustal deformation, reveal the influence that crustal architecture has exercised on the ways in which continental rifts have adjusted themselves to changes in plate motion through geological time.

In this volume, attention is focused on the role of the major dislocations that seam the continental crust. Some of these structures have persisted from Proterozoic or even Archaean time and have played many parts as the world tectonic scene has changed. The oldest of these lineaments originally developed in relation to tectonic régimes which we suspect were very different from those of the Phanerozoic. They provide some of the clues to the possible nature of those Precambrian régimes that we have yet to understand. The origins of other younger lineaments can be confidently linked with well understood Phanerozoic sea floor spreading and can be seen to have originated through crustal extension (rift zones, linear dyke-swarms, elongated batholiths, fractured continental margins), through crustal collision or shortening (sutures, margin thrust zones, linear aggregates of 'suspect' terranes) or as a result of transcurrent motions. All but those of very recent origin have been periodically reactivated as dislocations, or as conduits for magmas and other fluids. Studies of present-day earthquakes demonstrate the complexity of movement along lineaments active at the present day and prepares us for the complexity of the resulting structures. The study of lineaments both past and present provides fruitful examples of Hutton's famous dictum.

The papers in this Meeting deal with many aspects of major crustal lineaments and of the geological processes associated with them. This preliminary survey is intended to set the scene and to identify some of the problems that call for discussion.

In what follows we take up three topics: the mode of occurrence, introducing some of the geological phenomena related to lineaments; the extent to which we can place geologically ancient sets of lineaments in their contemporary tectonic settings, as has been done so successfully in understanding present-day plate movements; and thirdly the changing roles of some long-lived lineaments that have formed parts of successive global tectonic régimes as the pattern of mantle movement has varied through geological time.

## 1. Mode of occurrence

Many of the major lineaments that have influenced the evolution of the continental crust extend laterally for distances ranging from a few hundred to a thousand or more kilometres. Their length, their longevity and the fact that many have been the sites of mantle-derived igneous activity suggest that at least for a part of their existence they have extended vertically to the base of the crust, or in some instances to the base of the lithosphere.

When the trace of a lineament at the Earth's surface traverses crystalline rocks, it is often seen as a line or a zone, which may be many kilometres in width, of disturbance characterized by cataclasites, mylonites and other products of dislocations. Large-scale structural or geological anomalies and a variety of topographical features often best displayed by imagery obtained from satellites show that the disturbed zones may be as much as a couple of hundred kilometres in breadth. Only rarely is a lineament so narrow that it can be regarded for practical purposes as a single fault; most consist of many related faults or ductile shear zones enclosing blocks or lenses of less disturbed zones. Although the traces of the zones are more or less linear, important diversions, interruptions and snags are to be seen both in individual dislocations and in the zone of disturbance as a whole. Although brought about for different reasons, exactly the same comment can be made on the lineaments formed above subduction zones as when the crust is undergoing extension. The igneous rocks along active plate margins can take the form of plutonic lineaments, as Pitcher (1975) has called them, which vary in chemical composition, abundance, and position within the crust along the lineament. The rifting, volcanicity and sedimentation at spreading axes at sea or in rift valleys on land show equal variety. All such features emphasize the episodic nature of virtually every process contributing to the formation of lineaments. Understanding the reasons for such behaviour is fundamental. The general nature of the problem is simple enough, for it is obvious that lineaments formed as a more or less rigid crust respond intermittently to movements in a less rigid mantle. The range of time involved is very great, extending from the few seconds or minutes that may separate successive earthquakes to the millions and hundreds of millions of years that may elapse before a long-lived lineament in the continental crust is once more reactivated. While the root cause of this episodic behaviour is clear enough, a thorough understanding requires a range of enquiries into the seismicity, structures in the widest sense of the word, and into the chronology of lineaments. Great progress has been made in establishing the geological features of lineaments and in certain fields a start has been made in setting out hypotheses to account for what has been observed.

McKenzie (1978) has shown how mechanical extension of the crust leads to subsidence, rifting and deposition in the resulting sedimentary basin, in which subsidence continues as the asthenosphere continues to cool. His comments have been applied with success to explain the rift basin in the North Sea. Badley *et al.* (1984), for example, have exploited the unusually extensive stratigraphical and geophysical control available, to demonstrate the stages by which the Viking Graben developed as mechanical extension gave way to thermal subsidence in Mesozoic times.

The manner in which seismicity varies with time along an active lineament such as the San Andreas Fault system is well documented through historic time, and geological evidence extends this record, though in much less detail, for 150 Ma. It is well understood that only a small proportion ($< 10\,\%$) of seismic energy originates in the world rift system, where the crust is thin, and that the much greater activity where plates converge, and slide past one another, is connected with the larger area of contact between moving pieces of lithosphere in such situations. While we are still far from being able to predict earthquakes, there is a good understanding of earthquake mechanisms and of the complexity of the geological structures that result. Assuming that an earthquake on a major fault associated with rapid stick-slip fault movement following an increment of shear may take about 1 s, Price suggests that strain rates in those circumstances would be in the range $10^{-4}$ to $10^{-5}\ \mathrm{s}^{-1}$. Sibson *et al.* (1975) have investigated the origin of certain hydrothermal vein deposits found in the upper brittle regions of ancient fault zones. They suggest that these result from the passage of fluid rapidly redistributed through the crust following seismic faulting. The quantities of fluid are such that significant mineralization may result from each seismically induced fluid pulse. They note that this mechanism provides an explanation for the signs of episodic mineralization almost invariably shown by such hydrothermal vein deposits along fault traces.

Studies such as these indicate ways in which the length of time involved in certain episodic phenomena repeatedly developed along lineaments may be established. Each of the examples we have quoted explored conditions in a certain tectonic environment. Long-lived faults can display another type of episodic behaviour resulting from successive changes in tectonic setting. Thus a lineament formed by intraplate movements may, at a later time, serve as a fracture plane along which two blocks of continent separate. Kennedy (1964), for example, noted that the development of the continental margins of Africa in Mesozoic times was related in some way to structures formed 500 Ma ago, because the present margin of the continent lies almost entirely with the regions affected by Cambro–Ordovician (or Pan-African) events. We return to the affects of changing tectonic régimes on long-lived lineaments later.

A few major lineaments of the continental regions are marked at surface levels most obviously by anomalous developments of igneous rocks either as large linear intrusions such as the Peruvian batholith or through lines of smaller plutonic or volcanic centres such as those of the Montana region magma series (eastern North America). Some of these igneous lineaments are known to be related to deep dislocations as in Peru, and it may well be that shear zones in the lower crust or lithospheric mantle underlie other examples whose relation to the global tectonics of earlier times remains to be established. It is clearly relevant to consider such features along with more obvious dislocations.

In terms of their origins, the great dislocations of the continental lithosphere can be assigned to three groups, those linked with extension, with transcurrent movements, or with shortening and duplication. So far as their subsequent influence on crustal evolution is concerned, a simple distinction based on the inclination of the zone of disturbance many be more useful. Subvertical structures such as wrench zones provide a surface of attachment between two adjacent lithospheric blocks that is relatively small compared with low-angle structures, such as the distribution of earthquakes in central Asia indicates have resulted from the underthrusting of India below the Himalayas and Tibet. In contrast, the intersection of steep structures with the Moho lies vertically below their trace at the Earth's surface and any associated subcrustal magmatism should be more or less symmetrically distributed with respect to their trace as, for example, are ultrabasic masses along the Pyrenees. Low-angle dislocations will normally be more extensive and subject to the lithostatic pressure of the overlying slab, and may therefore form a relatively strong join accompanied by magmatic activity distributed across a wide belt of crust along the outcrop of the dislocation.

Although a few of the case histories discussed in later papers deal with dislocations so narrow that they can be considered as single faults, most lineaments are essentially tracts containing many faults, ductile shear zones or fractures occupied by dykes between which are large numbers of lenses or blocks of less disturbed rock. In transcurrent zones, the subsidiary dislocations often form a braided set, whereas in thrust and rift zones they tend to define complex but systematic geometrical patterns whose significances can be established, as Badley *et al.* (1984) have done in identifying the roles of normal and listric faulting in the complicated structures associated with the North Sea Viking Graben.

Some dislocation zones, particularly in Precambrian terranes, may be tens or even hundreds of kilometres wide as in the Proterozoic Ubendian Belt near Lake Tanganyika, where virtually the entire width of the belt consists of intensely deformed rock.

While to a first approximation dislocation zones form linear features at the Earth's surface, when considered in detail virtually every type of lineament displays diversions, echelon arrangements and other complications which, as will be seen in later papers, have been the sites of anomalous activities both at the time of origin and during reactivation. Some of these features emerge in the later part of this introduction when we examine the behaviour of lineaments as parts of larger structural systems that may extend over whole continents or even further and can persist through many global tectonic régimes.

## 2. The placing of lineaments in their contemporary tectonic setting

The success with which the plate tectonic hypothesis accounts for the Earth's seismicity suggests that we can explain present-day displacements. The palaeomagnetic record on land, and observations on the magnetism of the sea floor, allow quite precise records of plate movements to be established as far back as the ocean floor evidence extends and can be used to indicate continental displacements relative to the magnetic poles in times as distant as the Proterozoic. As work on these lines developed the importance of strike-slip movements became clear. Indeed when Mason *et al.* (1961) measured the movements taking place on the North Atlantic spreading axis in Iceland some twenty years ago with accurate distance-measuring equipment they rapidly found that motions were far from a simple outward displacement normal to the axis. It is obvious that movements of rather rigid plates about a spherical surface will involve more complex movements than an idealized picture of spreading and collision zones would suggest. The very irregularity of continental margins and the inhomogeneities within plates with which this Meeting is concerned add to the complexity. All the analyses of past ocean growth and destruction indicate the comparative rarity of motion normal to a plate boundary. It thus becomes a matter of great difficulty to visualize the movements of ocean crust that accompanied the known record of continental displacement further back in time than the record preserved in the surviving ocean floor. It is, however, possible to interpret the record preserved on continents in the shape of deformed rocks, variation in sedimentary facies, igneous activity and past positions relative to the magnetic pole, and to come to conclusions as to the relative positions of continents and to identify active and passive margins and zones of within-plate deformation. We understand, for example, the régime in which the Mesozoic faulting influenced sedimentation around the British Isles although these movements go back to the Permian, a period from which no ocean floor survives.

Any interpretation of an extensive continent-wide set of lineaments originating further back in time than the existing ocean floor record can take us is much to be welcomed. Michael Daly (this symposium) provides such an analysis of Precambrian shear zones in Africa, suggesting that structures observed at the surface are apparently linked in a lower crustal shear zone of continental dimensions. Such a hypothesis is a great step forward in our opinion, not only because it may be applied to other parts of the southern continent but because it may provide a stepping stone to understand conditions still further back in time when continents developed lineaments which may differ in some respects from those formed in Phanerozoic times.

Phanerozoic movements involve the repeated splitting of continents to develop new oceans. All the present-day oceans, and as far as we know all past new oceans such as the Teltiys or the Proto Atlantic Iapetus, were arms of the Pacific that originated when a continent was forced over a Pacific spreading axis which then split the overriding continent, the axis extending its length below the continent just as an Indian ocean axis linked with the east Pacific rise at one end is splitting apart Arabia and Africa at the other.

How far back in time could continents be split in this fashion? Daly suggests that the African late Phanerozoic 'mobile belts' can be interpreted as a continent-wide linked thrust and strike-slip shear-zone system. The implication is that Africa (and the remainder of Gondwanaland) may have moved as a unit suffering internal deformation as it travelled, but not at that time dissociating into separate continental blocks. In 1974 we explored, though less thoroughly than Daly and without his recognition of a possible linking deep crustal shear-zone system below the travelling continent, the significance of the long northeast-trending Proterozoic tectonic lineaments present in the Canadian Shield (Sutton & Watson 1974). This transcurrent movement is indicated by aeromagnetic maps demonstrating deflection of older structures. These lineaments, which can be traced below the United States under younger cover into Colorado but which are not present in the suspect terranes of rocks added more recently to the Pacific seaboard of North America, lie in small circles about an axis near the west end of the Aleutian arc. Dyke swarms in the Slave and Ungava regions of the Canadian Shield lie close to a great circle passing through a point of 20° from the axis and may, we suggested, record extensional rotation. We suggested that North America was undergoing clockwise movement parallel to the small circles defined by the transcurrent lineaments in a direction compatible with the appropriate polar wander path established by Donaldson *et al.* (1973). We considered that the dyke swarms and mobile belts such as the Coronation and Labrador geosyncline might mark 'tears' linked by northeasterly transform faults along which dyke swarms and small ocean floors were formed, the latter destroyed as the Slave and Ungava fold belts developed. We concluded that a distinctive feature of the early Proterozoic tectonic system was the record of internal deformation within large continental plates. The arrangement of transcurrent fractures and associated structures differs from that characteristic of both Archean and Phanerozoic tectonic regions. The hypothesis to be considered is essentially that travelling continents were disturbed but did not break apart in early Proterozoic times. By late Proterozoic there is evidence of widespread rifting, indicated by the formation of sedimentary basins of that age in North America. Continental fragmentation of the Proterozoic supercontinent envisaged by Piper (1976) might have started at that time. This hypothesis could be proved or disproved by dating the earliest lineaments producing by continent-to-continent collision and by further palaeomagnetic measurements. We accept the evidence of Windley (1976) and others that subduction of oceans below continental crust in some form operated at least as far back as the Archaean, for that proposal accounts for the great accessions of crust rich in tonalitic rocks which occurred in at least the last third of Archaean time.

Basic dyke swarms older than 3200 Ma have been found in W Greenland and in the Transvaal, for example. Many Archaean greenstone belts are known to extend only a few kilometres below the present surface and presumably were fed by fissures or pipes. There is thus good evidence that crust could be fractured throughout the entire known geological record, though the resulting greenstone and granite gneiss association whose original form is lost through deformation could be interpreted as indicating a continental environment, possibly with small seas within continents, but not marking the closure of large oceans. This, however, is no more than speculation at the present time.

One important question for the future is to determine how far back in time the continental crust was periodically fragmented, and whether the response of continental crust to movements within the mantle led only to distortion rather than wide separations of blocks of continent during any part of Precambrian time.



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

## 3. Lineaments through time

One of the most spectacular instances of the influence of pre-existing lineaments on subsequent fractures is the relation between Precambrian or early Palaeozoic mobile belts in the southern continents and the Mesozoic fracturing which led to African Rift Valleys and the oceans that now divide those continents. The rifts avoid the Archean cratons and follow, in general, Proterozoic or younger fold belts. In detail the relation is not precise. For instance, in the South Afar depression near the Red Sea, magnetic anomalies related to volcanic infilling within the rift run E–W, while gravity measurements suggest a NNE trend for underlying basement features preserved at greater depths. Igneous activity within the zones where Mesozoic fractures were to develop dates back to as far as 1700 Ma in the Proterozoic belts. Wide distribution of basalts through the cratonic region of Gondwanaland indicates abnormal conditions within the mantle leading to Jurassic vulcanicity in southeast and central Africa and Antarctica to late Jurassic in west Africa and Brazil, Cretaceous and early Tertiary activity in India, and basaltic activity within Ethiopia as recently as the Pleistocene. Igneous activity varied in nature through the system, abundant acid rocks being largely confined in Africa to the southeast in the Lebombo and Nuanetsi Ardos. The most extensive volcanicity was of course in the Indian and South Atlantic Ocean, where the rifts evolved into ocean spreading axes, extending and moving away from the continents where the rifts originated.

Kent (1975) has discussed the origin of the aseismic continental margins and shown that the Mesozoic rifting is a worldwide phenomenon. Not only do Pan-African mobile belts (Kennedy 1964) lie below the coasts of much of Africa, but Caledonian and Hercynian belts lie below the Mesozoic rift basin where the north Atlantic originated. Kent noted that the rifting operating between the Permian and Jurassic ended on a worldwide scale in the mid Cretaceous, when faulting ceased within a very short period within many marginal basins. Kent concludes that this requires a worldwide mechanism that is not yet understood (Kent 1977).

There is another geological situation that requires explanation. In what circumstances do long-established lineaments cease to be active? One can think of instances: the Great Dyke in Zimbabwe, the Murchison Ranges in South Africa, possibly the mid-continental high indicated by geophysical measurements in the U.S.A., where linear features are aseismic at the present and apparently have been for a long period in the past. One possibility is that new crust has sealed the weakness at depth. This raises the question of underplating, a vaguely defined concept but one we feel to be of importance in this connection. About four times as much continental crust is currently removed by erosion as is added at subduction zones, yet continents are not shrinking. Is the balance maintained by igneous intrusion below continents, possibly three times as abundant as that at the margins?

The sealing of lineaments provides a possible means of locating underplates both in time and place. Seismic data reveal flat-lying planes down to 300 km and indicate heterogeneity at least as deep. Isotopic studies indicate a complex origin for many igneous rocks involving derivation from more than one period of solidification and remelting within the lithosphere. Occasionally, when deeply eroded crust is exposed as in the Lewisian, we suggest that a block of older crust (the Scourian in that instance) is in fact underlain by younger igneous rock, the Laxfordian granites, which flank the Scourian in Sutherland and which are considered by some geologists to continue at depth below older granulites.

Changes in igneous activity can produce lineaments (for example, the doming which precedes the African rifts contributes to the rise of basaltic magma); it can define lineaments (the Hoggar to Cameroons line along which isolated volcanics occur); and, through addition of new crust at depth, may bring to an end the active life of long-established lineaments.

We may mention two aspects of relations between igneous activity and lineaments. First, the distribution of kimberlites: sometimes aligned as in the Nagsugtoqidian in Proterozoic belts, but rarely found in younger mobile zones, though most, but not all, kimberlites postdate the Precambrian. Not only the abundance but the composition of kimberlites varies with the age of the crust through which they were intruded, the most abundantly dominant forms occurring in Archean blocks. Another little understood relation is indicated by the occasional recurrence of the same abnormal mantle in a region that is repeatedly fractured; the abundance of chromium-bearing intrusives in central and southern Africa through the Precambrian for example. A second point concerns the timing of the arrival in the crust of deep-seated rocks emplaced through fractures extending to the mantle. MacIntyre (1977), in a discussion of anorogeric magmatism and plate motions, has noted that a common triggering motion, possibly major changes in plate motion, may account for the emplacement of carbonatites as in widely separated areas but similar time. He found that Mesozoic and Cenozoic carbonatites were emplaced in the following periods of time: 0–15, 25, 40, 60–70, possibly at 80 and 100, and at 130 Ma. He has noted that earlier carbonatites along rifts or lines of weakness such as the Jordan, East Africa and St Lawrence rifts, cluster in age round certain chromological peaks. He notes that mean times of emplacement occur at intervals of 230 Ma. This repetitive disturbance of lineaments might be linked with increased heat flow. As with the mid-Cretaceous, cessation of rifting at continental margins and the arrival of widely dispersed carbonatites at similar times indicated some worldwide cause originating at depth whose effects are localized by fractures. Such fractures which may have originated in quite different geological circumstances, provide yet another example of the way long-lived lineaments may play a part in a succession of tectonic events.

## References


Badley, M. E., Egeberg, T. & Nipen, O. 1984 Development of rift basins illustrated by the structural evolution of the Oseberg feature, Block 30/6, offshore Norway, *J. geol. Soc. Lond.* **141**, 639–650.

Donaldson, J. A., McGlynn, J. C. & Irving, E. 1973 Drift of the Canadian Shield. In *Implications of continental drift to the earth sciences*, vol. 1, pp. 3–17. London: Academic Press.

Kennedy, W. Q. 1964 The structural differentiation of Africa in the Pan-African (±500 Ma) tectonic episode. *A. Rep. Res. Inst. Africa Geol. Univ. Leeds* **8**, 48–49.

Kennedy, W. Q. 1965 The influence of basement structure on the evolution of the coastal (Mesozoic and Tertiary) basins. In *Salt basins around Africa*, pp. 7–16. London: Institute of Petroleum.

Kent, P. E. 1975 Review of North Sea basin development. *J. geol. Soc. Lond.* **131**, 435–468.

Kent, P. E. 1977 The Mesozoic development of aseismic continental margins. *J. geol. Soc. Lond.* **134**, 1–18.

McKenzie, D. P. 1978 Some remarks on the development of sedimentary basins. *Earth planet. Sci. Lett.* **40**, 25–32.

MacIntyre, R. M. (1977) Anorogenic magmatism, plate motion and Atlantic evolution. *J. geol. Soc. Lond.* **133**, 375–384.

Mason, R. G. & Raff, A. D. 1961 Magnetic survey off the west coast of North America, 32° N latitude to 42° N latitude. *Bull. geol. Soc. Am.* **72**, 1259–1266.

Piper, J. D. A. 1976 Palaeomagnetic evidence for a Proterozoic supercontinent. *Phil. Trans. R. Soc. Lond.* A **280**, 469–490.

Pitcher, W. S. 1974 The Mesozoic and Cenozoic batholiths of Peru. *Pacific Geol.* **8**, 51–61.

Pitcher, W. S. 1975 On the rate of emplacement of batholiths. *J. geol. Soc. Lond.* **131**, 587–591.

Price, N. J. 1975 Rates of deformation. *J. geol. Soc. Lond.* **131**, 553–575.

Sibson, R. H., Moore, J. McM. & Rankin, A. H. 1975 Seismic pumping – a hydrothermal fluid transport mechanism. *J. geol. Soc. Lond.* **131**, 653–659.

Sutton, J. & Watson, Janet V. 1974 Tectonic evolution of continents in early Proterozoic times. *Nature, Lond.* **247**, 433–435.

Windley, B. F. 1976 (ed.) *The early history of the Earth.* (619 pages.) London: Wiley.




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