of Mn (IV) minerals such as birnessite range up to 350 $m^2 g^{-1}$ (ref. 8) and the surface charge of freshly precipitated birnessite is also usually high, exceeding 100 $\mu C\ cm^{-2}$ at $pH = 8.0$ (ref. 9). The zero point of charge (ZPC or pH of zero net surface charge) for fresh birnessite and amorphous Mn (IV) oxides is often as low as $pH = 1.5$–2.0. Hence the manganese oxides have an unusually high negative surface charge and cation adsorption capacity over the pH range of most natural waters. For example, the cation-exchange capacity of MnO_2 at $pH = 8.3$ (as in seawater) is 1.5 equiv. per 100g while that of montmorillonite is only about 0.1 equiv. per 100g (ref. 10).

The identification of manganese oxides as strong radionuclide adsorbents in the ORNL disposal area has important ramifications for future radioactive waste disposal technology. Isolation alternatives for high-level waste currently include storage or disposal in deep geological formations such as salt, shale, or granite, and seabed disposal. Waste may or may not be solidified by processes such as calcination, cementation or vitrification into borosilicate or phosphate glass before burial[11]. Because of their toxicity and long half lives, buried actinides must be effectively isolated from the environment for several hundred thousand years. We recommend that finely-ground manganese oxides be added to the high-level waste before solidification into calcine, salt cake or cement. Alternatively, it may be feasible to coprecipitate and encapsulate the waste with manganese oxide at high temperature. Deep-sea manganese nodules, which may in the future be mined for their valuable trace metal contents[12], could serve as a plentiful and inexpensive supply of actinide adsorbent for use in future radioactive waste disposal operations.

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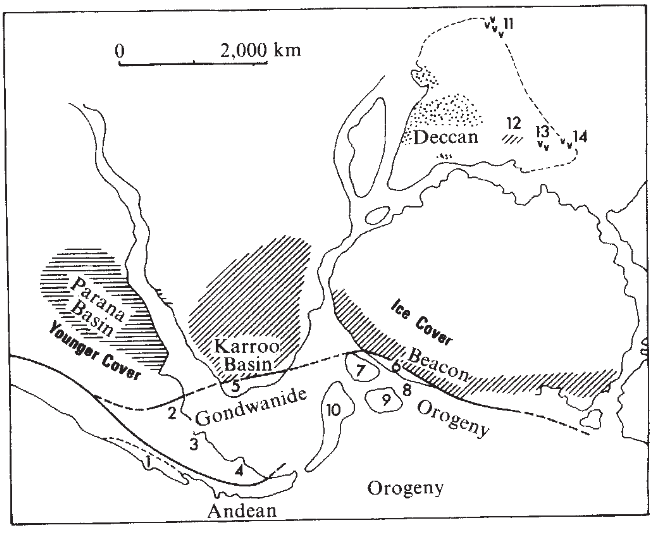
Flood basalts, subduction and the break-up of Gondwanaland

THE hypothesis of Du Toit[1] on a continuous zone of orogeny and sedimentation (the Samfrau geosyncline) along the Pacific side of Gondwanaland in Palaeozoic and early Mesozoic times has been supported by subsequent geological work. As originally conceived, the orogenic zone of the Gondwanide orogeny consisted only of a Triassic fold-belt seen, for example, in the Cape Fold Belt of South Africa and the Sierra de la Ventana in Argentina (see Fig. 1). Fragments of the belt are also known from the Antarctic continent in the Pensacola Mountains, Ellsworth Mountains, and the Antarctic Peninsula[2]. Radiometric dating has established that the Gondwanides also include metamorphic and plutonic rocks, exposed in South America in the Patagonian and Deseado massifs, and in the Cordillera Frontal of Argentina (see ref. 3). These have their Antarctic counterparts in the Antarctic peninsula, Eights Coast and Thurston Island, Maria Byrd Land, and at scattered exposures between the Ellsworth and Thiel Mountains[2] and in eastern Australia. Several of the occurrences listed are now caught-up within the late Mesozoic–early Cainozoic Andean orogenic zone. In terms of sedimentation, the Samfrau geosyncline consisted of a 'foredeep' (for example, the Paraná and Karroo basins) developing from the late Silurian onwards and receiving sediment of a shallow marine or nonmarine nature until at least the end of the Trias. To the north the 'foreland proper' showed the transgression of Carboniferous and later sediments on to Precambrian basement. More recent work in West Antarctica has shown the existence of a greywacke–shale facies lying to the Pacific side of du Toit's foredeep[2]. Craddock[4] sees the Pacific border of Gondwanaland as an active continental margin showing successive orogenic episodes within the Phanerozoic. The orogenic process is believed to involve the interaction of the Gondwanaland continent with the Pacific plate, and an accretionary process at the continental margin has been suggested. With reference to Antarctica, Stump[5] has raised the possibility of nearly continuous subduction from the late Precambrian to the Cretaceous. Dickinson[6] has referred to the 'Gondwana–Tasman orogenic trend' as a zone of inferred plate consumption. With the information now available I have examined some of the relationships between the Gondwanide orogeny and its foreland in more detail, and discuss here

Fig. 1 The Gondwanide orogeny along part of the Pacific margin of Gondwanaland. The continental fit of Smith and Hallam[24] is used modified in the region of the Antarctica Peninsula to show the pre-drift positions of the Antarctic Peninsula, Ellsworth, and Thurston microplates according to more recent work by Barker, Dalziel *et al.*[25] and de Wit[26]. Stipple, Deccan Traps (early Tertiary); horizontal shading, Paraná volcanism (early Cretaceous); diagonal shading, Karroo, Antarctic, and Rajmahal volcanism, (early Jurassic). v, the Panjal, Sylhet, and Arbor volcanics (late Palaeozoic to early Mesozoic age). 1, Cordillera Frontal; 2, Sierra de la Ventana; 3, Patagonian Massif; 4, Deseado Massif; 5, Cape Fold Belt; 6, Pensacola Mountains; 7, Ellsworth Mountains (pre-drift position); 8, area between Ellsworth and Thiel Mountains, 9, Eights Coast and Thurston Island (pre-drift); 10, Antarctic peninsula (pre-drift); 11, Pir Panjal range, Kashmir; 12, Rajmahal Traps; 13, Sylhet Traps; 14, Arbor volcanics.



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whether there may be a connection between flood basalt volcanism and orogeny.

The Gondwanide foreland is the site of three of the world's largest flood basalt provinces, each of which consists of an extrusive phase together with a voluminous suite of doleritic sills penetrating the underlying platform sediments. The basalts and dolerites of southern Africa (The Karroo)[7] and Antarctica (Ferrar Dolerites and Kirkpatrick Basalts associated with sediments of the Beacon supergroup)[2] are mostly of early Jurassic age and were probably erupted shortly before the Indian Ocean was established by the separation of Africa and Antarctica. The Paraná basalts are substantially younger (~125 Myr)[8] and are precursive to the opening of the South Atlantic. A small remnant of this province is preserved in the Kaokoveld area of southwestern Africa[9].

As du Toit remarked, one of the noteworthy features of the foreland geology of the Gondwanides is that tensional tectonic conditions developed during the Permian and Trias at the same time as compressional forces were operating in the adjacent fold belt. In southern Africa[10], for example, normal faulting accompanied the subsidence of sedimentary troughs from the Permian (Ecca) through to the onset of volcanism in the earliest Jurassic. At this stage numerous dyke swarms, running in a variety of directions show the extensional nature of the tectonic regime. Even large volcanic-filled synclines such as that of Nuanetsi in Rhodesia were accompanied by extension at right angles to fold axes. In southern Africa, because of a favourable erosion level and an absence of ice cover, it is also possible to examine the relationship between extensional zones of Karroo age and basement structure. Here there proves to be a very detailed correspondence, Karroo extension being largely taken up along the Zambesi and Limpopo zones where younger Precambrian orogenic belts intersect the Archaean craton, and along the Lebombo monocline which may mark the southwards continuation of the edge of the Mozambique belt. Within the Limpopo belt itself the control of Karroo tectonics by basement structure is seen on a relatively fine scale[10].

If southern Africa is accepted as a model, the foreland of the Gondwanides was at least from Permian onwards a region characterised by a general lateral expansion. Sedimentation was eventually succeeded by extraordinarily widespread basaltic volcanism (Karroo lavas and associated hypabyssal rocks probably, for example, affected an area of $\sim 2{,}000{,}000\ \text{km}^2$) which reached extreme thicknesses in linear zones such as the Lebombo. Tensional tectonics persisted and shortly afterwards continental fragmentation began. This stage was probably reached in the early Jurassic in southern Africa and Antarctica but the whole volcanic episode was delayed until the early Cretaceous in South America, as was the opening of the South Atlantic. Both the South Atlantic and the Indian Ocean rifts show a broad dependence on basement structure[11].

Elliot[2] has speculated on a possible connection between rifting, subduction beneath West Antarctica, and the basaltic volcanism of the foreland. The marginal basin environment[12,13] for the western Pacific was suggested as an analogy. This needs closer inspection because the Gondwanide foreland shows several important tectonic features of the back-arc environment in that the orogeny was bounded on the continental side by a zone showing subsidence, extension, widespread basalt volcanism, and continental break-up.

There are also many differences between the two environments. Although, for example, there is a comparability of scale in a direction parallel to the postulated subduction zone, the igneous and tectonic phenomena of the Gondwanide foreland extend for 2,000–3,000 km into the continent in a direction at right angles to this. Existing models of back-arc spreading, however, normally consider phenomena extending for only a few hundred kilometres in this direction. Additionally, when continental separation did take place within Gondwanaland, it occurred along basement-controlled lines lying at high angles to the orogenic zone, in contrast to the western Pacific where separation characteristically takes place relatively close to and parallel with the trenches. However, the spatial relationships of Fig. 1, and the time relations discussed, suggest the strong possibility of a genetic connection between the flood basalts and the orogenic process. Hence, despite the differences between the Gondwana foreland and the western Pacific back-arc environment a hypothesis that the flood basalts are related to subduction seems to be worthy of serious consideration.

This suggestion is highly speculative but it does prompt the query whether other flood basalt provinces might have a connection with subduction. Elsewhere, within Gondwanaland, there is some intriguing evidence; for example, in the Pir Panjal range at the southern edge of the Himalayas in Kashmir (see Fig. 1) the extensive Panjal Trap sequence indicates a considerable episode of basaltic and andesitic volcanism running from the Carboniferous through to the Trias and reaching its peak in the Permian. Wadia[14] comments that "a region of quiet marine sedimentation was converted into a great theatre of volcanicity, whereby an enormous superficial extent of the country was converted into a volcanic region such as Java and Sumatra in the Malay archipelago of the present day". Northern India also saw the eruption of the supposedly andesitic Sylhet Traps and Arbor volcanics at about the same time[14,15]. Thus, on the extreme northern border of Gondwanaland there may have been a mirroring of the events previously discussed in the south. This could imply that a subduction zone developed dipping southwards under India, and that as the continent subsequently migrated northwards part of the Tethys ocean floor was subducted beneath it. Whether this might be related to the eruption of the Rajmahal Traps (see Fig. 1) during the Jurassic or to the eruption of the Deccan Traps in the early Tertiary is a matter for future consideration.

To speculate on the Siberian Traps[16] or the North Atlantic Province is beyond the scope of this paper. In the latter case, a connection with any nearby orogenic zone of appropriate age is not obvious. However, if attention is restricted to the Mesozoic and younger provinces the most important remaining Northern Hemisphere occurrence, the Columbia River Plateau, shows close spatial relationship with an orogenic zone, and indeed has already been interpreted in terms of subduction processes[17]. Thus, the flood basalt provinces outside Gondwanaland may provide evidence in favour of the hypothesis, but the data at the moment seem to be equivocal.

The close relationship in space and time between the varied tectonic and igneous phenomena of the Gondwanide orogeny and its foreland imply a genetic relationship. No discussion would be complete without considering the possible mechanisms, which must introduce a more speculative element, but should not obscure the original factual observations.

Most mechanisms[12,13,18–20] suggested for back-arc spreading depend on the existence of a subducted lithospheric slab below the zone of spreading. Most tacitly assume that the subducted slab disappears at the bottom of the Benioff zone at a depth of about 700 km, and that the slab does not extend under the adjacent plate for more than about the same distance. Disappear, here, means that the subducted materials become indistinguishable from the surrounding mantle. However, the cessation[21,22] of earthquake activity in subducted lithosphere at a depth of 700 km does not necessarily mean that the subducted material ceases to exist as a definable unit beyond this point. The material may remain distinct from the surrounding mantle because of its motion, its temperature, or its composition. In examining existing models of back-arc spreading it must be remembered that they are mainly specifically designed to explain phenomena within a few hundred kilometres of the trench. The induced convection cell model of Toksöz and Bird, for example, derives its motive power from the movement of the subducted slab in the Benioff Zone itself and, hence, does not produce effects at a distance of more than about 700 km from the trench. They conclude that subduction beneath continential crust could not induce secondary spreading because the heating effect of the rising limb of the secondary convection cell is insufficient to thin the original continental lithosphere significantly. They do, however, envisage the possibility of a slow and diffuse extension of the continental lithosphere represented by faulted provinces such as the Basin and Range, a province which had earlier been interpreted[23] as being specifically related to subduction. I conclude that if the Toksöz and Bird model has any relevance to complete continental separation as seen in the Gondwanide foreland then it requires a larger scale than presently envisaged, both in terms of geometry and time.

The Oxburgh and Parmentier mechanism is based on a completely different principle, though there is no reason to believe that it could not act in conjunction with an induced secondary convective cell. The model postulates that mid-ocean ridge volcanism creates a depleted (harzburgitic) layer in the upper part of the oceanic lithosphere. After subduction and heating the depleted layer becomes buoyant relative to the surrounding rocks and separates into a series of diapirs which rise into the overlying upper mantle and lithosphere. The attraction of this model is that the depleted layer is compositionally distinct, and, unless some very thorough process of mantle homogenisation exists, is unlikely to lose its identity at the bottom of the Benioff Zone. Several thousands of kilometres of Pacific oceanic crust have been subducted since the beginning of the Mesozoic[6], and the record of orgeny in Antarctica indicates that the process may also have operated during the Palaeozoic. Thus, by the time fragmentation of Gondwanaland began, early in the Mesozoic, very large volumes of oceanic lithosphere may already have been subducted around its Pacific margins. It is possible that the continual emplacement of potentially buoyant depleted lithosphere underneath the continental margin was responsible for the foreland phenomena commented on, and even ultimately for the initiation of continental break-up. It is difficult to escape the conclusion that long-continued subduction is likely to displace some of the subducted material further and further underneath the adjacent plate, and hence phenomena essentially related to the subduction process might appear far into a continental interior. If volcanism is so induced its petrogenetic relationships are likely to be complex and difficult to predict. Rising harzburgite diapirs presumably supply the energy for volcanism but not the substance. The volcanic rocks seen at the surface might originate from envelopes of less-depleted mantle dragged up by rising diapirs, or by decompression during periods of lithospheric fracturing. The extension and eventual separation of the continental crust is presumably a response to the intrusion of numerous diapirs. This type of mechanism provides a plausible explanation of the more or less undirected tensional tectonics of the Karroo period in southern Africa, the lines of ultimate complete lithospheric failure and continental separation being controlled by existing basement trends. Apart from matters of scale already discussed, this latter point may be another essential difference between the break-up of Gondwanaland and the present geology of the western Pacific arcs and marginal basins. If subduction takes place along a continental margin which already possesses a pronounced structural grain parallel to the margin, as is the case round much of the circum-Pacific belt, back-arc spreading may produce marginal basins behind narrow continental slivers such as New Zealand. Furthermore, there may be a subsequent strong tendency for such basins to close. Alternatively, if strong structural grain in the foreland runs at a high angle to the subduction zone, as it does, for example, in the Mozambique belt of south eastern Africa, separation of the continental crust may produce an elongated oceanic basin which further subduction tends to widen rather than close up.

The final question is the extent to which these speculations can be tested. Regional geological studies will ultimately show whether the relationships seen in southern Gondwanaland are repeated elsewhere. Of more immediate concern is the assessment of the very large amount of geochemical data now available, much of it unpublished, for the flood basalt provinces of Gondwanaland. It will be very interesting to find out whether geochemical zonation fits into any sort of pattern consistent with the subduction hypothesis.

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Infracambrian glaciogenic sediments from Sierra Leone

THE Rokel River Group[1-3] is a sequence of generally marine sediments and interbedded volcanic rocks which extends into Sierra Leone from Guinea as a NNE–SSW trending, northwards plunging synclinorium (Fig. 1). It is divided into six formations[3] and rests unconformably on Archaean granitic basement. The Rokel River Group is considered to be late Precambrian to early Cambrian as it was folded and slightly metamorphosed near the present western outcrop margin, during the Rokelide orogeny[3,4] around 550 Myr ago, the date of the Pan–African thermo–tectonic episode[5]. It is unconformably overlain by probable late Ordovician sediments of the Saionia Scarp Group[1,6,7]. We have studied the basal formation of the Rokel River Group, the Tabe Formation[3], and describe here two members, the lower one exhibiting the characteristics of a glacial deposit. These glaciogenic sediments extend the known range of the Infracambrian–Eocambrian glaciation in West Africa.

The Tabe Formation has been examined mainly in the southern half of the Rokel River Group outcrop where two members can be recognised which we call the Tibai and Dodo Members. Details of localities, stratigraphy and sedimentology of the Tabe Formation will be given elsewhere.

The Dodo Member overlies the Tibai Member in places but elsewhere it rests unconformably on the Archaean basement. It is younger than the Tibai Member but may possibly, in places, be laterally equivalent. The Dodo Member, composed of feldspathic sandstones, crossbedded in places, is considered to be of a shallow water, possibly of intertidal origin.

The Tibai Member rests unconformably on Archaean granitic basement. It is composed of three lithologies, conglomerates, feldspathic sandstones and siltstone–fine sandstone rhythmites containing dispersed granatic clasts which on

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