Reports

Eastern Atlantic Continental Margin: Some Results of the 1972 Cruise of the R.V. Atlantis II

Abstract. *A geophysical survey of the southeastern Atlantic Ocean has been made as one of the programs of the International Decade of Ocean Exploration. A large ancient delta of the Orange River and a diapiric field off Angola were mapped. Both features were initiated during early stages of the separation of Africa and South America, and both may be potential sources of oil.*

A symposium on the eastern Atlantic continental margin, held at Cambridge, England, during March 1970 (*1*), showed that the least known major region of the floor of the Atlantic Ocean is that off western Africa. Accordingly, one of the programs of the International Decade of Ocean Exploration (IDOE) was designed as a reconnaissance geophysical and geological study of the region between Africa and the mid-Atlantic ridge, with particular emphasis on the continental margin (*2*). This 4-year program will provide a seaward extension of the geological knowledge available to the coastal nations of Africa, and may reveal new sea-floor mineral resources.

The study also can serve as a framework for later, more detailed work by organizations within these nations. Consequently, many foreign scientists participated in the first cruise of the program, from 20 January to 1 July 1972, aboard the R.V. *Atlantis II* of the Woods Hole Oceanographic Institution. During this period seven cruise legs having a total length of nearly 50,000 line kilometers were organized, mainly for the region between Port Elizabeth (South Africa) and the Congo River (Fig. 1). On one or more of the various legs were 21 scientists, technicians, and students from Argentina, Brazil, England, France, Portugal, Republic of the Congo, South Africa, and Spain; 5 others were from universities in the United States; and 26 were members of the scientific and technical research staff of the Woods Hole Oceanographic Institution. During the first half of 1973 the second and final cruise, of about the same length, will continue the work in the region between the Congo River and Lisbon, from the coast to the mid-Atlantic ridge (Fig. 2). Heavy participation of foreign scientists is again expected and invited.

During the cruises continuous profiles were made with simultaneous recording of bathymetry at 3.5 khz, seismic reflection with air guns as large as paired 300-cubic inch (4916 cm^3) ones, and gravity and geomagnetic measurements. Periodic measurements of acoustic velocity in the bottom strata are provided by radiosonobuoys, and many surface characteristics of the ocean are measured by various methods. Navigation is chiefly by satellite signals, with radar employed near the coast. Five computers aboard ship permit rapid processing of the geophysical data both as superimposed profiles and in map form. The bathymetry, seismic reflection horizons, magnetic anomalies, and both free-air and Bouguer gravity anomalies are routinely available in 24-hour units a half day later, permitting efficient readjustment of the traverses to provide the best coverage of geological structures. Maps, well logs, and other data from the adjacent land brought by the participating African scientists supplement the offshore geophysical measurements.

A bathymetric atlas (*3*) and preliminary reports on the geomagnetic measurements, gravity, and sediments were distributed to about 150 African and other interested scientists in January 1972. The profiles and charts of geophysical data from the 1972 cruise will be printed and distributed, and those from the 1973 cruise will also be provided. Many of the participating scientists copied profiles and charts during their stays aboard ship.

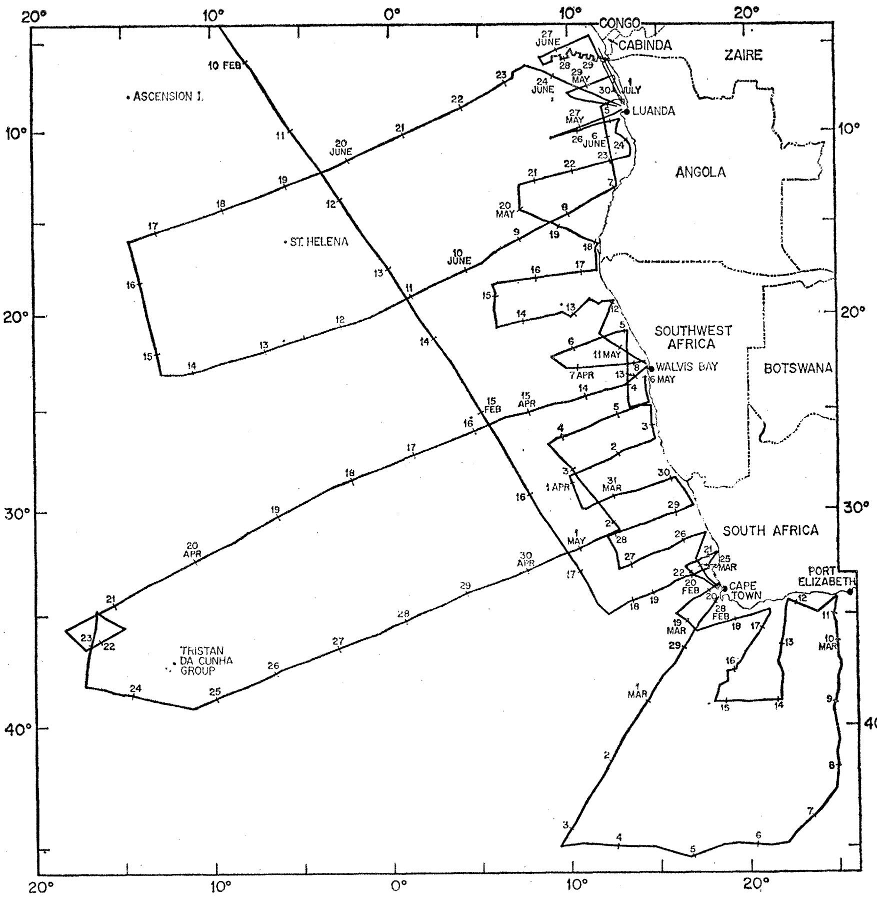
The 1972 cruise yielded interesting information on deep-ocean geology, including the Cape Agulhas fracture zone, another major unnamed fracture zone, magnetic reversals, Walvis ridge, and the stratigraphy of the Agulhas, Cape, and Angola basins. It also showed that the continental shelf along most of southwestern Africa is due to simple progradation of sediments, and that no tectonic barrier ridge underlies the shelf. Among the geological characteristics of the region are two features of the continental margin, which are illustrated here as examples of possible sites of oil and gas accumulations of potential economic interest. These are a huge ancient "delta" of the Orange River (a sediment apron largely beyond the base of the continental slope) and a field of numerous diapirs off Angola.

The ancient delta of the Orange River is shown by bathymetric contours that are broadly convex seaward (Fig. 3A). The same bulge is reflected by the isopach map of total sediments above basement (Fig. 3B); in the area of the illustration these sediments have a total volume of about 1.9×10^6 km^3 beneath water depths of 100 to 3600 m. A similar bulge with a lesser volume of 1.2×10^6 km^3 exists for all sediments above an acoustic reflecting horizon (Fig. 3C) believed to be correlative with horizon A of Cretaceous to middle Eocene age in the western Atlantic Ocean (*4*). No bulge exists for the 0.3×10^6 km^3 of sediments above a shallower acoustic reflecting horizon (Fig. 3D) believed to date from about the end of Paleogene time.

The relationships suggest that the delta began to be deposited soon after Africa rifted from South America and that deposition continued into Tertiary time but essentially ended before the middle Tertiary. There is some uncertainty in the date at which rifting began. The paleomagnetic orientation of Jurassic lavas and marginal deposition of Jurassic marine sediments (*5*) provide dates of about 160 million years ago. On the other hand, dating of magnetic reversals on the ocean floor suggests that active rifting was later, during the Early Cretaceous, perhaps about 130 million years ago (*6*). If the major rifting occurred at about Early Cretaceous time and the basement is 130 million years old, and if the deep acoustic reflector is 60 million years old and the shallower one 25 million years old, the corresponding rates of deposition of the Orange River delta are 10, 24, and 12 km^3 per 1000 years between each horizon, respectively. These figures indicate that the most rapid growth of the delta occurred during Paleogene time. For comparison, the present rate of contribution of sediment by the Congo River, about 2500 km farther north, is about 35 km^3 per 1000 years (*7*). The displacement of the delta approximately 200 km southward from a position concentric with the mouth of the Orange River may be due to transportation of the sediments by a countercurrent that flows southward beneath the Benguela Current, as indicated by its water properties (*8*).

The second feature is a large area of diapiric structures in water depths of 800 to 3000 m off Angola. Diapir-like structures have long been known from the deep ocean floor (*9*), and recently they were discovered in several geophysical traverses off Angola (*10*). Diapirs also occur on the adjacent land in the Cuanza Basin just southwest of Luanda in Angola (Fig. 4B), where they appear to have begun to rise in Albian time from Aptian and Albian (Early Cretaceous) evaporites (*11*). On this cruise of the R.V. *Atlantis II* the region of diapirs was outlined more completely than on the traverses by the previous ships, for which a study of the continental margin was incidental to other work. Altogether the 3800 km of seismic profiles within the diapir field off Angola show the field to extend from latitude 13°30′S to north of latitude 5°00′S. At these two latitudes the field is narrow compared with its width of 250 km at latitude 8°30′S. Diapirs reappear farther north in Gabon (*12*), but this diapir field is probably isolated from the deepwater one in the same way that the field on land in Angola is isolated.

The diapir field off Angola has a length of more than 1050 km and an area of at least 170,000 km^2. For comparison, the diapir field along the coast of the Gulf of Mexico in the United States (*13*) is 1100 km in length and about 350,000 km^2 in area. The Angola and Gulf of Mexico fields are similar in many other ways. Both have subaerial as well as submarine sections that extend to depths of about 3000 m, where both are marked by steep diapiric escarpments facing seaward (the Sigsbee escarpment in the Gulf of Mexico). Both escarpments rise almost 1 km above the adjacent ocean floor and extend nearly the same distance beneath the surface of the deep-ocean sediments. Also in both regions are some relatively isolated outlying diapirs, which indicate that the area of salt



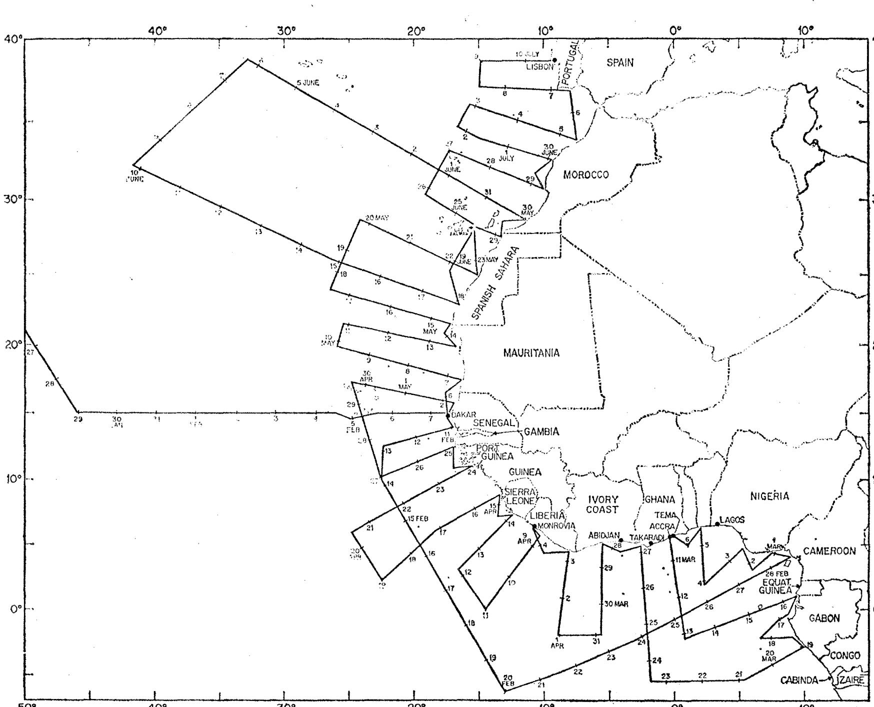
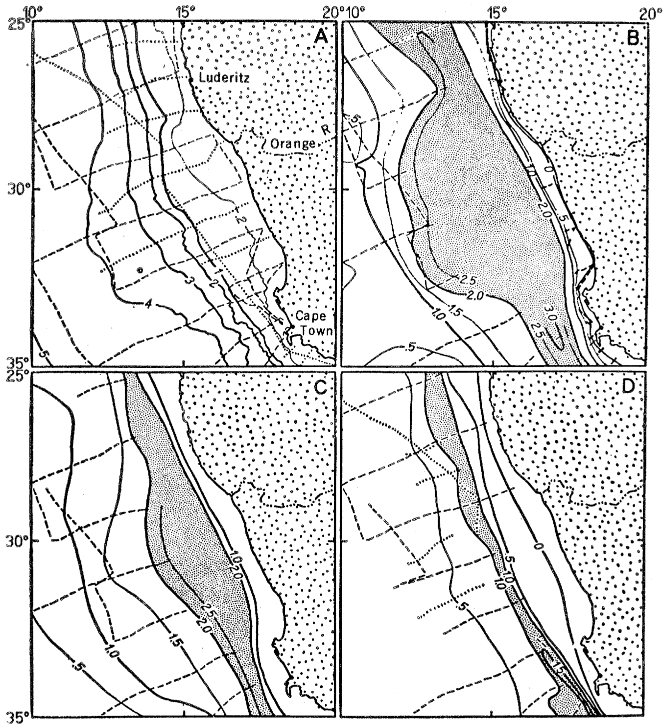


Fig. 1 (top). Geophysical traverses of the R.V. *Atlantis II* off southwestern Africa during its 1972 cruise. The cruise was part of the IDOE program to explore the continental margin of the eastern Atlantic Ocean. Fig. 2 (bottom). Geophysical traverses planned for 1973.



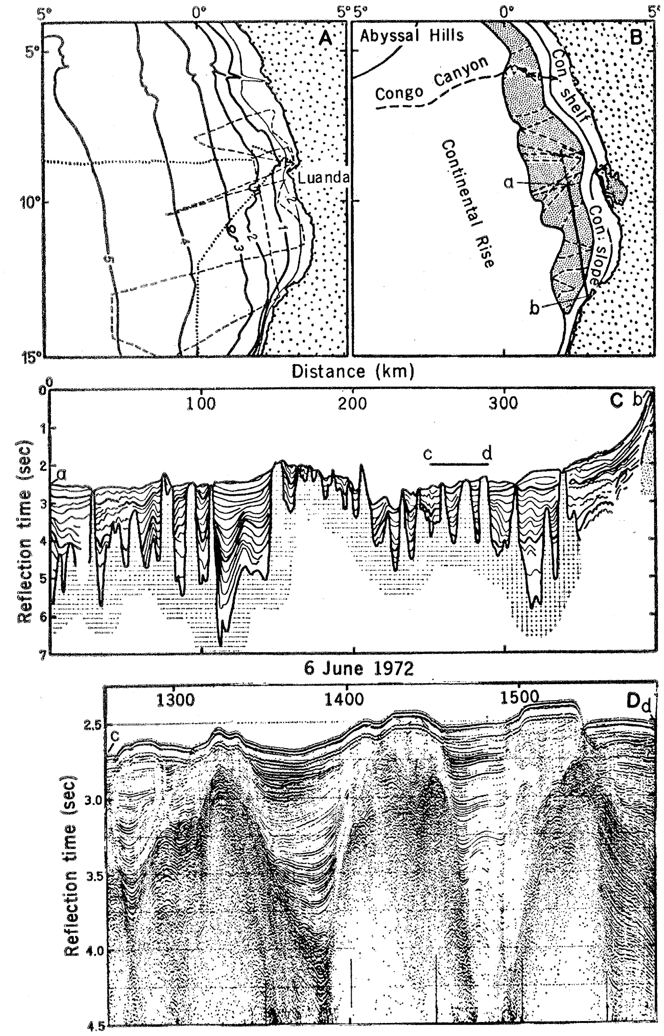


Fig. 3 (left). Ancient delta of the Orange River. (A) Bathymetry with contours in kilometers (*3*). The dashed lines denote the traverses of the R.V. *Atlantis II* in 1972; the dotted lines indicate the previous traverses of the R.V. *Chain* (data courtesy of H. Hoskins) and the R.V. *Thomas B. Davie* of the University of Cape Town (*14*). (B) Isopach map of the total sediments above the acoustic basement. Only the parts of traverses on which the acoustic basement was identified are shown. The contours are in seconds of reflection time (or kilometers if the acoustic velocity were 2 km/sec). The thickest part is accentuated by a dotted pattern. (C) Isopach map of sediments above a prominent acoustic reflector believed to be horizon A of Cretaceous to Eocene age. The symbols are the same as for B. (D) Isopach map of sediments above a prominent acoustic reflector believed to date from about the end of Paleogene times (middle Tertiary). The symbols are the same as for B. Fig. 4 (right). Diapirs off Angola. (A) Topography with contours in kilometers. The dashed lines show the traverses of the R.V. *Atlantis II* in 1972; the dotted ones show the traverses of the R.V. *Chain* in 1970. (B) Geomorphic provinces. The diapir field is dotted, with dashed lines showing all the continuous seismic reflection profiles across the diapirs made by the Woods Hole Oceanographic Institution, the Lamont-Doherty Geological Observatory, and the Scripps Institution of Oceanography (*9*). (C) Profile of diapirs and overlying disturbed sedimentary strata. The rock basement, probably Precambrian in age, is shown beneath the continental shelf at the right. The position of this north–south traverse (*a–b*) is given in B. (D) Photograph of an actual seismic reflection recording (*c–d*), whose position is given in C.

deposits is much greater than the area of the diapir fields. In both diapir fields the salt is ancient (Early Cretaceous in Angola, the Republic of the Congo, and Gabon, and Jurassic in the Gulf of Mexico). A pre-Late Cretaceous age for the submarine Angolan field is indicated by the salt escarpment having truncated the same prominent reflecting horizon (probably horizon A) that was identified in the ancient delta of the Orange River. Moreover, discontinuous fragments of this horizon are believed to be present between individual diapirs (the lower wide lines in the sediments shown by Fig. 4C). The upward movement of the diapirs has occurred throughout a long period of time, as shown by numerous unconformities and faults between individual diapirs and by the fact that the amplitude of the overlying folds is greater at depth than nearer the surface. In both the Angola and the Gulf of Mexico regions the upward movement of diapirs continues at present, as shown by the absence of horizontally bedded, ponded sediment between the individual diapirs. The subaerial and submarine diapiric fields in the Gulf of Mexico are known to be rich in oil and gas accumulations, and the subaerial part of the Angola diapiric field and its northern counterpart in Gabon are also productive, but the deepwater submarine part has yet to be tested by the drill.

The ancient delta of the Orange River and the diapiric field off Angola contain large volumes of sediment. Within the delta are probably numerous stratigraphic traps capable of retaining oil and gas if they are present, and within the diapir field are many structural traps caused by the upward movement of the salt. The landward side of both features underlies the outer continental shelf or the upper continental slope, but the major parts lie much deeper. Nearly all of both features lie within 200 nautical miles (362 km) of the adjacent coasts. While depths of more than about 100 m are too great for present economic exploitation of oil and gas, they may justify testing by the drill within a decade. Successful exploitation of the deepwater features can greatly modify the economy of the adjacent countries and broaden the petroleum supply for the rest of the world.

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15. Contribution No. 2913 of the Woods Hole Oceanographic Institution. Appreciation is due the International Decade of Ocean Exploration for funding through NSF grant 28193, and the many shipboard participants for their help. Particular acknowledgment is given the chief scientists of several of the cruise legs, Elazar Uchupi and J. D. Milliman.

2 August 1972

Ridge Transform Fault Spreading Pattern in Freezing Wax

Abstract. *A laboratory experiment shows that ridge-ridge transform faults, inactive fracture zones, and other features characteristic of spreading oceanic ridges can be produced in a variety of paraffins. Although the resultant pattern depends upon the temperature of the wax and the ratio of spreading rate to surface cooling, the characteristic orthogonal ridge transform fault system is a preferred mode of separation. Symmetric spreading occurs under conditions of no tensile strength across the ridge, and the stability of transform faults is a consequence of their lack of shear strength. The experiment also shows that properties characteristic of oceanic ridges occur under conditions of passive convection where upwelling of material at the ridge crest is a result only of hydrostatic forces in the fluid; that is, the plate separation is caused not by large convective forces beneath the ridge but rather by tensile forces in the plate.*

A fundamental problem of plate tectonics is how the orthogonal ridge transform fault pattern typical of spreading oceanic ridges has evolved and why it is maintained. The large time scales involved in the evolution of such patterns on the earth prohibit real time observation of their development. Despite the problems inherent in extrapolating the results from a laboratory model to the real earth, it is hoped that the discovery of a laboratory model which produces an orthogonal ridge transform fault pattern on a very short time scale might provide insight into ridge tectonics on the earth.

Materials ranging from sheet metal to partially melted wax have been used in laboratory models of spreading oceanic ridges. To our knowledge, no material under purely tensile stresses has given satisfactory results. Raff (*1*) obtained ridge-ridge transform faults under very restrictive conditions but was unable to find a method to keep the ridge transform pattern from degenerating. Duffield (*2*) has reported on a naturally occurring miniature version of plate tectonics found in Mauna Ulu, a crater on Kilauea Volcano in Hawaii. Although the floating basaltic plates provide some spectacular configurations of transform faults, spreading centers, and trenches, the analogy between the patterns observed in paraffin and processes active on the ocean floor seems much closer than that involving the basaltic plates and ocean floor processes.

The characteristics of spreading ridges, transform faults, and fracture zones have been given elsewhere (*3*, *4*), and only the basic features will be summarized here. In this preliminary investigation we have not obtained detailed information about the topography within the fracture zones and transform faults but have studied only the general geometrical features. In this discussion the term "ridge" has no topographic connotations and is equivalent to "spreading center." It refers only to the analogy with spreading oceanic ridges, and we have not verified that the actual topography in the wax is elevated near the spreading centers.

The relative motion of each lithospheric plate on the earth can be described in terms of a rigid rotation of the plate about a fixed point termed the pole of rotation. The relative movement of one plate away from another results in a fissure or spreading center along the boundary between the two plates. Hydrostatic pressure causes molten material from below to upwell along this spreading center (ridge crest). The material then solidifies, enlarging each plate equally (*5*). Since the hottest and therefore weakest portions of the plates remain at the center of the ridge crest, continued separation occurs there.

The ridge crest is usually offset by a number of ridge-ridge transform faults (*3*). A property which has been observed so frequently that is considered to be an "intrinsic property" (*6*) is the

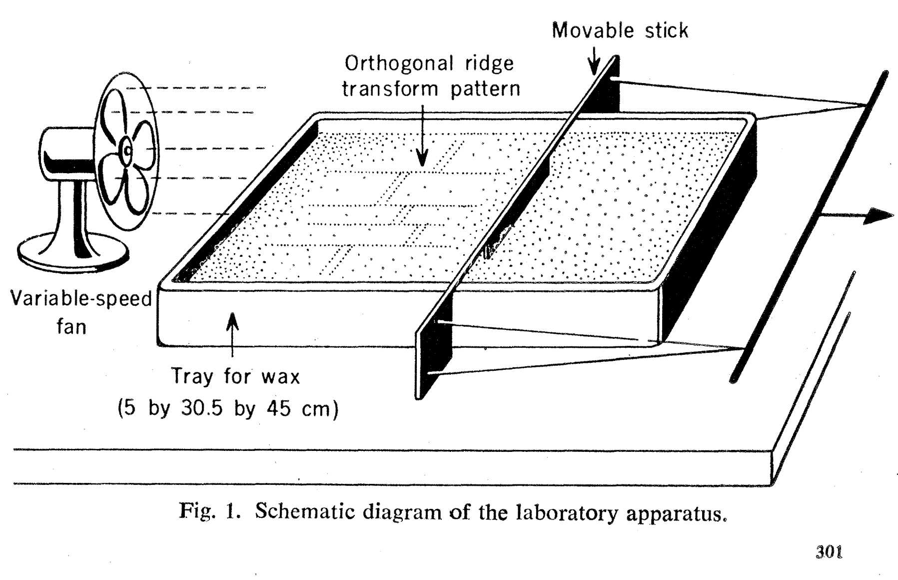

Fig. 1. Schematic diagram of the laboratory apparatus.