Journal of Structural Geology, Vol. 5, No. 6, pp. 629 to 632, 1983
Pergamon Press Ltd. Printed in Great Britain

BOOK REVIEWS

Rifts—down to earth

Morgan, P. & Baker, B. H. (editors) 1983. *Processes of Continental Rifting*. Elsevier, Amsterdam. 680 pp. Price: hardcover US $160.50, DFL 250.00.

This book, 19th in the series *Developments in Geotectonics* and a reprint of volume 94 of *Tectonophysics*, contains 35 papers selected from those presented to the Lunar and Planetary Institute Topical Conference on the Processes of Planetary Rifting held in 1981 at St. Helena, California.

In the Introduction, the editors state that the purpose was to bring the theoretical modellers face to face with geologists, geochemists, geophysicists and data collectors. The approach was to have been multidisciplinary. However, too many of those papers with a controversial element do not appear to have had their models or hypotheses subjected to rigorous testing. Such discussion and criticism as no doubt took place and was recorded, as well as written criticism, could with advantage have been published. This would have greatly increased the usefulness of the volume. As it is, it is a collection of papers more or less isolated. The peculiar benefit to be derived from personal contacts and interchange of ideas cannot be shared by the reader of this book.

For the approach to the subject of continental rifting processes to be effectively multidisciplinary, the construction of an acceptable model or hypothesis must be shared and must follow steps in an agreed procedure. Basically, rift valleys or graben are tectonic landforms, the surface expression of endogenetic processes which can be investigated only indirectly using geophysical and geochemical techniques. Professor Crough in the final paragraph of his paper stated "... the ultimate test of any tectonic model must be its consistency with the known geological record." This could imply that geology has the final word.

If constraints are to be accepted in advance, as appears to be suggested in this volume, the modeller will find himself working within a framework, the foundations of which are the constraints dictated by the known geology or geomorphology. If the basic model is unsound all that follows will risk being flawed. Having been subject to criticism and testing, a basic model should ideally retain no speculative elements, and be successfully used for prediction as the final confirmation.

There are wide variations in geomorphology, geology, structure and volcanicity of graben rift zones and ideally a separate model for each class should be constructed. Continental rift studies appear to have reached the stage where this should be possible. It is wrong to try to squeeze all rift valleys into one mould.

The Introduction includes a generalized account of what follows. It is emphasized that an extensional stress field in the crust or thinned lithosphere is necessary for formation of rift (graben) zones. Is this the 'taphrogenesis' of Krenkel? Deviatoric stress can be generated by the upward push of mantle against the downward pressure of the crust. This however, is only one possible mechanism. It implies lithospheric thinning to allow the rise of mantle or asthenosphere, at least to the base of the lithosphere. This is by one of three mechanisms: (1) heating with removal of the base of the lithosphere; (2) mechanical and geometrical by stretching under a regional stress field and (3) asthenosphere diapirism. The failure of the thinned crust under shear stress creates the rift zone. A fourth possible mechanism is not discussed. Simply stated, this fourth mechanism involves a split within the plate during plate motion, linked with the presence of lesions reopened by stresses generated during movement.

The editors go on to discuss the contributions. In addition to those wholly concerned with presentation of a specific model or hypothesis with arguments for or against, there are the geological papers. These are not necessarily confined to geological descriptions, but also relate to geophysics, especially gravity, conductivity and seismic data, including layer velocities and interfaces.

This review will deal particularly with the more significant papers and examine any shortcomings in the light of the approach described in the foregoing.

The paper by Bott & Mithen (p. 11) expands Bott's early papers on the wedge subsidence hypothesis (Bott 1976, 1981). This replaced the 'keystone' hypothesis of early workers which became untenable when it was realized that it was lateral or tangential tensile (not compressive) stress which operated. Bott in 1976 had advanced the model proposed by Vening Meinesz who in turn inherited the experimentally derived conclusions of Cloos (1930). Still earlier were the ideas of Taber (1927) who used floating wood blocks to illustrate them (see also Artemjev & Artyushkov 1971). In the paper under review, Bott & Mithen discuss only briefly the origin of the extensional stress field and regard it as deviatoric from vertical compression, due to the rise of underlying low density upper mantle against the loading of overlying thinned crust. Conditions of isostasy are emphasized.

The model was derived from that constructed originally by Vening Meinesz (1950) and Heiskanen & Vening Meinesz (1958). In the latter, Bullard's suggestion of a compression mechanism was discarded. Bott suggested a shallower depth for the brittle layer. The presentation by Bott & Mithen is elegant and superficially attractive. However, there are significant flaws in their model. It does not accord with nature. The first flaw is related to the upbending of the crust on the upthrow side of the fault. This upbending is supposed to give rise to the concave-upward 'slope to rift'. This does not exist in spite of its generally unquestioned acceptance. It is not recorded by field geologists working in the East African rifts. Dixey regarded it as 'illusory'. In Kenya, the shoulder or lip generally slopes towards, rather than away from, the rift where it traverses the Kenya domal uplift. Pulfrey (1960) and Baker *et al.* (1972) describe this. It has not been recorded anywhere in East Africa. There is, however, tilting of blocks. The introduction of this concept by Vening Meinesz and its retention by Bott is probably dictated by the desire for symmetry and by the geometry. It avoids crustal separation on the fault. Along the Western Rift system the elevation of the flanks is generally uniform and isostasy is achieved. They exhibit level surface remnants of at least one earlier erosion cycle. The form is not that assumed by Bott and others. Neither is it seen on the flanking blocks of the Rhinegraben.

Concerning the second fracture, it was recognised by Vening Meinesz (1958) but not by Bott that, "It is more difficult to explain why the second fault plane should dip towards the first instead of originating in a parallel direction, and it seems possible that the latter development also occurs; it would lead to tilted blocks . . .". In those cases where it can be observed, the second fault generally does dip towards what is assumed to be the first, but with a smaller throw. Vening Meinesz, and later Bott, had no support from field evidence for maintaining that ". . . once the second fault plane has come into being, the whole phenomenon is symmetrical, and we can assume that the central block resumes its horizontal position and thus the graben is formed." Bott & Mithen's 'finite element grid' assumes a symmetry not 'consistent with the known geological record.' Fuchs *et al.* (1981), considering the Rhinegraben, state "Asymmetries of structure . . are an important clue to the understanding of rift dynamics". Failure to recognize asymmetry is a bar to much fruitful research. The models and hypotheses are well presented in Bott & Mithen's paper and it can be regarded as the definitive and most refined account of the wedge subsidence hypothesis, unrealistic though it may be.

Crough's paper (p. 23) about geophysical constraints on causality contrasts with Bott & Mithen's account in that it adheres to Karl Popper's scientific methodology. Crough tests alternative models against the known geological record. The question he asks is: can rifting generate swells or can swells generate rifts? Comparison is made of oceanic ridge crests with continental swells. Only the latter, being under less compression, can generate rifting forces. He asks if deep-seated dyke intrusion into continental crust can sustain swells and concludes that this is impracticable. The unrifted Darfur swell, whose dimensions are presented in a later paper (Bermingham *et al.*, p. 205), cannot have formed in the manner advocated and critical examination of the data presented in the later paper reveals errors in presentation and reasoning. Crough examines swell-push and ridge-push for continental and oceanic settings, respectively. He also discusses hot-spot dimensions and shapes for creation of deviatoric stresses whether two dimensional or circular.

In Mechanisms of Active and Passive Rifting by Turcotte & Emerman (p. 39) the authors conclude that actual diapiric penetration rather than impingement of rising heated mantle on the crust is the probable mechanism by which hot mantle rock penetrates the lithosphere to the base of the continental crust. They, therefore, favour a passive rather than an active mechanism; asthenopheric diapirism rather than thermal thinning. Mareschal in Mechanisms of Uplift (p. 51) rules out thermal thinning either by conduction or by injection of magmas. Diapiric uprise as at present conceived is feasible but models require refinement and more detail before they can be tested against geological and geophysical constraints. Sphon & Schubert (p. 67) on the other hand regard convective thinning of the lithosphere as a mechanism for continental rifting and volcanism as a possible mechanism, but only if 5 to 10 times the normal flux is applied by mantle plumes. Comparison is made of the same process operating beneath the oceans and on Mars and Venus.

Neugebauer (p. 91) discusses mechanical aspects of thinning and the lateral transmission of mechanical energy via the lithosphere coming from collision-type plate interaction. A model is formulated. Mantle diapir development is the favoured concept for actual continental rifting. Jarvis (p. 109) discusses submarine rifting at mid-ocean ridges in terms of the zone of extension and the asthenosphere upwelling beneath it. The thermal structures produced passively by horizontal extension or actively by mantle convection are qualitatively similar, hence the difficulty in distinguishing cause and effect, crucial for understanding plate formation and movement.

The foregoing papers are primarily concerned with mechanisms for generating lithosphere thinning and uplift; the generation of deviatoric and extensional stress in the brittle crust leading to conditions for graben formation; or bringing this about directly in response to isostasy. The mechanism accepted for lithospheric thinning and the behaviour of the mantle or asthenosphere determines the geochemistry and nature of volcanism.

Implicit in most of the papers considered, is the assumption that volcanism is always associated with rifting. It must be stated emphatically that this is not the case. There is probably as great a total length of rifts without volcanism as there is with it. For example, there is no volcanism in the Tanganyika or Nyasa rifts and it is virtually absent from the Rhinegraben. Until heat flow measurements over all rift zones are studied it must be assumed that the mechanisms involving rising and heated asthenosphere are not exclusive.

For this reason it is suggested that the paper by Bailey (p. 585) could have general application and should be studied at this point. Bailey proposes changes in stress pattern and intraplate movement causing fracturing of the lithosphere without its prior removal or thinning, followed by gas fluxing and eventual rise of mantle material through channels provided by lesions in the plate. He states that the observed igneous activity of continental rifts "... is inexplicable from a source in upwelling mantle below the lithosphere." The spectrum, pattern, composition and age of igneous rocks in rifted and unrifted continental cratons in Africa (for example kimberlite bodies and carbonatites) are witness to this. He discusses distribution of igneous activity in the Gregory, Rukwa–Nyasa and Kivu–Ruwenzori rifts. This paper will be welcomed by geologists reluctant to place themselves too completely in the hands of geophysicists and by others who are concerned to subject their models to testing against the 'known geological record.'

Morgan (p. 123) has recorded hot-spot tracks in relation to the rifting of the Atlantic for the last 200 Ma. Tracks appear to become the locus of later rifting. Relative motions of continents are determined initially from magnetic anomaly isochrons. The paper is a record of some significance from which important conclusions can no doubt be drawn. De Rito *et al.* (p. 141) apply results of rift studies to the study and comparison of cratonic basins. Subsidence rate, isostasy factors, gravity anomalies, history and viscosity can be related. Sheridan (p. 169) is concerned with pulsation tectonics and spreading-rate through time in the eastern North American continental margin. Seismic and magnetic studies are linked.

The first pair of papers on geophysical constraints on rift models are by Browne & Fairhead and Bermingham, Fairhead & Stuart (p. 187 and p. 205 respectively). They deal with what they refer to as the 'Central African Rift System'. Crough's dictum "The ultimate test of any tectonic model must be its consistency with the known geological record" does not appear to have been applied. Gravity data alone, with unconvincing geological descriptions, is inadequate.

Inclusion of the Benue Trough and Chad Basin, especially reference to their gravity anomalies, is irrelevant. Only in the extreme west of the Ngaoundere 'rift' is there any geological and possibly geomorphological evidence for rift expression. Topographical and geological evidence for the eastern Ngaoundere and certainly for the Abu Gabra being rifts is absent. Abu Gabra appears to be merely the space between very moderate African swells (Vail 1978). Darfur is hardly a domal uplift but is a fairly typical African basement swell surmounted by not atypical volcanic activity. There are comparable centres of volcanic activity in the region. Figure 6 in the second paper shows that the swell rises about 500 m above the general level, surmounted by the Jebel Marra volcanic massif (see Crough, p. 26, for his rejection).

Even if they could be the so-called two rift arms, their alignments do not intersect at the Darfur swell but nearly 200 km to the south. They could not be the rift arms of an incipient triple junction. Comparisons with the East African rift systems and the suggestion that these 'rifts' presage continental fragmentation cannot be taken seriously. The value of these papers lies in the record of the body of painstakingly acquired gravity information. It is to be regretted that the authors have chosen to go so far beyond what the present state of their knoweldge justifies.

The comparison (p. 223) made by Logatchev *et al.* between the Baikal and Kenya rift zones is of interest but is controversial. The reference should be to the Gregory not the Kenya rift. There appears to be too easy an assumption regarding similarity of asthenosphere upwelling. Volcanic activity has little similarity. For topographic and some other comparisons, one is tempted to compare Baikal with the Tanganyika rift rather than with the Gregory.

Girdler (p. 241) makes interesting observations on the increase in the thinning of the lithosphere northward in Africa. On some grounds this is acceptable: magnitude of rift expression, increase in volcanicity, decrease in seismically active rifting. He abandons the simple stretching model and relates 'thinning' to faulting. He does not make comparison with the models for active and passive rifting involving heatflow from a rising asthenosphere.

In the paper which follows (p. 253) Crane & O'Connell record geothermal mapping of the Gregory rift zone and draw some inferences regarding frequency of occurrence and spacing of domes. This is a carefully prepared paper; a source-work of value for wider application. Morgan's paper (p. 277) on rift thermal processes records much data from a number of rifts and compares slow-thinning and rapid-thinning models and the conditions accompanying them. Non-volcanic sections of, for example, Tanganyika and Malawi of the Western System, do not have high heat flow. Jirack *et al.* (p. 299) reproduce, compare and interpret magnetotelluric results for Rio Grande and other rifts. There are implications for presence of crustal magma and trapped fluids.

There follow papers on the application of seismic refraction: that by Mooney *et al.* (p. 327) on the northern Mississippi embayment and comparison with other rifts; and that by Olsen (p. 349) on the general application to a number of rifts with comparison of interpretation on the presence of asthenosphere diapir.

Easton's crustal study (p. 371), based on sediments and volcanics of ancient continental margins and their comparison with modern rifts, indicates that processes of rifting as we known them may have persisted since the Precambrian. Some of the structures studied are among those generally classed as 'aulacogens'. In a related study, Keller *et al.* (p. 391) are concerned with the development of the midcontinent of North America. Three episodes are recognised. Rifts of different ages are compared. Again, some of these ancient rifts are classed as aulacogens.

A paper by Green (p. 413) on the Keweenawan Midcontinent Rift (MCR) follows. In this, plateau basalt provinces in general are described. The MCR extends southwest from Lake Superior to Kansas. This is one of the major plateau basalt provinces. Such basalts have been precursors of continental breakup: however, in this case breakup did not occur. There was broad subsidence rather than faulting. Various models are considered and compared with other rifts. Mantle upwelling and fracture of the lithosphere without doming is the preferred model. Further rifts and upwelling could accompany future crustal separation. Plate movement preceding fracture is discussed.

Gilbert (p. 439) discusses the Southern Oklahoma Aulacogen. The igneous activity, timing and sequence, structural and igneous history are recounted. The stages of development of the Southern Oklahoma aulacogen are then described and illustrated. This account of the development of an aulacogen is a valuable type description and can serve as a cross-sectional model for this class of aulacogen. A working definition of 'aulacogen' is given: "linear graben-like depressions of ancient platforms" (Milanovsky 1981). 'Inversion' (compression and thrusting) and 'cover' (sedimentation) can occur.

However, this definition is inadequate. Milanovsky (1981) following Schatsky & Bogdanov, recognised three types of aulacogen: 'through'; 'penetrating' and 'inner or blind'. The terms are self-explanatory. Only the second appears to be recognized in North American literature, and they appear generally to have been 'failed' arms of triple junctions; for example, the Benue trough or the main Ethiopian rift. Russian geologists on the other hand, are reluctant to refer to late Phanerozoic 'failed' arms as aulacogens. They regard true 'aulacogens' as 'dead'.

The Oslo graben (p. 457) Russel & Smythe claim to have been formed in Hercynian times over an aborted 'oceanic rift'. It developed over an aulacogen and was oriented according to the direction of extensional stress.

Fitton (p. 473) points out that the Benue trough is usually cited as an example of a 'failed' arm of an rRR triple junction. The author suggests that it is related to the Cameroon line or alkaline volcanic centres which originally was located where the Benue trough now is. Decoupling of the crust caused the eastward displacement. Comparison should be made with the paper by Browne *et al.* (p. 187) on the Ngaoundere rift.

Golobek *et al.* (p. 483) describe the Espanola basin of the Rio Grande rift and its development, using a sequence of diagrams. Lessons can be learnt for application to the Rio Grande rift. Mohr (p. 509) questions whether the thinning or attenuation of upper continental crust in the Western Afar resulted from block faulting and tilting (Morton–Black hypothesis) rather than direct dilatation in support of which he cites the presence of dyke-swarms.

Wood (p. 529) suggests that offsetting of rift valleys (rift jumps) should be seen as parallelling what happens to ocean rifts. It is not clear what the author has in mind regarding surface connection between the jumped segments. Where continental crust is exposed there does not appear to be visible evidence. He cites the example of Benue–Cameroon (refer to Fitton, p. 473).

Pollard *et al.* (p. 341) describe observations on surface deformation as related to dykes emplaced in volcanic rift zones and use observed data from Kilauea Volcano. Various cases are described. This is a useful and informative article combining observation of actual phenomena with theory (nature simulating modelling!).

Milanovsky is probably the leading figure in the study of rifting evolution in the earth's history. His extensive reviews of the subject of continental rifts, old and new, are classic accounts. It is therefore to be expected that his paper should be a comprehensive and balanced treatment of the subject, as indeed it is. He has not accepted plate tectonics but follows '. . . the concept of the pulsating Earth against the background of its general moderate and irregular expansion . . .'. This hypothesis on some counts is not necessarily in conflict with plate tectonics. Indeed the expanding earth model is regarded by many as offering acceptable solutions to certain anomalies. This paper cannot be less acceptable because it is based on a divergent world view. The value of the paper is not affected.

Three final papers, on porphyry-molydenum occurrence, mineral and gas accumulation in rift lakes, and geothermal resources, do not exhaust the economic possibilities of rifts and rift lakes. Most students of rifting mechanicsms disregard economic possibilities.

The reviewer believes that this volume, in certain important aspects, is a considerable advance on any previous collection of papers on rifts and rift valleys. It probably contains a better blend of modelling and formulation of hypotheses, with access to new information and the results of painstaking research, than any recent compilation. It is probably unique in the largely successful intentions of the authors to involve contributors in the aim 'to give modellers direct exposure to the constraints imposed by some of the available data.' A few authors have obviously yet to appreciate that this is the only approach which a scientist can make. The article which, above most others, must for these reasons be commended is that by the late Professor Crough to whose memory this volume is dedicated.

REFERENCES

Artemjev, M. E. & Artushko, E. V. 1971. Structure and isostasy of the Baikal Rift and the mechanisms of rifting. *J. geophys. Res.* **76**, 1197–1211.

Baker, B. H., Mohr, P. A. & Williams, L. A. J. 1972. Geology of the Eastern Rift System of Africa. *Spec. Pap. geol. Soc. Am.* **136**, 1–67.

Bott, M. H. P. 1976. Formation of sedimentary basins of graben type by extension of the continental crust. *Tectonophysics* **36**, 77–86.

Bott, M. H. P. 1981. Crustal doming and mechanism of continental rifting. *Tectonophysics* **73**, 1–8.

Cloos, H. 1930. Zur Experimentellen Tektonik. *Naturwissenschaften* **18**, 741–747.

Fuchs, K., Bonjer, K. P. & Prodehl, C. 1981. The continental rift system of the Rhinegraben. *Tectonophysics* **73**, 79–90.

Heiskan, W. A. & Vening Meinesz, F. A. 1958. *The Earth and its Gravity Field*. McGraw-Hill, New York.

Milanovsky, E. E. 1981. Aulacogens of ancient platforms: problems of their origin and tectonic development. *Tectonophysics* **73**, 213–248.

Pulfrey, W. 1960. Shape of the sub-Miocene erosion level in Kenya. *Bull. geol. Surv. Kenya* **3**, 1–18.

Taber, S. 1927. Fault troughs. *J. Geol.* **35**, 577–606.

Vail, J. R. 1978. Outline of the geology and mineral deposits of the Democratic Republic of the Sudan and adjacent areas. *Overseas Geol. & Min. Res.* **49**, 1–68.

Vening Meinesz, F. A. 1950. Les 'graben' Africains, resultant de compression ou de tension dans la croute terrestre? *Bull. Inst. R. Col. Belge* **21**, 539–552.

A. M. Quennell

A coherent view of the geological evolution of Europe

Ziegler, P. A. 1982. *Geological Atlas of Western and Central Europe*. Elsevier (in collaboration with Shell International Petroleum). Amsterdam. 130 pp., 40 boxed enclosures. Price: US $68.00, DFL 160.

Fifty or more years ago attempts to give an integrated view of the geology of Europe were not uncommon. But from then, until the publication in 1969 of M. G. Rutten's *The Geology of Western Europe* few syntheses in English appeared. During the last decade the tonic-effect of plate-tectonic models coupled with newly acquired subsurface and submarine data have stimulated the publication of several books concerned with Europe or large parts of it. Ziegler's exceptionally good-looking Atlas and accompanying commentary is clearly a by-product of the search for hydrocarbons. Shell International are to be applauded for permitting formerly confidential information to be included, subsidising publication (the enclosure box contains 37 A3-sized coloured maps) and encouraging Peter Ziegler to undertake the task of compilation and synthesis.

The seven chapters are: (1) Introduction, (2) Suturing of Pangea, (3) Permo-Triassic development of Pangea, (4) Pangean disintegration, (5) Late Cretaceous sea-floor spreading and onset of Alpine plate collision, (6) Cenozoic opening of the Norwegian–Greenland Sea, Alpine orogeny and Alpine late orogenic collapse system and (7) Thoughts on mechanisms of basin subsidence. There is also a 21-page list of references but, surprisingly, no index. The forty enclosures are grouped under five headings: (1) Tectonic and geological maps, (2) Palaeogeographic maps, (3) Isopach maps, (4) Stratigraphic correlation charts and (5) Legends. Enclosure 26, designed to be superimposed on the palaeogeographical maps, is a two-part transparent overlay showing political boundaries, rivers, towns and selected bathymetric features. Twenty-nine line drawings are included in the text.

Although according to its title coverage of the book is Western and Central Europe this is somewhat misleading. With the exception of a few brief asides the emphasis is firmly on Northwest and North Central Europe which, incidentally, is taken as extending as far east as Estonia (longitude 25°E). The geology of the North Sea is central to Ziegler's geographical scope as well as to many of his reconstructions. The Alpine deformation front is used as a convenient southern limit in many maps. From a temporal perspective Ziegler concentrates on history from the Late Silurian onwards, that is post-Caledonian events. Understandably, his principal tectonic concern is basin evolution and he tells a vivid story of basin superimposition and inversion. Ziegler recognizes five main stages in the Late Silurian to Recent evolution of Western and Central Europe and these he makes the headings of his Chapters 2 to 6.

Perhaps because they illuminated dark corners of my geological awareness the sections of the book I most enjoyed are those on Triassic rifts and Tethys transgression (3.2), Mid-Cimmerian revolution (4.3) and Late Middle and Late Jurassic polarization of the European rift systems (4.4). In these sections Ziegler analyses important episodes of crustal extension and demonstrates how normal and wrench faults bounding rifts controlled sedimentation, and how individual structures experienced episodes of activity and inactivity.

A temptingly easy target for a reviewer of a broad-ranging book such as this one is to see how it deals with some small patch familiar to him. In this respect Ziegler's maps generally emerge well from critical inspection but it is noticeable that the locations of some structures migrate from map to map or are incorrectly placed. For example, the Sticklepath fault shifts about 25 km west from Enclosure 3 to Enclosure 4 and on Enclosures 4, 19 and 20 the Jurassic Moreton-in-Marsh axis is shown about 60 km east-northeast of Moreton. These and other minor cartographic slips may be no more than artefacts of the drafting office.