Reports

Crustal Plates in the Central Atlantic: Evidence for at Least Two Poles of Rotation

Abstract. *A fracture zone that offsets the Mid-Atlantic Ridge at 24°N, 45°W was traced westward over a distance of 840 kilometers. The radius of curvature of the fracture zone changes at about 47°45′W; this suggests that the fracture zone was generated by rotation of crustal plates about at least two sequential poles.*

The theory of sea-floor spreading (*1*), which is supported by recent evidence (*2*, *3*), has lent new significance to the many fracture zones that interrupt the continuity of the Mid-Oceanic Ridge system. Wilson (*2*) defined transform faults as the seismically active portion of fracture zones lying between offset ridge axes, and he has proposed that the transform faults are parallel to the relative spreading direction of the crustal plates that bound the ridge axes. The seismically inactive portion of the fracture zones are the fossil trace of transform faults and therefore describe the relative motion of crustal plates in the past. McKenzie and Parker (*4*) and Morgan (*5*) demonstrated that the relative motion of these plates may be regarded as the rotation of one plate with respect to the other about a geocentric pole, and that the transform faults describe small circles with respect to this pole. The same arguments are applicable to the inactive portion of the fracture zones. Although in a strict sense these poles of relative motion must be regarded as instantaneous, Morgan and Le Pichon (*5*) found that, in several cases, a single stationary pole is adequate to describe the relative motion of the crustal plates of a particular region for long periods of time.

Detailed studies of only a few fracture zones in the Atlantic have been published (*6*), and most of these have traced only the seismically active portion of the transform faults which lies between the offset ridge axes. We now present the results of a survey made on R.V. *Vema* of a fracture zone in the North Atlantic at 24°N. During the survey a 12-kc echo sounder, a seismic reflection profiler, a towed magnetometer, and a satellite navigation system were used. Nine successful dredge hauls were obtained at selected localities.

An earlier study of the earthquake epicenter belt (*3*) showed that the axis of the Mid-Oceanic Ridge is offset in an apparent left-lateral sense at 24°N, 45°W (Fig. 1). Using the offset epicenter belt as an initial guideline, we traced the fracture zone 840 km westward from the easternmost margin of the rift valley.

The survey revealed that the fracture zone is a continuous, narrow, V-shaped, and steep-walled cleft ranging in depth from 4300 m in the area of the displaced ridge crest to 6000 m on the ridge flank (Fig. 2). The width of the fracture zone at the base of the escarpment varies from 2 to 10 km. The bounding escarpments rise 1000 to 2500 m above the floor of the fracture zone and have regional slopes as steep as 15° to 25°. Records of the seismic reflection profiler (*7*) show that both the escarpments and the trough of the fracture zone are sediment-free in the crestal area of the ridge. Farther out on the flanks the trough contains localized, stratified sediment ponds with a maximum thickness of 300 m.

Twenty-four closely spaced crossings over a distance of 840 km accurately define the trend of the fracture zone at

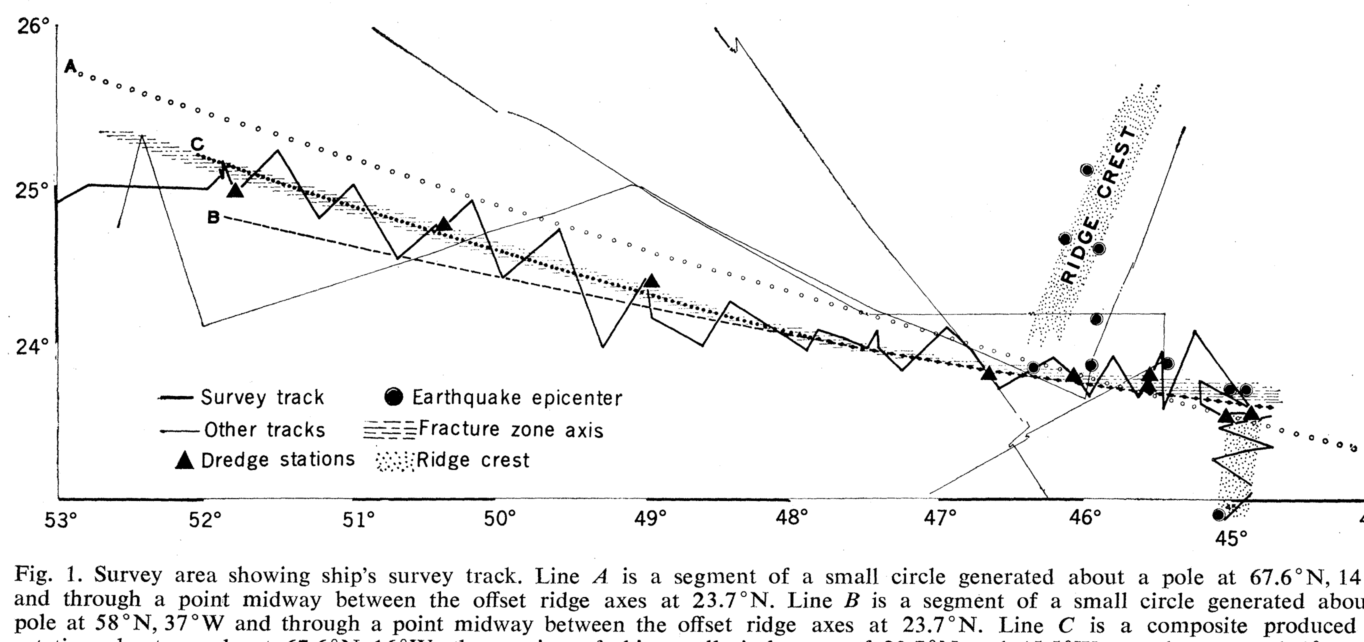

Fig. 1. Survey area showing ship's survey track. Line *A* is a segment of a small circle generated about a pole at 67.6°N, 14°W and through a point midway between the offset ridge axes at 23.7°N. Line *B* is a segment of a small circle generated about a pole at 58°N, 37°W and through a point midway between the offset ridge axes at 23.7°N. Line *C* is a composite produced by rotation about a pole at 67.6°N, 16°W; the portion of this small circle west of 23.7°N and 45.5°W was then rotated 4° to the west about a pole at 58°N and 37°W.

24°N (Fig. 1). The trend of the fracture zone axis appears to follow not the arc of a single small circle but that of two small circles intersecting at about 47° 45′W(Fig. 1). This suggests the the fracture zone was generated by a rotation about at least two sequential poles. Inferences of more than a single pole of rotation have been previously made to explain apparent changes in the trend of fracture zones in other regions (see *5*, *8*).

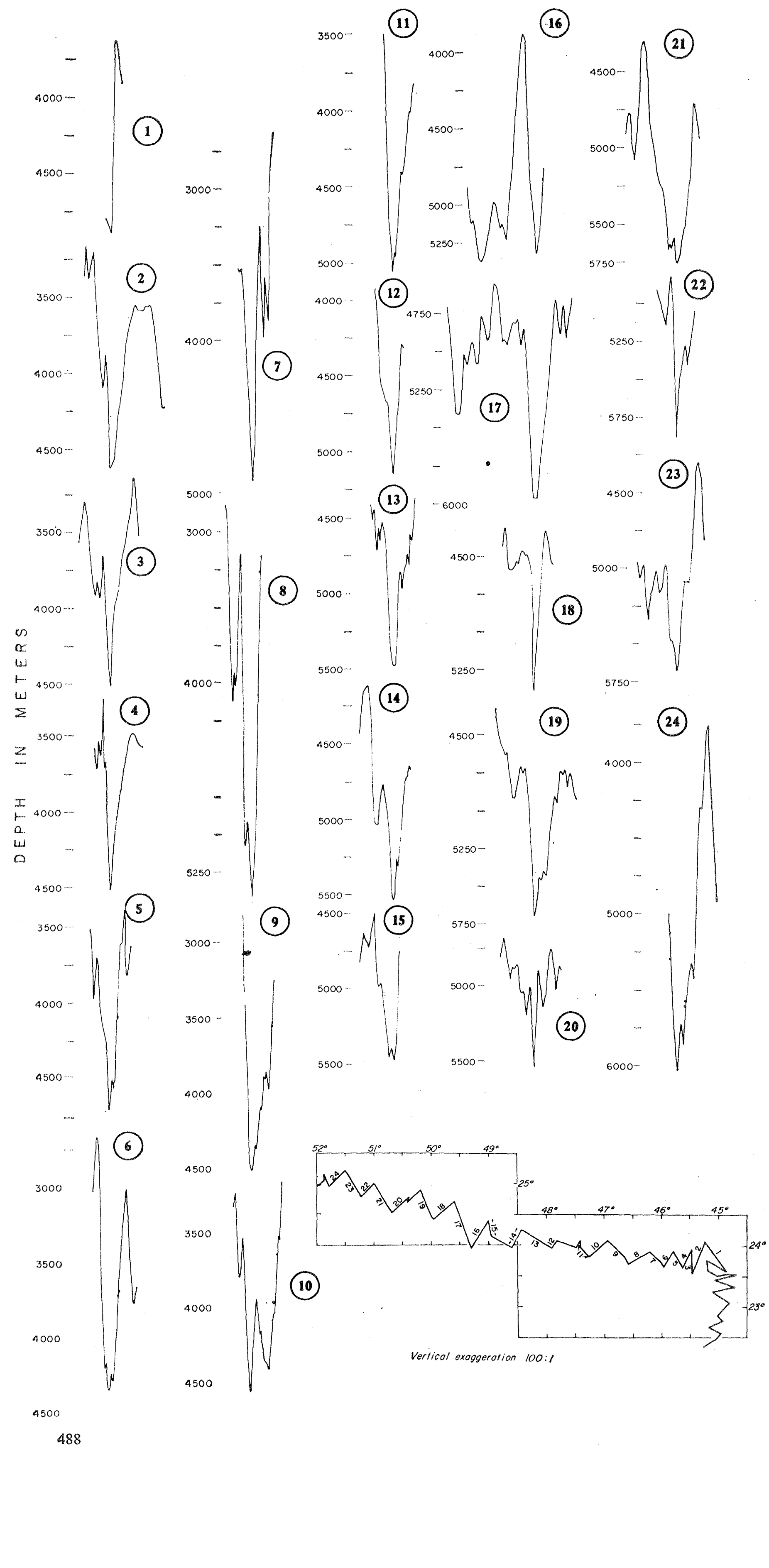

Fig. 2. Bathymetric profiles have been projected onto a north-south line to simulate a traverse normal to the strike of the fracture zone with south on the left. The map (lower part of the figure) serves as an index to the profiles.

Morgan and Le Pichon (*5*) calculated a pole at 58°N, 37°W for the recent relative motion of the equatorial Atlantic crustal plates by making a least-squares fit to the azimuth and position of 18 fracture zones. They used azimuths and positions for that portion of the fracture zones lying perpendicular to the offset ridge axis. We have recalculated the position of the pole, determined by Morgan and Le Pichon for recent spreading, after incorporating the new data obtained during the survey, and it was found not to be significantly different. A small circle about this pole (58°N, 37°W) and through a point midway between the offset axis of the ridge at 24°N is shown by the dashed line in Fig. 1, and the small circle approximates only that portion of the surveyed fracture zone lying between 47°45′W and the easternmost edge of the ridge crest.

The trace of a second small circle about a pole at 67.6°N and 14°W [the pole defined by Bullard *et al.* (*9*) to describe the total separation of North America and Africa] and through a point midway between the offset ridge axis is shown by open dots (Fig. 1). This small circle does not coincide with any portion of the fracture zone, but west of 47°45′W it parallels the observed trend.

We computed a third hypothetical trace of the fracture zone by assuming two sequential poles of rotation. The initial rotation at 67.6°N and 16°W, which is 2° farther to the west than that of Bullard *et al.*, was chosen in order to slightly improve the fit of the computed small circle with the observed trend of the fracture zone. The portion of this small circle lying west of 23.7°N and 45.5°W was then rotated 4° to the west about a pole at 58°N and 37°W. The synthesized fracture zone is thus a composite, shown as the line of solid dots in Fig. 1. This relatively good fit suggests that there have been at least two directions of spreading within the Central Atlantic.

The cause or causes of a change in the pole of rotation of crustal plates is still obscure, but two explanations have been offered. Van Andel *et al.* (*8*), in order to explain the change in trend and shape of the Vema Fracture

Zone at 10°N, have suggested that the pole of rotation about which crustal plates are rotating changes during a hiatus in spreading. Ewing and Ewing and Schneider and Vogt (*10*) have suggested that there was a hiatus in spreading in the North Atlantic 10 million years ago. Another explanation, which is more appealing, is that the pole of rotation migrates as a result of the interaction of the crustal plates of the Central Atlantic with other systems of moving plates.

The change in the radius of curvature of the fracture zone occurs about 130 km away from the portion of the ridge offset to the west. If we assume an average spreading rate of 1.4 cm/year for the past 10 million years (*11*) for this region, the change in the pole of relative motion occurred about 9 million years ago.

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Clathrate Hydrates of Air in Antarctic Ice

Abstract. *Measurements of the dissociation pressure of nitrogen hydrate and oxygen hydrate show that the clathrate hydrate of air with the formula* $(N_2,O_2) \cdot 6H_2O$ *should exist below about 800 meters in the Antarctic ice sheet. This accounts for the disappearance of gas bubbles at depths greater than 1200 meters. The hydrate should exist from this depth to the bottom of the core and should comprise 0.06 percent of the ice.*

Gow *et al.* (*1*) have described an Antarctic ice core (2164 m deep) and have observed air bubbles to a depth of 1200 m below which they disappear. Although no bubbles can be seen, air is still present since gas is evolved on melting the deep ice.

These observations can be accounted for on the basis of an air hydrate. The structure and properties of gas clathrate hydrates have been reviewed (*2*, *3*), and the occurrence of various hydrates on the other planets in the solar system has been discussed (*4*). The structure of the air hydrate would be the same as that of N_2 and O_2—structure I hydrate with a cubic unit cell of 12 Å, containing 46 water molecules and 8 cages for the gas molecules (*5*). This gives an ideal formula of $(N_2,O_2) \cdot 5\frac{3}{4}H_2O$, but the actual formula is approximately $(N_2O_2) \cdot 6H_2O$ because the cages are not completely filled with gas molecules (*2*, *6*).

A hydrate of air is stable if the pressure in the bubble is equal to or greater than the dissociation pressure of the hydrate. These dissociation pressures can be considered analogous to vapor pressures of a liquid or solid in that the hydrate is unstable below the dissociation pressure, and all the gas is converted to hydrate above the dissociation pressure, provided there is sufficient water present.

The pressure at which the air hydrate begins to form is given approximately by (*4*)

$$P_{\mathrm{air}} = P^0{}_{\mathrm{N_2}} X_{\mathrm{N_2}} + P^0{}_{\mathrm{O_2}} X_{\mathrm{O_2}} \qquad (1)$$

where $P^0{}_{\mathrm{N_2}}$ and $P^0{}_{\mathrm{O_2}}$ are the respective dissociation pressures of pure N_2 and O_2 hydrates, and $X_{\mathrm{N_2}}$ and $X_{\mathrm{O_2}}$ are the respective mole fractions in the gas phase. Since O_2 is concentrated in the hydrate, the dissociation pressure where the gas bubble completely disappears is nearly that of pure N_2 hydrate. The small amount of Ar and CO_2 in air would not affect the dissociation pressure significantly. These gases as well as the traces of Ne, H_2, and He would be incorporated into the air hydrate.

In order to estimate the dissociation pressure of the air hydrate at the ice core temperatures, I measured a dissociation pressure for N_2 hydrate of 61.9 ± 0.5 atm at $-35.04°C$ (*6–8*). This value combined with the quadruple point (*6*) of 141.5 atm and $-1.3°C$ gives

$$\log P_{\mathrm{N_2}} = 4.6849 - 688.9/T \qquad (2)$$

The O_2 dissociation pressure is given by (*9*, *10*)

$$\log \quad P_{\mathrm{O_2}} = 4.673 - 717/T \qquad (3)$$

The temperatures and pressures in the ice core are shown in Fig. 1, along with the dissociation pressures of N_2, O_2, and air hydrates. The pressures in the core were calculated from the density data (*1*). The data in the figure show that the air hydrate should begin to form at approximately 800 m, and that by 850 m all the air should have formed hydrate, leaving no bubbles. At greater depths the temperature rises, thus requiring a higher pressure to stabilize the hydrate, but since the pressure increase with depth is greater than this, the hydrate would be stable to the bottom of the ice core. Hydrate equilibrium should be attained in the core, since the rate of formation of N_2 and O_2 hydrates is rapid with finely divided ice, and large crystals of ice would be expected to form hydrate in times much shorter than the age of the ice at large depths.

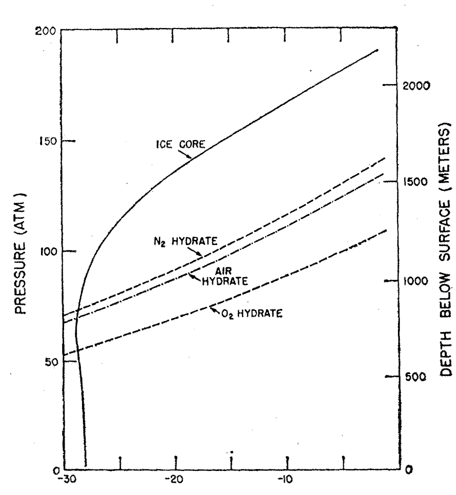

Fig. 1. Relation between temperature, pressure, depth of ice core and dissociation pressures of N_2, O_2, and air hydrates.