Reports

Mechanistic Interpretation of Rift Valley Formation

Abstract. *The stress distribution on the lithospheric plate due to excess magma pressure is obtained from an exact solution of the three-dimensional theory of elasticity. The analysis indicates that rift valley formation and associated structural and geophysical characteristics can be suitably explained by dike-like intrusions of magma or igneous mush into the lithospheric plate.*

The worldwide system of rift valleys is one of the earth's most prominent tectonic features. Although it is widely accepted that lithospheric plates are spreading at rift valleys or oceanic ridges, or both, models of rift valley formation are still speculative. Rift valleys are generally characterized by certain important features which must be considered in attempting to determine how they were formed. These are (i) gentle, wide domal uplifts on both sides of the rift valley; (ii) subsidence of a long central block between a set of normal faults along the central rifts; (iii) connection of many rift valleys to form worldwide ridge systems; (iv) isolation or weak connection by obscure graben zones to the worldwide rift system of some rift valleys (for example, the Baikal graben), despite the fact that, in many parts of the world, they are arranged in en echelon patterns; (v) close association of volcanic activity with rift valleys, although some rift valleys (such as Lake Tanganyika) show no local sign of volcanism (*1*); (vi) characterization of rift valleys by magnetic, seismic, and gravity anomalies and high heat flow; and (vii) similarity in width (20 to 60 km) of the majority of the rift valleys (*1, 2*).

Among the ideas proposed for the formation of rift valleys, horizontal compression (*1, 3*) is not well supported by recent studies (*4*). Horizontal tension, which may be produced by drag of the moving currents in the mantle, cannot fully account for the formation of linear features of the rift valleys and the associated gentle domal uplift. In addition, rocks cannot transmit large tensile stress. Domal uplift around a rift valley is usually broad and gentle, and not all domal uplifted areas are necessarily associated with rifts (*1*). The crustal extension at rift valleys is much more than could result from simple doming (*5*). Therefore bending by domal uplift (*6*) alone is not an adequate explanation for the formation of rift valleys. High heat flow and strong magnetic, seismic, and gravity anomalies indicate some sort of igneous intrusion at depth under rift valleys. Vogt *et al.* (*7*) proposed as a model the intrusion of a thick ultrabasic mass into the upper mantle, which adds to the regional tension at the surface of the uplifted crustal province and leads to the formation of wedge-shaped graben. Their mechanism combines the domal hypothesis of Cloos (*6*) and the keystone analogy of Gregory (*8*). Holmes (*1*) pointed out the limitations of the keystone analogy. Orowan (*9*) suggested dike-like intrusion of magma or igneous mush into the lithospheric plate at ridge centers. Recently, Noble (*10*) suggested that changes in stress or flow patterns in the asthenosphere due to motion of the plates may cause gravitational instability which, in turn, may produce upward movement of large diapiric mantle material. Shaw's (*11*) suggested mechanism of viscous shear heating, Anderson and Perkins' (*12*) thermal feedback process producing runaway temperatures in the asthenosphere, and the deep-seated plumes or "hot spots" of Wilson (*13*) and Morgan (*14*) all would be expected to produce partial melting and to be responsible for magma generation and diapiric intrusions.

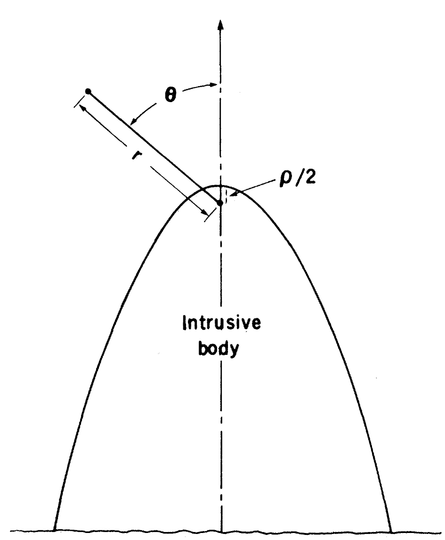

Fig. 1. Diagrammatic representation of a vertically elongated thin oblate intrusion for maximum stress estimation at arbitrary points, such as (r, θ).

Diapiric intrusion of magma or crystal mush into the lithospheric plate is similar to forceful intrusion of dikes into fractures in brittle rocks, as opposed to slow viscous or plastic convective coring. Gass (*15*) proposed magmatic evolution of the "Afro-Arabian dome" and the injection of magma along the axial zones of weakness in the Red Sea, Gulf of Aden, and Ethiopian rift region in brittle rocks, but the mechanism of injection envisioned is unclear. Rice's (*16*) quench spalling mechanism seems to offer a viable process for the origin of double rift valleys. In this report we show, from our analyses of the distribution on the lithospheric plate of stress due to excess magma pressure, that rift valley formation and associated structural and geophysical characteristics can be suitably explained by dike-like intrusions of magma or igneous mush into the lithospheric plate when magma (mush) pressure exceeds lithostatic pressure.

Under high pressure at depth, rocks are ductile and long linear tension fractures are not expected to develop (*17, 18*). However, where high interstitial fluid pressure is present, extension fractures can propagate and extend linearly according to the criterion of Griffith's theory of fractures (*19*). Experiments also show that rocks become brittle when interstitial fluid pressure approaches lithostatic pressure, although permeability may affect the actual strength and ductility of the rocks (*19, 20*). Around igneous intrusions, interstitial fluid pressures are generally very high because magmas or hydrothermal fluids expelled or heated by the intrusion penetrate surrounding fractures (*21*). Hydrothermal metamorphism around ridges indicates permeation by hot, hydrothermal solution, probably brine (*22*).

Thus, we have assumed the igneous body to be fluid and the lithospheric plate to be elastic. If the fractures are propagated in an essentially brittle manner, this idealized assumption may be used as a first approximation. The igneous intrusion is assumed to be oblate spheroid in shape. Because of the gravity, seismic, and magnetic anomalies (*23*) over the 35-km-wide central trough of the Red Sea (*2*) and dike-like injections within a 12-km-wide band at the Mid-Atlantic Ridge (*24*), intrusion of the igneous bodies into the lithospheric plate is considered to have been in the form of thin vertical slabs under the rift valley. Such a slab-like intrusion can be simulated by a thin oblate fracture containing pressurized fluid (Fig. 1).

The stress distribution around an oblate fracture in an infinite and homogeneous elastic rock body was obtained from an exact solution of the three-dimensional theory of elasticity (*21, 25, 26*). An example of the maximum stress distribution obtained is shown in Fig. 2; this is for an oblate dike-like intrusion with an aspect ratio of 1 : 100 and an excess magma pressure of − 1 kbar. At greater depth, high lithostatic and tectonic stresses cannot be neglected. However, if isotropic lithostatic stress is assumed as a first approximation at depth, the stress at any point can be easily estimated from the stress distribution in Fig. 2. For example, the maximum stress at the apex of the intrusion can be expressed approximately as

$$\sigma_{\max} = \frac{4S}{\pi}(\sigma_l - P) + \sigma_l \qquad (1)$$

where S is the aspect ratio, σ_l is the lithostatic stress, and P is the pressure of magma or igneous mush. The magnitude of the stress concentration is a function of the aspect ratio of the dike-like intrusion and of the excess magma pressure. If the aspect ratio is high, the stress concentration factor is generally very large and excess magma pressure may produce tensile stress around the apex of the intrusion. In the area of stress concentration, fractures may propagate continuously or discontinuously, along the lines of existing weaknesses or inhomogeneous spots. Due to high tensile stress concentration and high interstitial fluid pressure, tension fractures will occur at the apex and propagate straight upward near the intrusion. However, further up, fractures tend to branch outward into a set of fracture zones along stress concentration trajectories. While tensile fractures occur almost vertically above the intrusion, these fracture zones dip inward at about 45° (in the range 30° to 60°). Hence, these fracture zones become en echelon and eventually evolve into a set of normal faults. Blocks inside funnel-shaped normal faults may subside to produce graben structures (Figs. 2 and 3). Interestingly, the pattern of stress concentration (Fig. 2) is hardly affected by isotropic lithostatic stress.

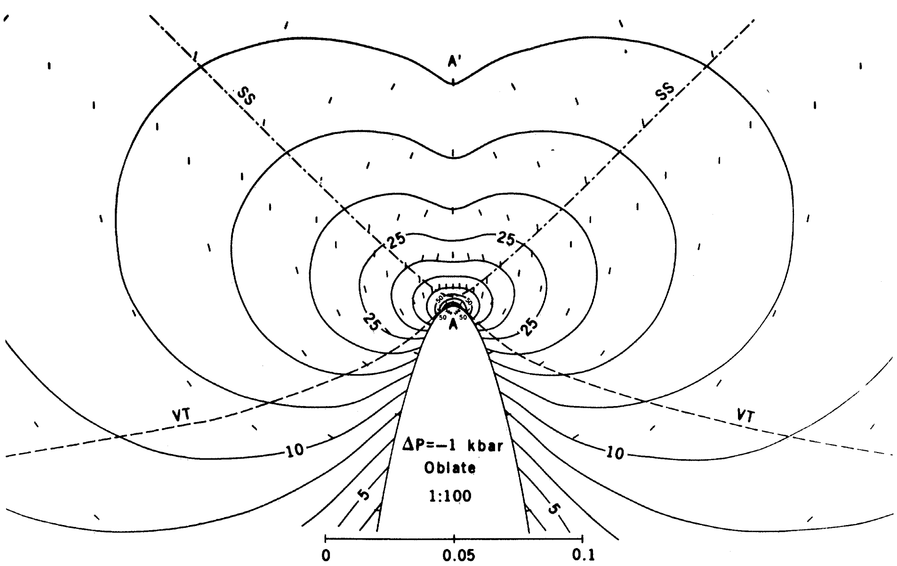

Fig. 2. Contour diagram of maximum tensile stress (in kilobars) around the apex of a thin dike-like oblate intrusion of aspect ratio 1 : 100 due to an excess magma pressure P over lithostatic stress σ_l ($\Delta P = P - \sigma_l = -1$ kbar). Tensile stress is indicated as positive. Only the contours around the apex are shown. All normal stresses are three-dimensionally tensile within the funnel-shaped surface (*VT*) although absolute tensile stress actually occurs close to the tip of the intrusion. Short straight lines indicate the directions of minimum tensile stress. The unit of scale is arbitrary. Abbreviations: *SS*, shear surface; *VT*, vertical tension.

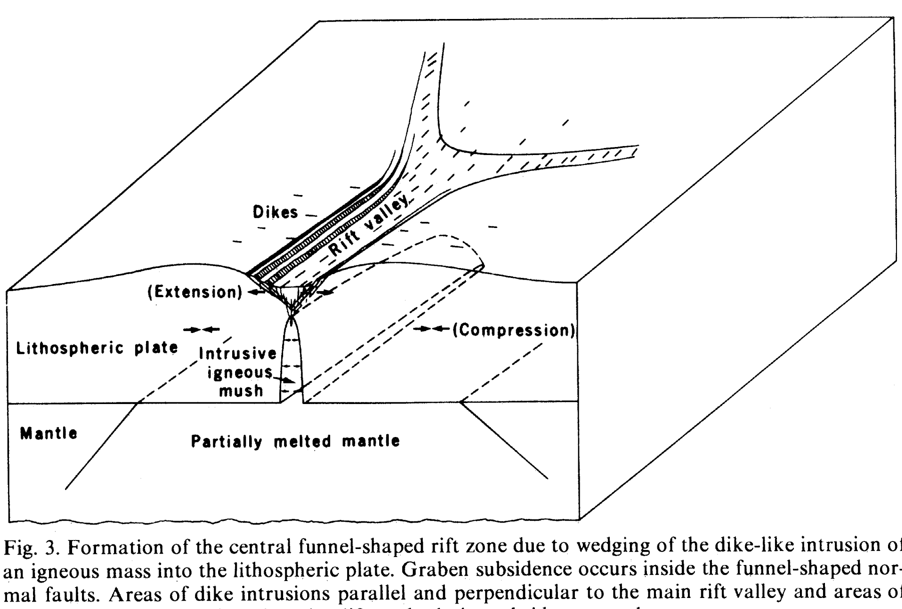

Fig. 3. Formation of the central funnel-shaped rift zone due to wedging of the dike-like intrusion of an igneous mass into the lithospheric plate. Graben subsidence occurs inside the funnel-shaped normal faults. Areas of dike intrusions parallel and perpendicular to the main rift valley and areas of compression and extension, domal uplift, and relative subsidence are shown.

Although the stress distribution in Fig. 2 was calculated by the exact solution (*25*), the approximate maximum stress (σ_1) at arbitrary points (r, θ) near the apex of a thin oblate intrusion (Fig. 1) can be estimated from

$$\sigma_1 = \sigma_l + \frac{K_1}{(2\pi r)^{1/2}}\left\{\cos\left(\frac{\theta}{2}\right) + \left[\sin^2\left(\frac{\theta}{2}\right)\cos^2\left(\frac{\theta}{2}\right) + \frac{\rho^2}{2r^2}\right]^{1/2}\right\} \qquad (2)$$

where ρ is the radius of curvature at the apex of the dike, $K_1 = 2(C/\pi)^{1/2}(\sigma_l - P)$, and C is the maximum radius of the oblate body (that is, the half-length of the dike-like intrusion). In linear fracture mechanics, K_1 is usually referred to as the stress intensity factor, although $K_1 = (\pi C)^{1/2}(\sigma_l - P)$ for two-dimensional elliptical fractures.

It may appear paradoxical that an igneous intrusion with excess magma pressure forms graben immediately above the intrusion. Magma intrusion tends to push the near-vertical side walls of a dike horizontally by wedging, as well as to produce doming by pushing the roof upward above the curved surface of the intrusive body. As the area along the side walls of a thin, vertically elongated oblate magma body is much larger than the area around its roof, the wedging effect will be much greater than the effect of doming. However, the doming effect will predominate in a broad, domal igneous mush. Various combinations of domal uplift and graben may occur, their form principally controlled by the shape of the intrusion. Our analyses show that in the case of a thin oblate intrusive body, the doming effect is observed only close to its roof, while the wedging effect produces horizontal tensile stress over the entire intrusive body (Figs. 2 and 3).

An important feature of the stress distribution (Fig. 2) is that the maximum stress concentration is highest immediately above the top of the intrusive body, but the contour of stress concentration has two peaks in the higher part over the intrusive body. Another important point is that the direction of maximum compression (minimum tensile stress), indicated by short lines in Fig. 2, is nearly vertical over the intrusive body but becomes progressively more horizontal away from the axis of the body. Such stress distribution due to wedging of a magmatic body at depth would produce horizontal extension above the igneous mass and horizontal compression outward and at the side perpendicular to the direction of elongation of the intrusive body (Fig. 3). Such horizontal compressions have been measured outside the rift valley in Iceland by Hast (*27*). In many areas dikes occur perpendicular to the trend of the central rift valley or inclined in a conjugate system. These dike swarms also suggest horizontal compression perpendicular to the trend of the rift valley (Fig. 3). Roberts (*28*) estimated maximum excess magma pressure on the order of ~ 1 kbar at a depth of 10 to 30 km, if basaltic magma is in equilibrium with lithostatic stress at a depth of about 60 km. Convection of heated water in the crust can raise pore pressure over the intrusion and helps brittle fracturing. If the aspect ratio of the basaltic intrusive body is more than 1 : 10, our analyses show that fractures can develop extensively when the top of the intrusive body is at a depth of 10 to 30 km (that is, at ~ 1 kbar excess magma pressure) because stress becomes effectively tensile or near tensile in a wide area around its apex (Eq. 1). This depth for the top of intrusion is consistent with the general width of rift valleys of 20 to 60 km (*2*).

Calderas have characteristics similar to rift valleys except for the difference in horizontal dimension. We indicated earlier (*21*) that calderas may have formed over the intrusion of prolate magma bodies whose plan view is circular instead of elliptical. Stress concentrations around such prolate intrusions are found to be of much lower magnitude than around oblate intrusions, and generally produce radial, radial-concentric, and concentric fracturing around the prolate protrusions with increase in aspect ratio and stress.

This analysis suggests that excess magma pressure in vertical dike-like intrusions pushes lithospheric plates apart almost horizontally. Graben subsidence occurs inside the funnel-shaped normal faults above the intrusion. Horizontal transverse compression produces domal uplift on the flanks of a rift valley, and secondary dike intrusions or rift valleys can also develop perpendicular to the main rift valley. Rift valleys can also branch into a set of conjugate strike-slip faults at the ends, producing triple junction fracture geometry (*29*). Such rift valley branching is observed in the Carlsberge, Mid-Atlantic Ridge, East Pacific Rise, Rhine graben, and Red Sea regions.

H. KOIDE*, S. BHATTACHARJI
Department of Geology, Brooklyn College of the City University of New York, Brooklyn 11210

References and Notes

1. A. Holmes, *Principles of Physical Geology* (Ronald, New York, 1965).
2. V. V. Beloussov, *Geophys. Monogr. 13* (1969), p. 539.
3. E. J. Wayland, Ed., "Rift valleys and Lake Victoria," *C. R. Int. Geol. Congr. S. Afr.* **2**, 223 (1930).
4. B. C. Heezen and M. Ewing, in *The Sea*, H. N. Hill, Ed. (Interscience, London, 1963), vol. 3, p. 388.
5. B. H. Baker and J. Wohlenburg, *Nature (Lond.)* **299**, 531 (1971).
6. H. Cloos, *Geol. Rundsch.* **30**, 405 (1930).
7. P. R. Vogt, E. D. Schneider, G. L. Johnson, *Geophys. Monogr. 13* (1969), p. 556.
8. J. W. Gregory, *The Rift Valleys and Geology of East Africa* (Sealy, Service, London, 1921).
9. E. Orowan, *Science* **146**, 1003 (1964).
10. D. C. Noble, *Earth Planet. Sci. Lett.* **17**, 142 (1972).
11. H. R. Shaw, *Geol. Soc. Am. Bull.* **84**, 1505 (1973).
12. O. Anderson and P. Perkins, *J. Geophys. Res.* **79**, 2138 (1974).
13. J. T. Wilson, *Sci. Am.* **208**, 86 (1963).
14. W. J. Morgan, *Am. Assoc. Pet. Geol. Mem. 56* (1972), p. 203.
15. I. G. Gass, in *African Magmatism and Tectonics*, T. N. Clifford and I. G. Gass, Eds. (Hafner, Darien, Conn., 1970), p. 285.
16. A. Rice, *Geol. Soc. Am. Abstr. Programs* **6**, 18 (1974).
17. W. F. Brace and E. G. Bombolakis, *J. Geophys. Res.* **68**, 3709 (1963).
18. H. Koide, *Soc. Min. Geol. Jpn. Spec. Issue No. 3* (1971), p. 107.
19. ______, K. Hoshino, K. Inami, *Bull. Geol. Surv. Jpn.* **25**, 89 (1974).
20. J. Handin, R. V. Hager, Jr., M. Friedman, J. N. Feather, *Am. Assoc. Pet. Geol. Bull.* **47**, 717 (1973).
21. H. Koide and S. Bhattacharji, *Econ. Geol.* **70**, 4 (1975).
22. W. G. Melson, G. Thompson, T. H. van Andel, *J. Geophys. Res.* **73**, 5925 (1968).
23. C. L. Drake and R. W. Girdler, *Geophys. J.* **8**, 473 (1964).
24. C. G. A. Harrison, *J. Geophys. Res.* **73**, 2137 (1968).
25. H. Koide, *J. Mater. Sci. Soc. Jpn.* **7**, 252 (1970).
26. ______, *Proc. Int. Conf. Mech. Behav. Mater.* **4**, 455 (1972).
N. Hast, *Philos. Trans. R. Soc. Lond. Ser. A Math. Phys. Sci.* **274**, 409 (1973).
28. J. L. Roberts, in *Mechanism of Igneous Intrusion*, G. Newall and N. Rast, Eds. (Gallery, Liverpool, 1970), p. 287.
29. S. Bhattacharji and H. Koide, *Nature (Lond.)* **255**, 21 (1975).
30. Supported by a faculty research grant from the City University of New York to S.B. We thank D. M. Gabriel for providing additional financial support and computer facilities and L. Bhattacharji for helping with this manuscript.
* Present address: Geological Survey of Japan, Shinjuku-Ku, Tokyo.

12 March 1975; revised 5 May 1975

Flash Hydrogenation of a Bituminous Coal

Abstract. *Flash heating of Illinois coal (to 700°C in 1 second) in flowing hydrogen at 100 atmospheres, limiting the vapor residence time at 700°C to 3 seconds, converts 14 percent of the coal's carbon to methane, 7 percent to ethane, and 10 percent to benzene, toluene, and xylenes. The remainder is coke; the carbon balance shows that heavy tar, if any exists, is less than 3 percent.*

We believe that economics will soon cause a turning away from the practice of burning chemically bound hydrogen for the large-scale production of electricity. Bound hydrogen in coal will be viewed as too valuable to burn and send as water vapor to a stack. This hydrogen can become part of some clean fuel, more convenient and more valuable than coal. The hydrogen-rich fuel would be "creamed off," leaving a residue that would be burned to generate electricity.

This idea is, of course, not original with us. The by-product coke oven is 100 years old, and many teams have attempted to displace it with improved coking procedures. The first step in such procedures is crucial in determining what products will be obtained and how difficult subsequent processing will be. A step with a minimum yield of heavy tar will be preferred, since tar is difficult to upgrade by hydrogenation and has little value.

In our search for a likely first step, we were struck by U.S. Bureau of Mines data from rapid noncatalytic hydrogenation of bituminous (*1*) and subbituminous (*2*) coals at 69 and 400 atm, respectively, and 800°C. An earlier experiment (*3*) was modified so that vapor products were swept from the reaction zone into a cooler region in a few seconds.

Rapid heating of coal avoids polymerization reactions that produce a solid of high molecular weight before much evolution of light species has occurred (*4*). The presence of hydrogen directs free radicals evolving from rapidly heated coal into reaction paths that lead to light stable species.

What was new in the Bureau's rapid hydrogenation (*5*) was the short gas residence time at the reaction temperature. Following Dent's lead of just 40 years ago (*6*) and with methane as the objective, researchers have treated coal with hydrogen at pressure in experiments with slow heating (*7*), with rapid heating (approximately 1 to 2