Vertical Tectonics Associated with Rifting and Spreading [and Discussion]

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Vertical tectonics associated with rifting and spreading

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Aseismic continental margins round the world have a much longer history as belts of subsidence than the lateral spreading which produced the oceans which they now flank. Additionally, they show a synchroneity of major development phases which appear to be in part independent of the opening of adjacent oceans.

In many cases the margins coincide with areas which were prone to subsidence as far back as the Lower Palaeozoic; almost universally the rifting which began their main development dates back to the early Permian. In a majority of cases (not all) the main rift phase ended abruptly during the Lower Cretaceous to be succeeded by progradation and major unfaulted subsidence. In some regions (e.g. East Africa and south Australia) a further phase of major faulting continued until the Miocene, the time of a further globally controlled event.

In this long history of vertical movement, extending back throughout the Phanerozoic the subsiding belts which became the sites of sutures between the major plates contrast sharply with East Africa and the Red Sea, often used as tectonic models. Additionally, there is a lack of evidence that oceanic rifting was preceded by anticlinal warping – indeed, along many ocean edges both the faulting and the tilting towards the continent are demonstrably syn-sedimentary, associated with rotation of the marginal blocks as Permo–Triassic and later Mesozoic rocks accumulated.

1. INTRODUCTION

The sequence of plate movements and their dating is now well established. A great deal is understood about the development of the ocean basins, particularly the dating of the central ridge system derived from the pattern of magnetic stripes and the formation of new ocean floor. Nevertheless some of the fundamental processes are still unclear, particularly those relevant to the vertical movements and comparative history of continental margins in what Burk & Drake called 'the belt of ignorance'. These movements are now becoming progressively accurately documented in the course of deep industrial exploration and are an important aspect of this problem.

Mesozoic aspects of the history of worldwide continental shelf development were reviewed by the present writer in a Presidential Address to the Geological Society of London (1977), and are treated only in outline here.

2. MODERN PLATE MARGINS AND PRE-PERMIAN STRUCTURE

In the North Atlantic, the modern continental margins cut obliquely across the trends of Caledonian and Hercynian folding, both of which are held by some authors to be the effects of former subduction and continental collision. The situation is different, however, in the former Gondwanaland, where the belts later to be the sutures of the modern plates lie parallel to the crustal grain and frequently show a history of subsidence extending back through the Phanerozoic.

The Precambrian shields are structural entities which have remained massive and unsubsiding (in fact buoyant and subject to continuous denudation) between linear downwarps which must represent deep seated belts of weakness, later to be the site of continental parting. This is particularly well demonstrated in Africa by the peripheral Pan-African geosyncline and orogenic belt, which flanks the central group of massifs and follows the modern outline of the continent (Kennedy 1965). Delteil *et al.* (1974) also emphasized that the African – South American parting followed ancient lines of weakness, which are responsible *inter alia* for the outline of the Gulf of Guinea.

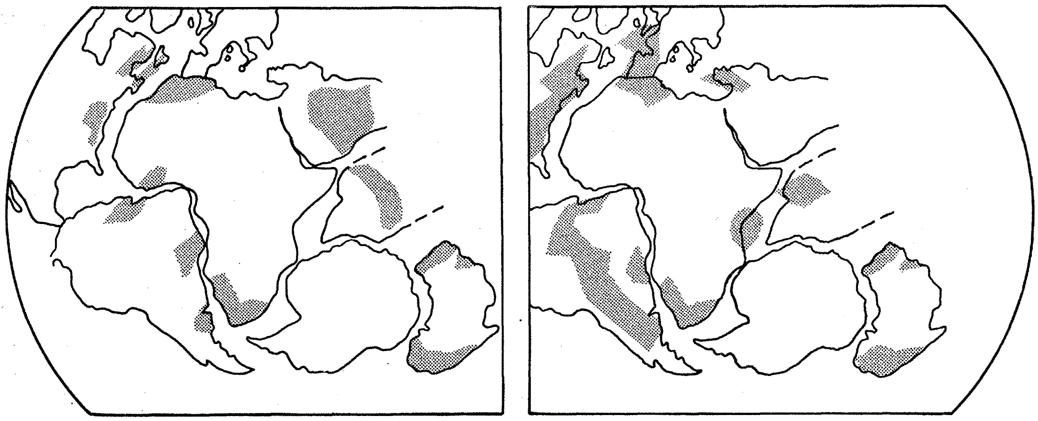
Lower Palaeozoic Upper Palaeozoic

FIGURE 1. Generalized diagram illustrating the relation of Palaeozoic basins to margins of southern continents. Stippling represents Palaeozoic basins.

The regional data bearing on the Palaeozoic history of Gondwanaland have been documented by Teichert (1974), who has shown that the region was probably never a continuous land area, whether or not it was a single plate, since it suffered major, long-lasting marine transgressions during which many thousands of metres of Palaeozoic and Mesozoic rocks were deposited within its boundaries. Thus marine Cambrian is known in northeastern coastal U.S.A., in southwest Africa, in northwestern Australia (1500 m in the Bonaparte Gulf) and in Antarctica. Ordovician occurs in southern Africa, Argentina and on the western Australian margin. Marine Silurian is reported from equatorial Guinea, eastern South America and from the Carnarvon Basin of western Australia (3000 m thick together with the Ordovician). Devonian occurs in the northeastern U.S.A., in easterly South America, South Africa and Western Australia (1550 m, dominantly marine).

Relations of the Palaeozoic basins to the modern continental margin there are clearly demonstrated in Western Australia, as a result of extensive hydrocarbon exploration (McWhae *et al.* 1958; Veevers 1971; Teichert 1974; Powell 1976). Thus the Perth, Exmouth and Carnarvon basins are sectors of a major syn-sedimentary Palaeozoic depression containing unmetamorphosed sediments, now fault bounded, which adjoins and partly underlies the later rocks of the faulted Mesozoic and Tertiary basin along the west coast. These basins were active in the lower Palaeozoic and again in the Devonian and Carboniferous, with a general northward transition from mainly non-marine in the south to mainly marine in the north (Veevers 1974, p. 612). This development relates to a tectonic régime comparable to that of the Mesozoic.

Along the northwest sector of Australia, the Bonaparte Gulf and Fitzroy Palaeozoic Basins cut the coast at right angles, and are regarded as facing open ocean throughout Phanerozoic times (Veevers 1971). Their sections beneath the shelf continued to sink during the Mesozoic. Development of this basin system can be recognized during the Cambrian, Ordovician, Devonian, Carboniferous, Permian, Jurassic and Lower Cretaceous as depressions opening northeastwards onto the present continental shelf. The rifting developed at least as early as the Devonian and continued into the Upper Jurassic. By the Permian the western and northwestern basin systems had become continuous and peripheral to the modern Australian continental block.

On the outer periphery of Gondwanaland, external Lower Palaeozoic basins are known in South America (now lying between the Western Cordillera and the Shield areas) and in the Tethyan belt, as exemplified by the long marine Lower Palaeozoic and Devonian sequences of the Sahara, and the similarly non-metamorphosed Cambrian, Ordovician and Silurian of Arabia and the Persian Gulf, all of which accumulated on the contemporary aseismic margins of this plate.

Not all these occurrences are necessarily related to the present continental outlines, and there are also belts of strongly deformed Palaeozoic rocks (such as the Tasman geosyncline) within the modern cratonic areas, but many of them fit the pattern of the major plate edges, and Mesozoic rifts tend to occur in close association with deep Palaeozoic troughs.

3. Permian and Mesozoic rifting

The Permian was marked by a worldwide marine transgression, commonly across a peneplained continental surface. This is documented for example in northern Alaska, northern Canada, northwest Europe, Tunisia, Arabia, Iran, peninsular India, Madagascar, western Australia and Papua New Guinea. The ubiquity of this transgression indicates a major eustatic rise of sea level, which is presumably at least in part related to the melting of the Permo–Carboniferous ice cap. Two other points, however, deserve emphasis.

First, the areas flooded by the Permian transgression were largely those later to be chosen for plate separation, were frequently in part coincidental with earlier Palaeozoic marine basins, and in many of the areas were the immediate predecessor to Mesozoic rifted basins, as in northern Alaska, the North Sea, East Africa, western Australia, etc. This history of subsidence leaves no place for a postulated anticlinal phase preceding inception of Mesozoic rifting and continental separation, and any hypothesis which requires a linear ‘welt’ as a preliminary to oceanic opening is at variance with this evidence, a subject discussed further below.

Secondly, the Permian was one of the world’s great rifting periods. The Karroo rifts of East Africa, at least in part syn-sedimentary, extend through coastal Kenya (Lamu embayment and Mombasa area), in coastal Tanzania (Tanga area in the north, Dar-es-Salaam embayment in central Tanzania and the Mandawa area in the south) as well as in coastal Mozambique and northern and western Madagascar. The Karroo rifts are matched by contemporary sediment-filled rifts from northern Alaska and the North Sea to western Australia, frequently located on subsequent continental margins but extending also well away from continental edges. Eustatic sea level rise and continental shelf loading could have triggered subsidence along incipient or pre-existing faults on oceanic margins, but the much wider extent of the tensional phenomena at this time indicates a more fundamental cause.

The beginning of the Triassic period was marked by a major regression, so globally widespread that it has proved to be a major problem to find a type area where a marine sequence from Permian into Trias can be established. This must mark a eustatic withdrawal of the seas comparable in size to the earlier Permian transgression. It was not, however, associated with an interruption of subsidence, for continental and evaporitic sediments of major thicknesses accumulated in basins along the plate sutures, now located on the margins of the Atlantic and Indian oceans as well as in many parts of Tethys. Basin subsidence is in this case clearly independent of eustatic effects on the world scale, and neither of these features was very obviously linked to the lateral movement of continental plates.

On the world's continental shelves Lower Jurassic rocks are found only infrequently, but Middle Jurassic rocks are rather more widely distributed, and Upper Jurassic and Lower Cretaceous are widespread; these stages in the process of fluctuating eustatic submergence of the continental edges are documented by Hallam & Sellwood (1976), Vail *et al.* (1976) and others. Part or all of this Mesozoic sequence commonly occurs in major pre-Upper Cretaceous rifts, believed in many cases to be syn-sedimentary in their development, in other cases characterized by major faulting at particular periods, notably during the Middle Jurassic and late Upper Jurassic (Kent 1975, 1977).

The remarkably widespread termination of the rift phase in the middle Cretaceous, at dates within the narrow time range end-Neocomian – Lower Aptian – Upper Aptian, has been catalogued elsewhere (Kent 1977). A point of critical importance is that this date still applies in areas such as the Norwegian Sea where plate separation is believed to have come much later (Talwani & Eldholm 1974), and where the mechanism of a straightforward change of tensional régime associated with exposure and cooling of open ocean crust can hardly apply. It could, however, reflect a change from widely distributed tensional stress to localized relief along newly-formed mid-ocean fracture zones, even though the actual opening came later.

4. General comment

Several points of significance arise from this brief review in relation to the working of the global system.

(*a*) *Longevity of continental margins*

First, as has been stressed in the preceding pages, the continental selvedges are relatively ancient; not only were most modern continental margins the sites of Permian to Lower Cretaceous rifts, but where the older history is known it is common to find the margins coincident with, or at least adjacent to, parallel-trending older Palaeozoic rifts and basins. This applies particularly to the dismemberment of the former Gondwana plate, which took place along ancient lines of weakness and subsidence.

As previously observed, this history of break-up along zones prone to subsidence through most of Phanerozoic time is a major difference from that of the Red Sea region, so frequently quoted as a model for continental separation.

Secondly, it appears that continental margins share much of their tectonic history with continental interiors. Thus the Karroo rifting of coastal Africa has its precise parallel 500 km inland in deep, long lasting rifts, similarly believed to be syn-sedimentary. The Neogene history of tensional movement of the coastal area in Tanzania is closely linked to that of the central African rift system (Kent *et al.* 1971). The North Sea is discussed and analysed as a section of continental margin, but it was a long way from the oceanic edge until some time in the Eocene (Talwani & Eldholm 1974), and it shares the progradational post-rifting stage with true oceanic margins, even though no oceanic crust was exposed either then or later, to provide the favoured cooling–contraction mechanism. So also does the Benue trough, closely analogous to the West African coastal basins in its rift phase followed by progradation, although no-one would there suggest subsidence by cooling of exposed oceanic crust. I am not suggesting that existing hypotheses are in error, but that they need supplementing: that other factors must exist, presumably related to much deeper crustal structure.

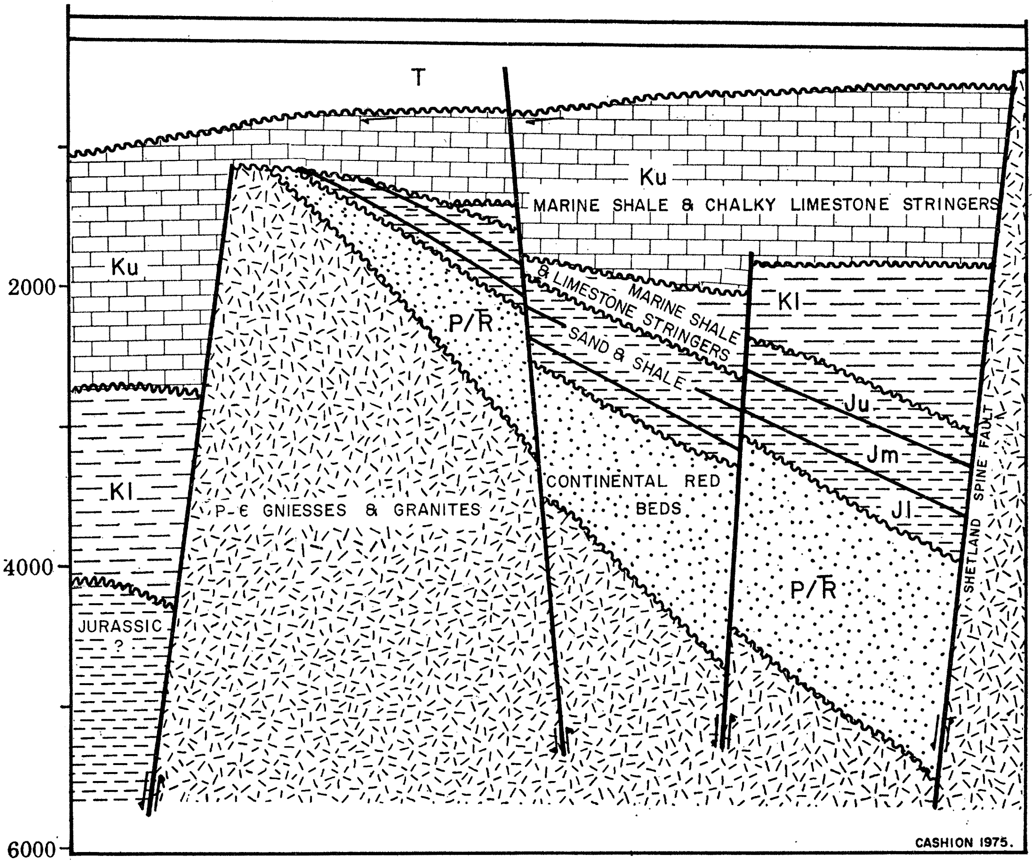

Figure 2. Stratigraphic section through the sedimentary wedge west of the Shetland Islands (West Shetland Basin), after Cashion (1975). Vertical scale greatly exaggerated.

(*b*) *The hypothesis of domal inception of rifting*

Several of the concepts of plate separation postulate an initial phase of doming, preceding the rift phase (see, for example, Sleep 1973). This is, in part, based on use of the Red Sea as a model, which seems (to the present author) to be an inappropriate comparison in terms of temporal development as emphasized above. (The Red Sea may in fact have had a rather different history, as I. G. Gass has reported in the discussion following presentation of this paper.)

The physical evidence for a domal phase appears to be mainly the outward tilting of rift blocks, dipping away from developing oceans or proto-oceans. Two points arise in relation to this feature. First, the rotation of blocks, when it can be dated stratigraphically, is a long-term secular process developing contemporaneously with rifting. This is particularly clearly demonstrated on the Atlantic margin west of the Shetlands (Cashion 1975) (figure 2) and is seen also on the opposite ocean coast in Greenland (Collinson 1972); it is true of such North Sea structures as Brent. There are many other cases of 'trapdoor' development of major faults on ocean coasts. Quoting comparable cases recently figured, in which contemporary rotation of fault blocks is indicated by sedimentary thicknesses, one may cite the seamounts off Portugal (Montadert *et al.* 1974, pp. 326–327); horsts and rifts in the Gulf of Guinea (Delteil *et al.* 1974, figures 9 and 10) and the Meriadzeck terrace of the Bay of Biscay (Montadert & Roberts, this volume). It is emphasized that the well-established large-scale rotation of blocks contemporaneous with rifting and sedimentation is incompatible with the hypothesis of an initial dome as the cause of peripheral dips on oceanic margins.

In the North Sea, the Piper area east of the Moray Firth has been quoted as a prime example of a trilete junction and hot spot subject to initial doming (Whiteman *et al.* 1975). This is an area where the east–west Moray Firth fault trend meets the central (north–south) rift, the latter being offset at the intersection. The area suffered a phase of extrusive volcanism in the Bathonian–Bajocian (Howitt *et al.* 1975). The basic trilete junction concept could be criticized on the grounds that the Moray Firth faults are not normal rifts but are splays from the Great Glen fault, which is fundamentally transcurrent and hence is responsible for the offset of the otherwise continuous north–south central rift (Kent 1975, p. 20). More critically, the well-established stratigraphy of the adjoining Piper oilfield shows, first, that this block (upthrown from the rifts) is located over Carboniferous, and hence was synclinal at the beginning of the rift phase, and, although subject to numerous interruptions in deposition, nevertheless includes representatives of Permian, Trias, Middle Jurassic and Upper Jurassic; so that although it was a relatively buoyant block it was never subject to uplift and erosion important on a regional scale. This is a rather different picture from that given by Burke (1977, p. 386) in interpreting regional structure in terms of an aulacogen.

Viewed in broader terms, the North Sea basin itself has been synclinal since the Upper Palaeozoic, the Permian floor of the Northern North Sea Basin being mainly Devonian (between Pre-Cambrian blocks) and that of the Southern North Sea Basin being Upper Carboniferous. In the Southern North Sea, occurrences of shallow Lower Palaeozoic rocks lie between the main rifts. In the southern part of the Northern North Sea Upper Palaeozoic occurs both in rifts and on blocks. In the Northern North Sea the presence of crystalline metamorphic rocks has, however, been proved beneath Mesozoic in parts of the Viking graben, but until we can compile a map of the pre-Permian floor it is not possible to say whether or not this establishes early anticlinal warping. Certainly the rotation of blocks in the Brent group of oilfields is largely syn-sedimentary.

In ocean margin areas, evidence of the nature of the floor of Mesozoic rifts is generally lacking, for the rocks concerned are mostly out of reach of conventional hydrocarbon exploration operations and tend to be low-grade objectives. None the less, one can quote the occurrence of Silurian in Ghana beneath the Mesozoic rift, and at least partial coincidence of Mesozoic and Palaeozoic rifts in Western Australia (Veevers 1974; Powell 1976) as demonstrating that on these ocean margins also Mesozoic rifting was not necessarily preceded by domal uplift.

(*c*) *Uplift of rift margins*

It is generally assumed that rift (or fault block) subsidence is approximately balanced by uplift of the flanks, as, for example, in the Red Sea. There are, however, exceptions to this simple arrangement, and their existence is important in relation to the fundamental control of vertical movements on ocean margins.

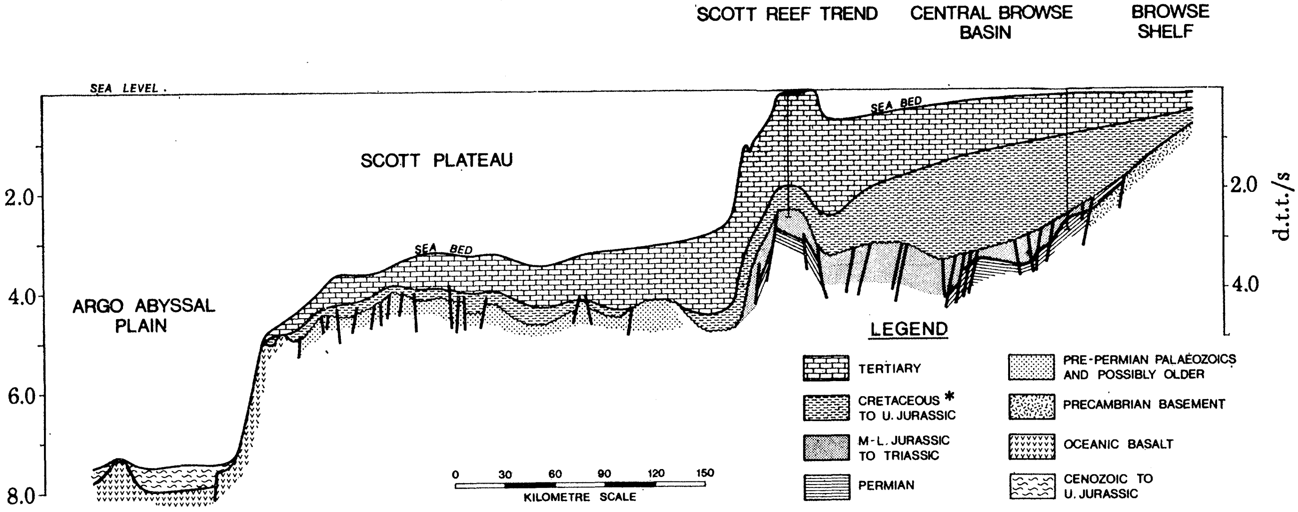

FIGURE 3. Generalized section across the north-west Australian continental shelf and the Scott plateau, after Powell (1976).

On a small scale the relation can be studied on intra-Mesozoic uplifts in Britain and the North Sea, where buoyant blocks of size varying from a small oilfield to that of the East Anglian Massif have, for long periods, maintained a regionally even elevation close to sea level, with minor transgression and minor phases of erosion, between sinking troughs. On a continental scale the same feature is intermittently traceable, with the transgressive deposits surviving on the upthrown side of major faults (e.g. in northern Tanzania, where Middle Jurassic rocks sit on the upthrown block that bounds the coastal basin, in Somaliland south of Berbera, on the Ethiopian rift edge and no doubt in other places) indicating that positive movement of the high blocks has been of relatively minor consequence compared with the subsidence of the troughs alongside; in fact the upthrown blocks have tended to remain stable near sea level. This feature points towards crustal attenuation rather than simple isostatic adjustments as a controlling factor in continental margin development, a matter which could be further documented by investigation of erosion surfaces and the history of vertical movements in other places, such as northwestern Scotland and Rockall.

It was not the purpose of this paper to comment on the fundamental tectonic processes which have controlled the location and timing of the vertical movements on aseismic continental margins. However, it is hoped that taking account of the history and special characteristic of oceanic margins in widely separated parts of the world will facilitate distinction between the various hypotheses of their development, recognizing their long ancestry.

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Discussion

D. A. Robson (*Department of Geology, The University, Newcastle upon Tyne, U.K.*). In the course of his address, the speaker showed a number of diagrammatic cross-sections cutting through fault blocks, from various regions of rift faulting. Most of these cross-sections indicate that the bounding faults of the blocks are steeply dipping, normal, synthetic fractures. However, in that of the Brent field, North Sea, the dip of these faults decreases with depth and it is assumed that they eventually attain horizontality – probably at a depth below 12000 ft. The pattern is well illustrated by Bowen (1975), with a cross-section at natural scale.

One of the difficulties in interpreting the true dip of the faults shown on diagrams of seismic data is that the vertical scale generally far exceeds that of the horizontal; therefore, faults which are portrayed as steeply-dipping may, in fact, possess quite a low dip. This is the case, for example, in Cumming & Wyndham (1975) where, in a section across the North Sea Hewett field, a fault northeast of well 52/5–1 appears to have a dip of about 70°, but if this section is redrawn at natural scale, the angle of dip approximates to 40°. Is it not therefore of great importance, if the tectonic patterns of rift faulting are to be correctly interpreted, that the true dip of all faults should be accurately recorded?

At least some of these important fractures associated with fault blocks seems to show a concave-upward profile and the nature of their origin presents a problem. Sir Peter regards them as of less fundamental importance than the steeply dipping faults, and seems inclined to regard them as somewhat akin to a gravity slide. But can this be wholly true, in that the blocks themselves are invariably tilted? Does this not indicate that there must have been an upthrow as well as a downthrow movement? One wonders how typical these shallow-dipping faults are, and to what extent they reflect the true pattern of rift faulting.

Sir Peter also questions the development of doming in association with rift faulting. Perhaps not doming, but certainly arching occurred during the development, for example, of the Clysmic Rift of the Gulf of Suez, Egypt (Robson 1971). This rift valley is a great broken arch, for the Pre-Cambrian surface, which forms the shoulders of the rift, dips outwards on either flank at low angles. Beyond the western margin of the Clysmic Rift, from a suitable vantage point, these westerly dips can be traced for many kilometres towards the Nile valley.

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Sir Peter Kent, F.R.S. Dr Robson commented on the contrasting styles of faulting illustrated at Brent (Northern North Sea) and other places, and asked (1) if the author had an explanation and (2) whether transcurrent movement was recognized.

In reply the author said that he regarded the low dipping faults of the Brent type as essentially shallow, and due to a form of collapse towards a deeper central depression. Comparable features could be quoted in the East African rift, as well as the examples off the West African continental margin (Morocco) quoted by Y. Lancelot.

The steep faults bounding the Mesozoic and Palaeozoic rifts in Australia and other places are usually quoted as being of normal type, and do not show the variable throws associated with transcurrent faulting.

T. J. G. Francis (*Institute of Oceanographic Sciences, Blacknest, Brimpton, Reading, Berkshire, U.K.*). I would like to say something about the seismicity of passive continental margins. Although passive margins are much less seismic than active ones, they are by no means aseismic. Quite large earthquakes have been associated with passive continental margins. The best known is undoubtedly the Grand Banks earthquake of 1929, which had a Richter magnitude of 7.2. A smaller earthquake ($m_b = 4.6$) occurred at the southern end of Rockall Bank in 1970, in a region from which no earthquakes had previously been reported. Earthquakes are quite frequently associated with the Norwegian shelf edge. No doubt other shelf edge earthquakes can be identified. Thus there is a small input of seismological data relevant to studies of passive continental margins. Detailed studies of these earthquakes should help to refine our understanding of the tectonics of passive margins.

I. G. Gass (*Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, England*). Several times during this meeting it has been demonstrated that regional uplift is not an essential precursor to translithospheric rifting. Sir Peter Kent emphasized this point and, in cautioning against the injudicious application of the 'Red Sea model' seems to imply that in the Red Sea rifting was consequent upon regional uplift. Indeed, although this relation has been proposed many times, it is now quite evident that, here too, rifting occurred before uplift, although the flanking crystalline basement was subsequently uplifted by as much as two kilometres after the initial production of the Red Sea oceanic crust at near sea level (Coleman *et al.* 1975; Gass 1977).

Uplift and rifting are obviously not always consequent one upon the other. None the less, there is an undeniable spatial and temporal correlation between uplift, rifting and volcanism. For the African Cainozoic it has been demonstrated (Fairhead & Reeves 1979; Gass *et al.* 1978) that surface uplift delimits areas where the continental lithosphere has been attenuated by regional thermal pertubations within the mantle. So, although the primary thermal energy thus made available can be expended on uplift and/or rifting and volcanism, there is no particular reason why one process should precede the other. Indeed, in the case of the Afar depression there is good evidence that uplift and volcanism have, for the main part, been mutually exclusive for the last 30 Ma (Pilger & Rosler 1975).

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M. F. Osmaston (*The White Cottage, Sendmarsh, Ripley, Woking, Surrey GU23 6JT, U.K.*) The lengthy pre-oceanic subsidence history of many of today's passive-type ocean margins, to which Sir Peter has rightly directed closer attention, is given even greater significance by evidence that the same early pattern of basins and horsts have often been caused by later events to reappear, or to be re-emphasized, sometimes on several occasions. This strongly suggests that the explanation for the detailed differential epeirogenic behaviour of passive-type margins and of their predecessor strings of basins, should be sought, not in terms of an improbably detailed coherence between successive tectonic events, but rather in terms of long-lived differences in the epeirogenic properties of the lithosphere beneath sharply defined basin and non-basin areas. These differences would need to be such as would show up in the presence of broad tectonic and thermal stimuli.

I have shown in considerable detail elsewhere (Osmaston 1973, 1977) that these requirements are closely fulfilled if the subsidence-prone areas are underlain by lithosphere created by limited plate separation at an earlier time. Ocean floor studies teach us that the potential subsidence of new lithosphere, due to cooling and sedimentary loading up to sealevel, is 20 km or more. In the restricted environment arising from limited plate separation, however, subsidence of the young lithosphere would be hampered mechanically by the adjacent older and non-subsiding parts of the plate. Subsidence would therefore tend to be episodic and might need to be triggered by the application of a suitable tectonic stress. Particularly important examples of the latter would result from any renewal of plate separation, which would have the effect of removing one of the subsidence-impeding boundaries and substituting a rapidly subsiding one, i.e., freshly generated lithosphere. The widely recognized 'rifting' phase, which precedes the oceanic separative phase and produces widespread selective down-dropping of 'continental' crust, may thus indicate, in part, the locations of the early separative basins.

Clearly, these arguments would be to no avail unless the geometries, dispositions, and possible lithosphere genesis ages of the subsidence-prone areas concerned can be shown to conform to a plate tectonic interpretation. Fortunately, although the work of analysis in this regard is still only in its infancy, it is already evident that, for some regions at least, it is very probable that these requirements are indeed met with considerable precision.

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