

TOPOGRAPHY AND TECTONICS OF THE INTERSECTIONS
OF FRACTURE ZONE WITH CENTRAL RIFTS

by

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SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF
SCIENCE

at the

MASSACHUSETTS INSTITUTE OF
TECHNOLOGY

May, 1969

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Submitted to the Department of Earth and
Planetary Science in May, 1969 in partial
fulfillment of the requirement for the de-
gree of Master of Science.

Deep basins with up to 2 km of relief occur at intersections of fracture zones with the central rift of mid-ocean ridges. The cause of these depressions may be the loss of hydraulic head due to the viscosity of the material that upwells passively at ridges to produce new sea floor. At such intersections the transform fault truncates the central rift imposing an additional boundary to which the upwelling material tends to stick. More head loss and therefore a deeper rift is required for the material upwelling near the fault. Atlantic fracture zones may obtain their topography through a partial freezing of the basin into the spreading sea floor. Pacific fracture zones have been affected by changes in spreading direction. As a transform fault offsetting a rifted ridge may leak, more mapping is required to determine the principle cause of Atlantic fracture zones.

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INTRODUCTION

When studying something as complex as global tectonics, it is often useful to examine features of such limited extent that they have negligible influence on the outcome of the processes under study. The purpose of this paper is to examine the topography of the intersections of fracture zones with the central rifts of mid-ocean ridges with reference to sea-floor spreading and the origin of these central rifts. This topography is certainly an effect, not the cause, of sea-floor spreading.

DEEP BASINS

Relatively deep basins with up to 2 km of relief exist at the intersections of the central rifts of the mid-Atlantic ridge and the Gorda rise with fracture zones (Heezen and Tharp, 1965; McManus, 1965, 1967). A similar feature occurs at an offset of the Carlsberg rise (Cann and Vine, 1966). The basins on the Gorda rise are associated with large negative free air gravity anomalies (Dehlinger, et al., 1968). The Atlantis fracture zone (figure 1) is used as the type example in this paper since it has been mapped in detail.

The central rift of a mid-ocean ridge can not be the result of erosion. Since the lithosphere is unusually thin at ridges, as indicated by: the attenuation of S_n waves (Molnar and Oliver, 1969), the outcrop of recent metamorphic and igneous rocks (for example, Melson, et al.,

1968), seismic strain release data (Brune, 1968), and heat flow models (McKenzie, 1967; Sleep, 1969), and since central rifts are not isostatically compensated in the crust (Loncarevic, et al., 1966), it is unlikely that central rifts are static features supported by the finite strength of the lithosphere. Central rifts are also too deep to be isostatic grabens (Sleep, 1969).

It is tempting to consider a central rift to be a "dead spot" at the peak of ascending and diverging material. This is analogous to the dead spots at the center of fountains. It appears that downgoing material from the "fountain" on one side of the transform fault could drag down material upwelling on the other side. Upon close examination the analogy breaks down. Inertial forces dominate the flow of fountains, while viscous forces dominate the flow in the earth. Although the crust opposite the end of an offset rift has already descended to a lower elevation by virtue of the fact that it has spread from its own rift an amount equal to the offset, this lower elevation is much less than the depth of the basin.

If the new material which forms the spreading seafloor upwells passively, head loss due to the viscosity of the upwelling material may produce central rifts (Sleep, 1969). The tectonics of the Gorda rise area can be interpreted as resulting from passive intrusions into a zone of

relative tension along the rise axes (Dehlinger, 1969). In this paper the zone in which material upwells will be referred to as a dike; although the intrusion could also be called a passive diapir.

The viscous upwelling material will tend to stick to the walls of the dike. The transform fault truncates the dike imposing an additional boundary to which the upwelling material also sticks. More head loss is thus required for material to upwell near the fault. Therefore, the rift will be deeper near the fault. (See figure 2)

The complications imposed by the solidification of the crust and by the increase of the viscosity of the upwelling material when it cools on contact with the transform fault make it extremely difficult to construct a detailed mathematical model. However, the depth of the basin may be estimated by modeling the region near the fault with a vertical cylinder the same diameter as the width of the dike. The basin should not be deeper below the floor of the rift than the rift is below the surrounding terrain, since the head loss in the dike is $3/8$ the head loss in the cylinder if the average velocity in both bodies is the same. The width of the basin should be similar to the width of the central rift, since the effect of the fault is strongest on material which is nearer to the fault than to the walls

of the dike. Since material behaves continuously, the depth of the central rift decreases gradually for a considerable distance away from the deeper part of the basin. The observed data (McManus, 1967; Heezen and Tharp, 1965) support these deductions.

ATLANTIC FRACTURE ZONES

Fracture zones in the Atlantic (van Andel, et al., 1967; Heezen, et al., 1964a, 1964b; Heezen and Tharp, 1965), parts of the Blanco fracture zone (McManus, 1965), and the Vema trench in the Indian Ocean (Heezen and Nafe, 1964) consist of a 20-km wide valley flanked by parallel walls. A -170 mgal free air anomaly is associated with the Romanche trench, the deepest fracture zone in the Atlantic, but positive anomalies associated with the surrounding highlands cause the regional average anomaly to be small (Heezen, et al., 1964a).

Outside the zone of offset a transform fault may be somewhat locked. As the crust spreads away from the rift, recovery of lost head lifts the crust to normal elevation (Sleep, 1969; Atwater and Mudie, 1968). More lost head has to be recovered near the basin, but the lithosphere near the fault should be thick enough to behave coherently with the lithosphere farther from the fault. A regional equilibrium may be achieved by lifting the general region of the fracture zone to form a deep valley with two walls elevated above the general elevation

of the ridge. Note that this mechanism can operate only if a rifted ridge is offset. Erosion and deposition will modify the landforms which result.

Within the zone of offset, strike-slip movement on the transform fault complicates the tectonics. Recent mapping of the Oceanographer fracture zone confirms that basins are elongate (Fox, et al., 1969). As the elongation extends only into the zone of offset, it must either be related to coupling between the basins or to movement on the transform fault. One possibility is that the transform fault zone is significantly wide, consisting of several parallel faults. In this case, the floor of the basin may be decoupled from the major blocks when it has spread into the region where the walls of the central rift are uplifted. The floor of the basin may rise later due to second upwelling along the transform fault or it may become coupled to the major blocks and frozen into the spreading sea floor. As a large variability in the extent of coupling and rate of secondary upwelling is likely, the extent of elongation should also be variable. Detailed mapping is needed to determine if transform fault zones consist of several parallel faults.

PACIFIC FRACTURE ZONES

"Zed" patterns result from a minimization of rift length after a change in spreading direction. Existing

transform faults may then leak (Menard and Atwater, 1968). As the spreading rate is low, the upwelling material will cool rapidly and the zone of upwelling will be narrow. A large head loss is required for fluid to upwell in a narrow dike. Thus, a large topographic depression can originate. If the change in spreading direction is small, the fault will not open much. The upwelling material then will be thermally assimilated before the depression is eliminated. This depression will then spread with the sea floor.

Transform faults, other than the ridge-ridge kind, may leak. The Cayman trough may leak due to a yet undiscovered change in spreading direction. This trough is an arc-arc transform fault (Isacks, et al., 1968), which has apparently opened due to tension (Ewing and Heezen, 1955; Bowin 1968) at about 0.1 to 0.3 cm/yr (Bowin, 1968). The trough has a thin crust. Large depressions and negative free air anomalies are associated with the trough, although the region is in general isostatic equilibrium (Bowin, 1968).

At this low spreading rate a large tensional depression will be generated before there is a head loss large enough to cause the upwelling of the substratum to replace the material which spreads out. A 2 to 3 km deep depression which is 40 km wide could thus be the low spreading rate equivalent of the central rifts

of mid-ocean ridges. This spreading draws so little material that the asthenosphere is affected by the trough much as it would be by a static mass deficiency in the crust. Thus the region remains in isostatic equilibrium. Ewing and Heezen (1955) therefore appear to be essentially correct in stating that the Cayman trough is a tensional extension which the substratum has not yet risen to fill. Note that the presence of upwelling material along a transform fault may reduce seismicity from strike-slip movement.

Changes in spreading direction and minor spreading at transform faults support the hypothesis (Elsasser, 1967) of a competent lithosphere able to transmit stress (Menard and Atwater, 1968). After a minor change in spreading direction, the motion normal to the fault is small. Spreading ceases once the fault has aligned its strike with the new spreading direction. Afterwards a depression is frozen into the crust.

CONCLUSIONS

The topography at intersections of fracture zones with central rifts can be interpreted as a direct consequence of sea-floor spreading and of the viscodynamic origin of central rifts. The topography of Atlantic fracture zones may be caused by partial freezing into the spreading sea floor of basins which occur at the intersections of central rifts and fracture zones.

Spreading produced by forceful injection of dikes along the ridge axis seems incapable of causing these features.

Pacific fracture zones and possibly the Cayman trough obtained their topography after a change in spreading direction. This process may also affect rifted rises, for example, the Vema fracture zone (van Andel, et al., 1969). If a transform fault is quite leaky the rift zone will not be sharply truncated. Thus the wall required for the production of basins may not exist. A volcanic zone may even form at the intersection (Bass, personal communication). Further mapping of each Atlantic fracture zone is needed to tell whether leaky transform faults or viscous forces associated with central rifts cause the topography. Both active leaky transform faults and the offset regions of ridges affected by the mechanism proposed in this paper may appear to the asthenosphere as static mass deficiencies and be regionally compensated by a general uparching of the zone of offset.

Compositional differences between ridges may also affect their relative topographic roughness (Cann, 1968). As composition affects viscosity, there is no direct conflict between this theory and a viscodynamic origin of central rifts.

ACKNOWLEDGEMENTS

I would like to thank Prof. Shawn Biehler and Manuel Bass for critically reading the manuscript and for helpful suggestions, Paul Kasameyer who pointed out to me the existence of the topography studied above, and P. Molnar and J. Oliver for a preprint of their paper. This research was undertaken during tenure of a National Science Foundation Graduate Fellowship.

REFERENCES

- Atwater, Tanya, and J. Mudie, Block faulting on the Gorda rise, Science, 159, 729, 1968.
- Bowin, C., Geophysical study of the Cayman trough, J. Geophys. Res., 73, 5159, 1968.
- Brune, J., Seismic moment, seismicity, and rate of slip along major fault zones, J. Geophys. Res., 73, 777, 1968.
- Cann, J. R., Geological processes at mid-ocean ridge crests, Geophys. J. R. astr. soc., 15, 331, 1968.
- Cann, J. R., and F. Vine, An area on the crest of the Carlsberg ridge: petrology and magnetic survey, Royal Soc. London Philo. Trans., A259, 198, 1966.
- Dehlinger, P., Tectonic processes in the Juan de Fuca and Gorda ridges, and their implications for global tectonics (abstract), Trans. Amer. Geophys. Union, 50, 186, 1969.
- Dehlinger, P., R. Couch, and M. Gemperle, Continental and oceanic structure of the Oregon coast westward across the Juan de Fuca ridge, Can. J. Earth Sci., 5, 1079, 1968.
- Elsasser, W., Convection and stress propagation in the mantle, Princeton Univ. Tech. Rept. 5, June 15, 1967.
- Ewing, M., and B. Heezen, Puerto Rica trench topographic and geophysical data, in Geol. Soc. Amer., Special Paper 62, 255, 1955.

- Fox, P., A. Lowrie, Jr., and B. Heezen, Oceanographer fracture zone, Deep-Sea Res., 16, 59, 1969.
- Heezen, B., E. Bunce, J. Hersey, and M. Tharp, Chain and Romanche fracture zones, Deep-Sea Res., 11, 11, 1964a.
- Heezen, B., R. Gerard and M. Tharp, Vema fracture zone: equatorial Atlantic, J. Geophys. Res., 69, 733, 1964b.
- Heezen, B., and J. Nafe, Vema trench: Western Indian Ocean, Deep-Sea Res., 11, 79, 1964.
- Heezen, B., and M. Tharp, Tectonic fabric of the Atlantic and Indian Oceans and continental drift, Royal Soc. London. Philo. Trans., A258, 90, 1965.
- Isacks, B., J. Oliver, and L. Sykes, Seismology and the new global tectonics, J. Geophys. Res., 73, 5855, 1968.
- Loncarevic, B., C. Mason, and D. Mathews, Mid-Atlantic ridge near 45° North, I. the median valley, Can. J. Earth Sci., 3, 327, 1966.
- McKenzie, D., Some remarks on heat flow and gravity anomalies, J. Geophys. Res., 72, 6261, 1967.
- McManus, D., Blanco fracture zone, Northeast Pacific Ocean, Marine Geol., 3, 429, 1965.
- McManus, D., Physiography of the Cobb and Gorda rises Northeast Pacific Ocean, Geol. Soc. Am. Bull., 78, 527, 1967.
- Melson, W., G. Thompson, and Tj. van Andel, Volcanism and metamorphism in the mid-Atlantic ridge, 22° N Latitude, J. Geophys. Res., 73, 5925, 1968.
- Menard, H., and T. Atwater, Changes in direction of sea-floor spreading, Nature, 219, 463, 1968.

- Molnar, P., and J. Oliver, Lateral variation of attenuation in the upper mantle and discontinuities in the lithosphere, J. Geophys. Res., 74, in press, 1969.
- Sleep, N., Sensitivity of heat flow and gravity to the mechanism of sea-floor spreading, J. Geophys. Res., 74, 542, 1969.
- van Andel, Tj., J. Corliss, and V. Bowen, Intersection between the mid-Atlantic ridge and the Vema fracture zone in the North Atlantic, J. Marine Res., 25, 343, 1967.
- van Andel, Tj., J. Phillips, and R. Von Herzen, Rifting origin for the Vema fracture in the North Atlantic, Earth and Planetary Science Letters, 5, 296, 1969.

Figure 1: Atlantis fracture zone

Bathymetric map of the Atlantis fracture zone is contoured at 400 fms interval (0.73 km). Deep basins occur at the intersections of the central rift with the fracture zone. The basins are elongate into the zone of offset. The width of the basins and of the depression of the fracture zone is similar to the width of the central rift. After Heezen and Tharp (1965).

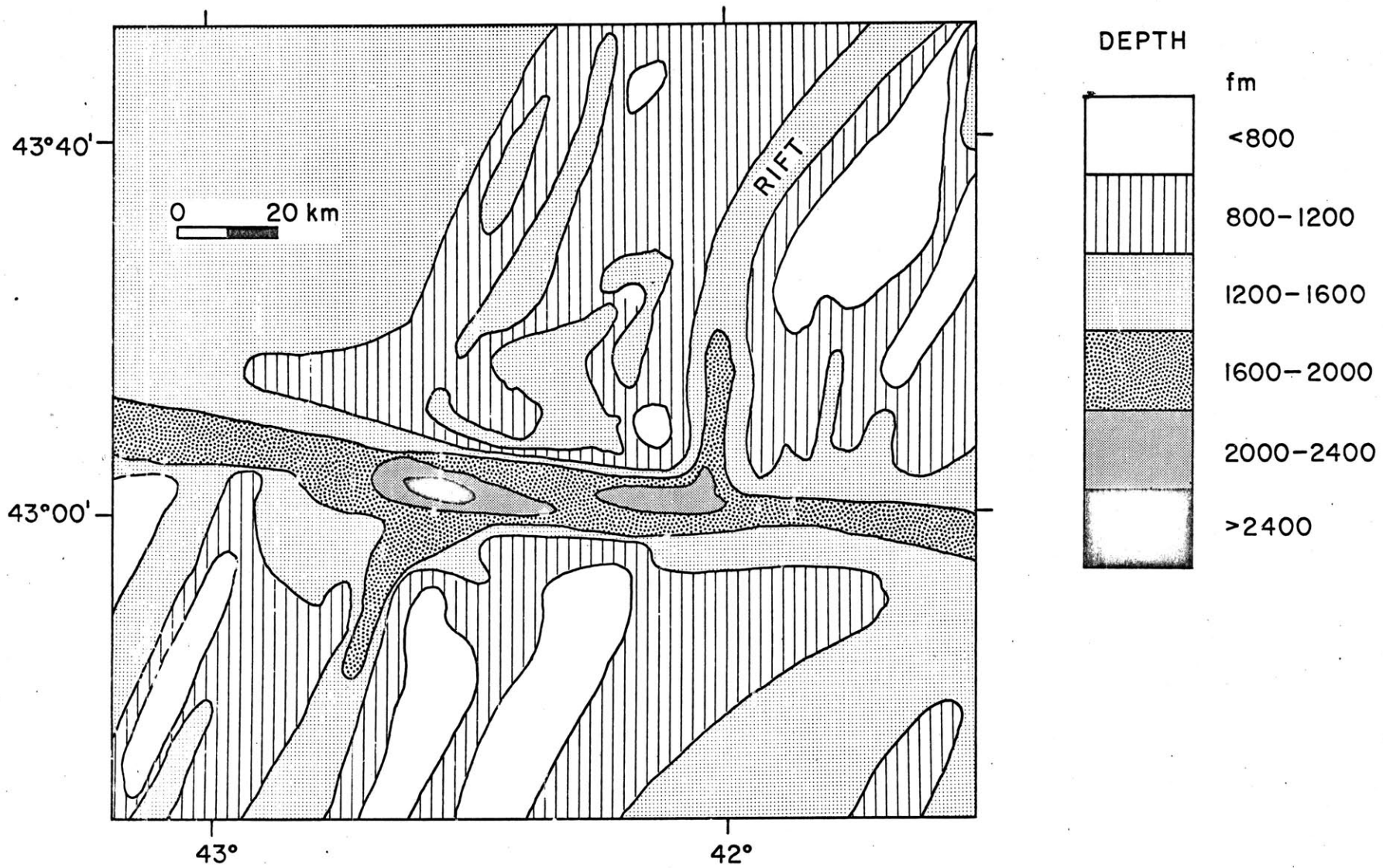


Figure 2: Three dimensional cutaway view of the intersection of a fracture zone with the central rift of a midocean ridge

The material upwelling to form new sea floor tends to stick to cooler material farther from the ridge axis. The zone where the fluid tends to stick is shown here as the walls (A and B) of a dike. Head loss due to the viscosity of the upwelling material causes the central rift. The transform fault (C) imposes an additional wall to which fluid tends to stick. More head loss and therefore a deeper rift is associated with the material upwelling near the fault.

