

VERTICAL CRUSTAL MOVEMENTS AND THE RIFTING OF CONTINENTS

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ABSTRACT

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Verticalism and mobilistic philosophies in geotectonics are seen as integrally joined in modern plate tectonic theory. This theme is illustrated under two topics: lineaments and rifting (with examples from Gondwanaland); and cratonic planation-surface chronology (with an example from Western Australia).

INTRODUCTION

Some people might have thought that the triumph of the plate tectonic revolution in the two decades of the 1960's and 1970's would have spelled out the death of verticalism. Fixism could certainly be set back on the shelf of philosophic byegones, but verticalism is alive and well, prospering in the logical illumination provided by the new mobilism.

This paper will discuss two aspects of verticalism. First to be noted will be the fundamental lineaments of cratonic structure and their role in predetermining the sites of both intra-continental rifts and the future transoceanic fracture zones (transform faults). Secondly, a revolutionary new approach to the whole question of landscape chronology is being provided for geomorphology by the geological record of plate tectonics. There is also an increasing interest in neotectonics which ought to be considered (the author is the president of the *INQUA Commission on Neotectonics*), but this will have to be treated elsewhere.

It is most fitting that this little paper should be dedicated to the honour of Reinout Willem van Bemmelen. As a young student, the present writer was brought up in the fixist traditions of the day, but had the good fortune of reading Wegener in the 1924 English translation. In 1936, I found myself on my Oxford thesis work exploring the Klippes Zone in the Carpathians and later in the Alps. In no way could these phenomena be explained by fixism, as Ampferer, Lugeon, and Kober had clearly shown. In 1938 as a tyro oil geologist I was sent to the Middle East which was then the scene of an exciting battle between the verticalists and the mobilists. Back in 1869, a young French student, Lartet, in his doctoral thesis (published in 1876) proposed that the Jordan-Dead Sea rift was a strike-slip, a transcurrent fault, with 110 km of left-lateral displacement. My company chief, Wellings (see WILLIS, 1938), drew attention to this critical discovery, but it was 'before its time'. Baily Willis, in his study of rift valleys, was impressed by the gravimetric data but was misled by poor stratigraphy, favouring therefore a compressive 'ramp' hypothesis. And then there were the verticalists, perhaps most influenced by

Picard in Jerusalem, and by Dubertet in the Lebanon, where the monoclinical dips across the rift zone are so impressive. Certainly there was field evidence to support all three approaches. Van Bemmelen provided us then with a first logical integration of verticalism and horizontal stress expressions (the *bicausality principle*). His recent philosophical reexaminations of the 'undation theory' provide illuminating insights into the evolution of a science, and specifically into the background of 20th century geology (VAN BEMMELEN, 1976, 1977, 1978).

LINEAMENTS AND RIFTING

Lineament tectonics have been known since the 1830's, but have suddenly come into the spotlight again with the development of satellite sensing. Numerous correlations with ore deposits have been proposed and few economic geologists today would deny the usefulness of the new satellite pictures, although some of the 'El Dorado' dreams have been somewhat oversold. Several important meetings dedicated to the 'new basement tectonics' have been held (HODGSON ET AL., 1976).

At first sight the intracratonic (and largely Precambrian) character of lineaments would appear to have little in common with the oceanic fractures, which are limited to the last 180 Ma of geologic history. Quite the contrary, several important papers disclose that the Precambrian fracture patterns are picked up and propagated by the newly created ocean crust. The clearest example is seen in the case of the Red Sea (GARSON & KRS, 1976), but transatlantic examples are of much larger dimensions; revived activity is clearly being propagated also *inland*, leading to neotectonic activities (SYKES, 1978).

When a new rift zone begins to develop, why does it 'select' one lineament belt rather than another? In reconsidering the break-up of Gondwanaland (FAIRBRIDGE, 1978, 1979) I have come to the conclusion that a megacontinent of the size of Gondwanaland or Laurasia can only remain stable as long as there is no large-scale shift of the relative pole position. As pointed out by WEGENER (1912) and FAIRBRIDGE (1961), a change in the relative pole orientation requires an adjustment of the geoid. Indeed, I have calculated that for 1° of an instan-

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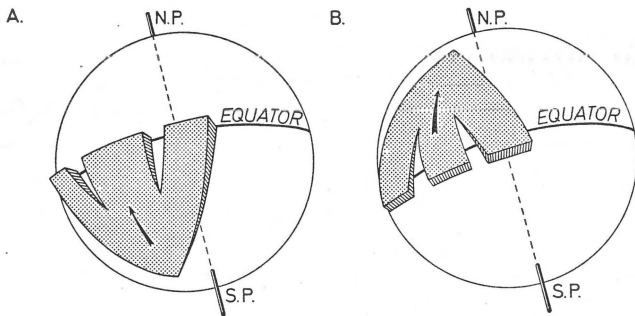


Fig. 1
Idealized diagram to illustrate the tendency of giant continents to develop V-shaped rifts (A) along their leading edges as they advance (relatively) towards the equator; and (B) along their trailing edges as they pass over the equator. In Gondwanaland most of the aulacogens of type A appeared during the Palaeozoic when the entire megacontinent lay south of the equator. Those of type B appeared mostly in the late Mesozoic and Tertiary as the Gondwana continents moved across the equator. This observation prompts the thought, already expressed by others, that the rifting of the lithosphere is not primarily caused by convection currents in the mantle, but by mechanical adjustment to the greater equatorial radius of the earth as continents drift towards or over the equator.

taneous shift in the relative pole, there will be up to 375 m (plus and minus) in vertical adjustment of the geoid (in the plane of the shift, falling to zero in the axis at 90°). This anomaly will be eventually compensated for by isostatic adjustment, but in the meantime important erosional and sedimentary effects can be predicted.

Continental drift across palaeolatitude lines can be expected to lead not only to vertical adjustments but also to stresses in the horizontal sense. It is an important outcome of both palaeomagnetic studies and sea-floor spreading work that the rates of drift vary from time to time by more than one order of magnitude. Indeed, there appear to be lengthy periods of near-quiescence or very sluggish motion, interrupted by episodes of extremely rapid motion. India's 6000 km late-Mesozoic trip from Antarctica to Asia was perhaps the most spectacular, but even on a small scale the sea-floor spreading activity is clearly episodic.

A consequence of short, sharp crustal motions across palaeolatitude belts will be the re-opening of pre-existing brittle fractures. Sluggish motion would perhaps allow for some degree of plastic adjustment, but abrupt tensile stress applied to the brittle nature of the Precambrian cratonic surface must inevitably lead to fracture (TURCOTTE & OXBURGH, 1973). Over a broad arc a crustal plate moving towards the equator will be subject to an east-west extension corresponding to the larger earth radius (Fig. 1). This stress is likely to lead to rupture at the plate margin, and the creation of an aulacogen-type reentrant (FAIRBRIDGE, 1978, 1979). These aulacogens are commonly developed as 'failed arms' along the hot-spots of the zig-zag margin of a rifted continent (BURKE, 1977), and will be the site of evaporite and taphrogenic sediment filling (BURKE, 1975). Because of its geometrical position, as a reentrant often reaching deep into a continent, the site of an aulacogen

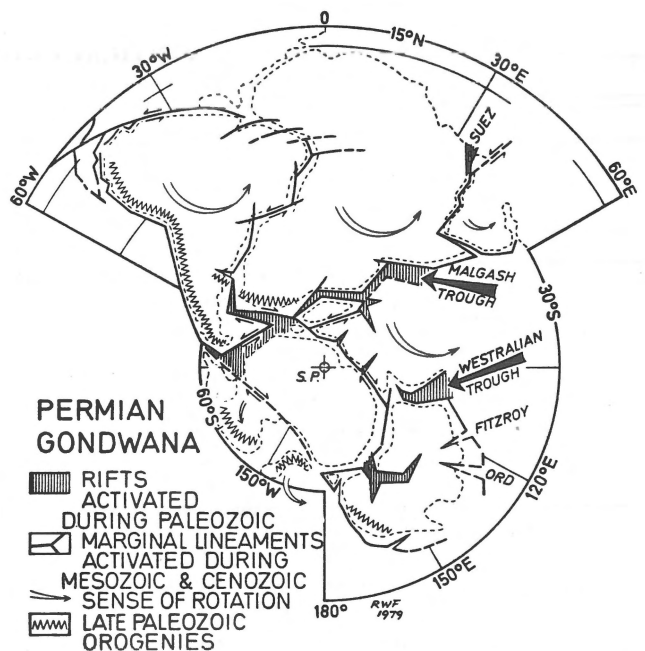


Fig. 2

A reconstruction of Gondwanaland in Permian time, extended in the Cape Belt to the Triassic. The map is centered on the South Pole (SP) of the day, with meridians approximating those of the present time. Madagascar, instead of fitting into the Tanzania-Kenya reentrant, is placed next to Mozambique. There appear to be two wedge-like gaps (aulacogens) separating India from East Africa and Australia respectively. These belts were occupied in Permian (and earlier) time by extensive marine gulfs, open to the north, and well-known to stratigraphers as the Malgash Trough and the Westralian Trough. Also indicated is a postulated Argentina Gulf, the Proterozoic Adelaidian Gulf (partly active also in the Palaeozoic), and smaller rifts (Suez, India, N. Australia). The opening of these wedges corresponds in time to the apparent motions of the South Pole into Antarctica, i.e. the drift of the Gondwana crust northward, the splitting being required by the increase of global radius in lower latitudes. The fractures correspond to revivals of ancient lineaments (modified after Fairbridge, 1978).

tends to become the great river valley of the future, and the former hot-spot, now cooling, becomes the site of the future delta. The aulacogen margins become fan-delta sites. As an aulacogen moves poleward, corresponding to a reduced earth radius one may observe some compressional folding, as Burke has demonstrated within the Benue graben, which has been moving into the northern hemisphere during the late Cenozoic.

The history of Gondwanaland break-up (FAIRBRIDGE, 1978, 1979) shows two distinctive categories of taphrogenesis:

(1) *Rifting*: An episodic succession of aulacogen development, that appears to have been concentrated around three particular taphrogenic phases in crustal history:

- *Mid-Proterozoic*, notably the Adelaidian-Amadeus rifting belt across southern and central Australia;
- *Ordovician*, notably the Westralian Trough which forms a rectilinear belt along the entire western border of Australia; and around southwestern Africa;
- *Carboniferous*, notably along the eastern margin of Africa, the Malgash Trough, the ancestral Suez Graben, and all around India, with three wedges that almost transect the pen-

insular region.

(2) *Drifting and sea-floor spreading*: A renewed taphrogenic episodocity took place along the rifts that had developed during the Mid-Proterozoic regime, but in this new development the continental cratonic regions broke apart and sea-floor spreading began. Thick taphrogenic sediments were thus left behind in what are now the coastal plains on one side or the other of the 'trailing edge' continental margins (KINSMAN, 1975). In the case of the Westralian Trough, some 10,000 m of such sediments accumulated during the Palaeozoic and early Mesozoic (FAIRBRIDGE & FINKL, 1978; FINKL & FAIRBRIDGE, 1979). The sea-floor spreading was rapid and episodic:

- *Mid-Jurassic*, eastern Indian Ocean and central Atlantic;
- *Early Cretaceous*, South Atlantic and western Indian Ocean;
- *Late Cretaceous*, Tasman Sea;
- *Early Tertiary*, Southern Ocean.

It seems significant that as intracratonic ocean basins opened out within Gondwanaland, there were simultaneous compressive orogenic episodes around the margins, notably in eastern Australia and in the Andes of South America.

Furthermore, as the cratonic blocks successively swung free from the constraints of their rifting margins in Mesozoic-Cenozoic times, they almost all swung *counterclockwise* (Fig. 2). AUSTIN & WILLIAMS (1978) observed that in the Palaeozoic, eastern Australia played a 'leading-edge' role in Gondwanide tectonics, which was accompanied by a counterclockwise shift in both compressive and tensional regimes, corresponding to a clockwise rotation of Palaeozoic Gondwanaland. The effect was to develop a discontinuous but repeated east-west compression. Both structural phenomena appear to point once more to the 'West-drift' of WEGENER (1912).

Recently KANE (1972) has suggested two mechanisms for the West-drift tendency: rotational inertia of the continental plates; and triggering by lunar tidal torque with respect to a core that is not inextricably locked to the lower mantle boundary. Episodicity appears to be supplied by accelerated or decelerated global spin rates. ANDERSON (1974) has shown that during the last century and a half, spin rate and rotational wobble correlate with seismic energy development, to which we may also add the evidence of major volcanic explosions. On the long-term record, the cyclicity also seems to have a planetary explanation (CREER, 1975).

Although the rifting of continents clearly relates to hot-spot development (DEWEY & BURKE, 1974), there is as yet no logical correlation of those sites within a comprehensive theory of mantle convection. On the contrary, it would appear that heat flow within the mantle would lead to periodic runaway convective events (RICE & FAIRBRIDGE, 1976). The physical location of those sites would appear rather to be located in terms of the general stress systems of the crust. In other words, it is felt that mantle convection is not a cause but a consequence of exogenetically induced crustal stresses. Thus sea-floor spreading is an episodically triggered phenomenon, and not a continuous or steady-state system. It would be premature to suggest that this idea is anything more than an 'impression' at this stage, but it might provide useful food for thought.

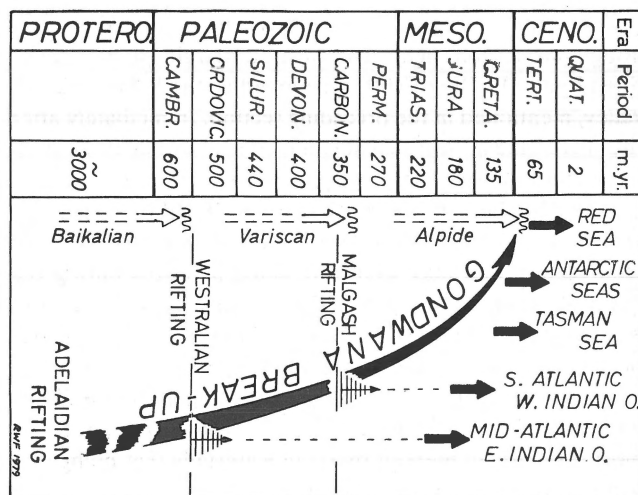


Fig. 3

The step-by-step break-up of Gondwanaland. Rifting (Adelaiddian, Westralian and Malgash) indicated by pyramids with fine arrows. Drifting and sea-floor spreading by solid black arrows. Orogenic cycles by open arrows.

CRATONIC PLANATION-SURFACE CHRONOLOGY

Stimulated by a discussion with J. Tuzo Wilson a few years ago, I made an initial attempt to correlate the upwarped peneplain surfaces of the Appalachians (WILSON & FAIRBRIDGE, 1971; abstract only). This was followed up by an analysis of the cratonic surfaces of North America, which led to the discovery that the mean level of the craton was around 250-300 m (FAIRBRIDGE, 1976; also abstract only; my preliminary map appears in SYKES, 1978).

Calculations by PITMAN (1978 and earlier) suggest that the amplified level of heat flow associated with the high peak in the rate of sea-floor spreading in mid-Cretaceous times would result in a eustatic level of the ocean of the order of 300 m. Thus, although a considerable volume of water (equivalent to about 65 m of sea-level lowering) is locked up glacio-eustatically at the present time, the general fall of sea level from the Cretaceous to the Quaternary is probably related more to a tectono-eustatic explanation — a periodic but progressively decreasing rate of sea-floor spreading.

Turning now to the West-Australian craton (FAIRBRIDGE & FINKL, 1978; FINKL & FAIRBRIDGE, 1979), it has been discovered that a similar mean elevation persists, although many contrasting features appear, not least being the incidence of the Quarternary glaciation over much of the North American craton whereas the West Australian craton was extensively glaciated in the Permo-Carboniferous periods. Since that time, very little has happened in the interior. Permian fluvioglacial gravels are still preserved (with siliceous cements) on ridge lines, while the valleys are occupied by Mesozoic and early Cenozoic alluvial deposits. The average rate of lowering of the cratonic surface is only 10 cm per million years, a quite astonishing figure. It is partly explicable in terms of the low relative relief, the intensive crust hardening due to lateritization and the palaeoclimatic history.

Consideration of the Western Australia's cratonic margins bring considerable light. The western margin (mainly identified by the Darling Fault) developed as the Palaeozoic rift valley, mentioned in the preceding section. Immediately after rifting it would appear that augmented heat would have raised the cratonic margin, permitting the incision of deep marginal canyons. In places in the north these are filled by Palaeozoic sediments, but in the southwest they appear to have been scoured out, and may well have acted as fjords during the Permo-Carboniferous, just as did similar marginal gorges in Namibia (MARTIN, 1976). In any case these gorges became rias during the Mesozoic and were probably partly filled and reexcavated several times. The astonishing thing is that the 280 m nickpoints which transect the Eocene valley systems are in most cases today marked by small waterfalls that plunge, as hanging valleys, into those same gorges.

The broad conclusion from these cratonic studies is that the principal peneplanation of the Archean shields can be traced back to the early Proterozoic. This fundamental surface can often be identified disappearing beneath nearly flat-lying Proterozoic sedimentary rocks. Elsewhere, it has been extensively stripped; in short, it is often an exhumed surface. But this Proterozoic covering is not the only protection it has received. Subsequently, whenever there was a globally high sea-level phase the craton was veneered by a thin cap of marine or continental sediments. Gentle warping of the craton has occurred from time to time and the depressions now afford relics of those former sedimentary veneers. Upward areas have repeatedly been worked back to the Archean surface. This surface is today very deeply weathered. In Western Australia there are many deep mines that penetrate this zone, so that the weathering front can easily be studied underground. It is highly uneven but in many places exceeds 200 m.

One must ask therefore why the remnants of this surface remain so stable? The answer is partly the very low relative relief in the interior. It is partly the palaeoclimatic history. But perhaps most significant are the massive duricrusts, laterites and silcretes, that constitute a sort of armour-plating over much of the interior surface.

CONCLUSIONS

Plate tectonics have done far more for geology than provide an elegant mechanism for explaining the dynamics and history of ocean basins. We may see vistas opening in all directions that provide continuing and exciting challenges for the rising generations. We salute R. W. van Bemmelen as one of those true scientists who in his time has had the courage to look ahead, and thereby inspire his fellows and successors.

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