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Manned Submersible Observations in the FAMOUS Area: Mid-Atlantic Ridge

Volcanic and tectonic processes associated with an active spreading center have been directly observed.

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Project FAMOUS (French-American Mid-Ocean Undersea Study) was conceived three years ago, its objectives being to define the tectonic and volcanic processes associated with genesis of new oceanic crust. A small area on the Mid-Atlantic Ridge centered at about 36°50′N was selected for detailed study on the basis of scientific and logistic criteria (Fig. 1). More than 25 cruises were made to the area by surface ships from the United States, France, Canada, and England, culminating in the first manned submersible studies of a mid-ocean ridge by the French submersible *Archimède* in 1973, and by *Archimède*, *Cyana*, and the American submersible *Alvin* during the summer of 1974. The regional setting of the dive site was established by narrow-beam echo sounding, dredging, side-scan sonar and deep-tow surveys, photography, aeromagnetic surveys, and magnetic and gravity surveys from shipboard. The *Glomar Challenger*, on leg 37 of the Deep Sea Drilling Project (DSDP), drilled four holes starting about 18 nautical miles west of the dive site. The final phase of the surface ship surveys, carried out by R.V. *Knorr* concurrently with the submersible program, consisted of dredging, coring, detailed photographic and thermal surveys, and deployment of ocean bottom seismographs. In this article we present a preliminary summary and interpretation of some of the unique observations made by the manned submersible *Alvin* during the summer of 1974. Data from the surface ship surveys, most of which are yet unpublished, have contributed significantly to the success of the project and to some of the interpretations presented here. The accompanying article describes the related French program.

The submersible *Alvin* carries two scientists and a pilot; normal bottom time was 4 to 5 hours, during which time the submersible traversed from 1 to nearly 4 kilometers across the bottom. The submersible was continuously navigated in real time relative to three acoustic beacons. Precision varied with bottom conditions but was generally better than ± 5 meters. Headings were obtained by gyrocompass, with a backup magnetic system. Precise measurements of depth, height off bottom, and heading were automatically logged as a function of time; these combined with the navigation data were plotted as X, Y, Z coordinates of the track at 20- or 40-second intervals. Rock, water, and sediment samples were collected routinely and stored in a compartmented "lazy susan" basket. Nearly continuous visual records by the scientists were augmented by photographs recorded by semiautomatic external still cameras, internal still and movie cameras, and a television camera with video tape recording. The *Alvin* completed 15 dives in the median valley and two dives in Fracture Zone B (Fig. 1). Overall, *Alvin* collected about 400 kilograms of rock samples, 50 water samples, and 42 sediment samples, all precisely located relative to a 5-fathom contour map of the inner rift valley floor. Some 15,000 color and black-and-white photographs were taken, and about 140 scientific man-hours of visual observation and notes documented the 27 km of sea floor traversed.

Geologic Setting

The area selected for the prime dive site (Fig. 1) consists of a median valley segment about 20 km long, bounded on the north and south by transform faults, which are called Fracture Zone A and Fracture Zone B, respectively. The median valley floor is about 1 km wide at its center, with depths averaging about 1400 fathoms; at either end it widens to more than 8 km with depths reaching 1700 fathoms. The west wall rises abruptly within a distance of 1 to 2 km to a broad, undulating terrace with an average depth of about 1000 fathoms. To the east, the slopes rise more gradually in a series of steps to the base of the main east wall 2 to 3 km from the center of the valley. This bathymetric asymmetry is matched by a corresponding asymmetry in magnetic anomalies, with an inferred spreading rate of about 0.8 cm/year to the west and about 1.3 cm/year to the east (*1*). Within 10 to 12 km from the center of the valley, rift mountain peaks rise to depths typically about 800 fathoms. Each of the transform faults is marked by a narrow trough and by a linear zone of microearthquakes (*2*).

The center of the median valley floor is marked by a series of rugged linear hills which have been considered to be recent volcanic extrusions (*3*). Much of the submarine operation was centered around two of these hills, the French working on the flanks and to the north of Mt. Venus, and the American group working south of Mt. Venus and around Mt. Pluto (Fig. 1).

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Real-Time Events

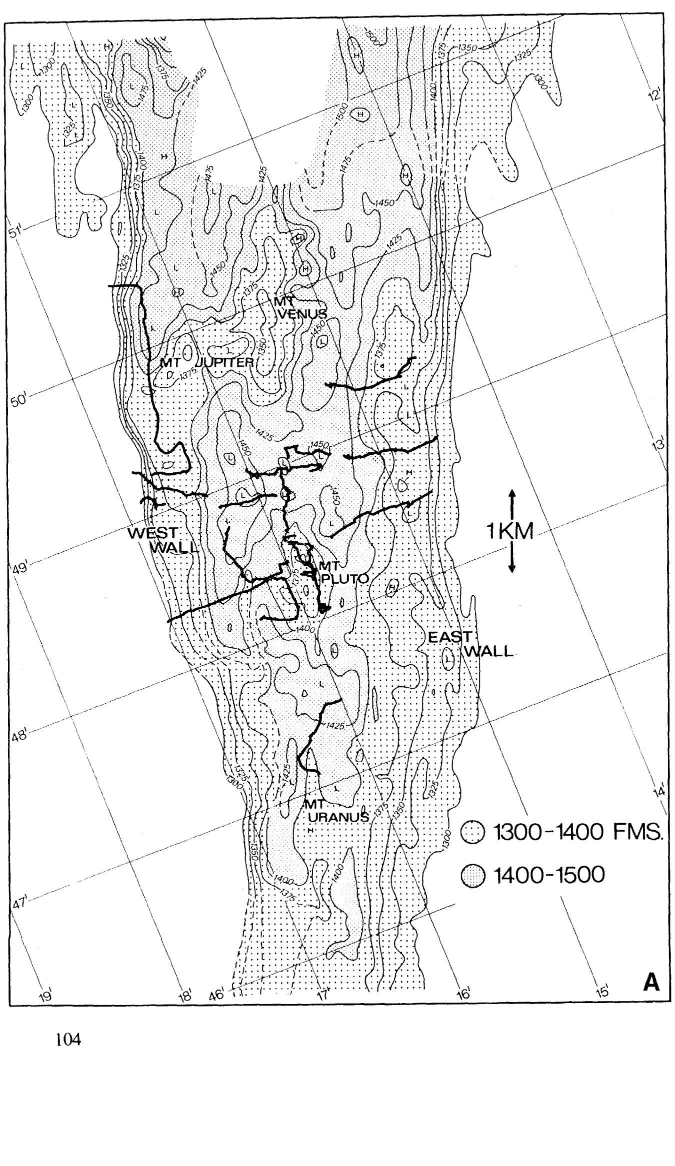
For reasons of both scientific interest and personal safety, much attention was devoted to the detection of volcanic, seismic, and thermal activity in the process of occurrence. Sonobuoy arrays were deployed on the sea surface and seismometers on the sea floor by the R.V. *Knorr* during some of the dives. Although microearthquakes were noted in the general area of the submersible, no movement of the sea floor or unusual disturbance of the sediment was observed. In fact, no evidence of ambient acoustic energy of any sort was observed in the submersible for the frequency range of about 100 hertz to 100 kilohertz for which she was instrumented. No volcanic features were seen being extruded and, as suggested elsewhere in this article, visual observation of the degree of sediment cover and attached faunal population suggested that the youngest lava forms were at least hundreds, if not thousands, of years old.

Thermal measurements of the water mass were made by *Alvin* and by probes on a camera frame used extensively from the *Knorr*. The *Alvin* probe had a resolution of about 0.01°C and observed no sea floor anomalies, either over recent volcanic forms or inside fissures. The *Knorr* probe, also with a resolution of about 0.01°C, did observe several anomalies due to entrapment of water in major enclosed basins and to small-scale water movement. It did not observe any anomalies that could be attributed to hydrothermal circulation.

Volcanic Processes

Observations confirmed that Mt. Venus and Mt. Pluto are the sites of most recent volcanic activity. The flanks of these hills consist of broad, steep-fronted flow lobes with relatively little sediment cover or attached organisms. The flow fronts consist of tubular lava extrusions elongated downslope, resembling in some respects terrestrial pahoehoe lava. On the near-horizontal upper surfaces of these flows, a variety of bulbous, pillow-like lava forms are developed (Fig. 2). Often the surfaces of these pillows are partly covered by abundant lumpy or tubular lava extrusions, which may be variously described as lava "fingers" or "toes." Some bulbous pillows are hollow, blister-like forms and are found in various stages of collapse. Many of these hollow pillows, and hollow lava tubes as well, show multiple internal, nearly horizontal "high lava marks," which indicate successive falls in lava level before final quenching (Fig. 3). These frozen-in lava levels provide a reliable guide to sample orientation for paleomagnetic studies. Other pillows display a variety of intriguing "trapdoor" extrusions, in which a broken piece of crust sits like a hat on a projecting neck of lava. The pillows and tubes are typically 30 to 100 cm in diamter, and the fingers and toes are several centimeters in diameter.

The summit of Mt. Pluto consists of a series of conical peaks 20 to 30 m high aligned parallel to the trend of the median valley. Tubular pahoehoe lava descends in all directions on the flanks of the peaks and forms a radiating pattern in the surrounding region; collapsed blister pillows are common on summits of the peaks. Similar conical peaks on a smaller scale were occasionally observed elsewhere in the median valley. They may mark the main vents that fed the principal lava flows. The summits of peaks on Mt. Pluto are remarkably con-



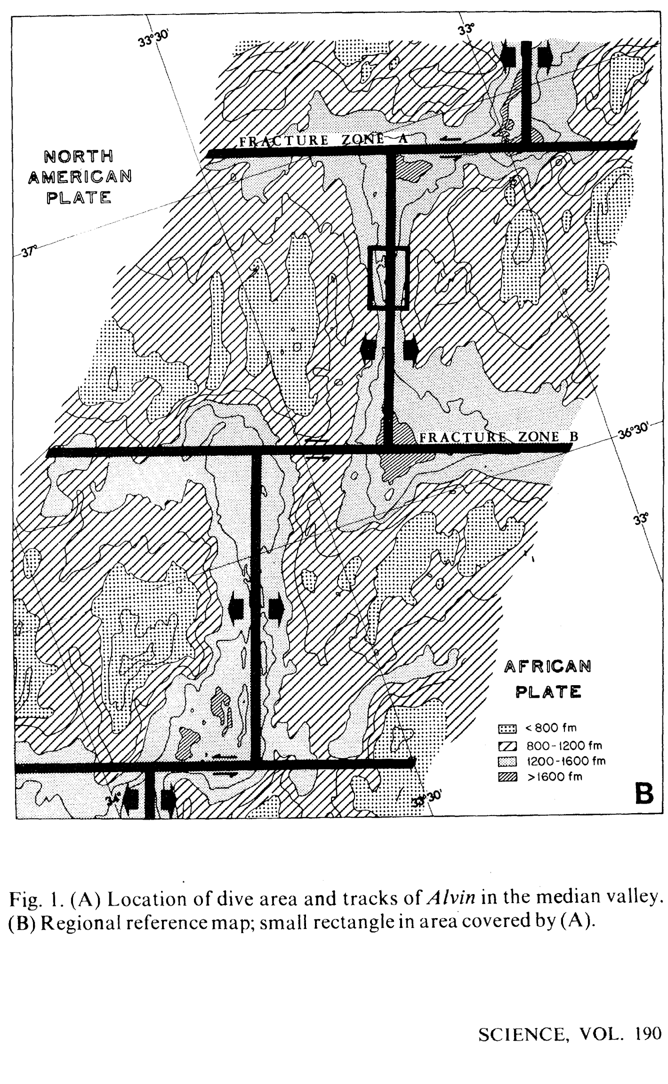


Fig. 1. (A) Location of dive area and tracks of *Alvin* in the median valley. (B) Regional reference map; small rectangle in area covered by (A).

cordant at about 1300 fathoms, suggesting that they have grown in response to a common hydraulic head of lava in a shallow magma chamber.

Large tumuli, 4 m or more in diameter, were occasionally observed on flow surfaces. Some resemble small-scale driblet cones, while others are better described as giant pillows. As on terrestrial lava flows, they appear to represent short-lived secondary centers of tumescence and extrusion.

Growth of the central volcanic hills and advancement of the lava flows appears to take place almost entirely by tumescence, fracturing of crust, budding, tumescence of the new extrusions, fracturing, budding, and so on. In fact, the large volcanic hills probably could be regarded as very large compound tumuli which have repeatedly fractured and budded to give rise to the major lava flows. The flows themselves fracture and bud down to the scale of the individual lava fingers and toes, at which point the available lava presumably becomes exhausted. Detached, subspherical pillows were rarely seen; the few examples appeared to have pulled loose from the ends of lava tubes on steep slopes, but this is not common.

Most of the recent extrusive activity appears to be restricted to vents in the median valley associated with Mt. Pluto or Mt. Venus. However, limited flank volcanism was observed on the lower walls of the valley immediately to the east and west of the valley floor. This zone of flank volcanism seems wider and better developed to the east than to the west, in harmony with the faster spreading rate to the east. However, in all traverses from the center of the valley outward to the flanks we were impressed by the rapid increase in sediment cover and bottom life and by the intense tectonic degradation to which the extrusive lava forms were subjected. Generally, within 300 m of the valley center to the west and within 500 m to the east, most of the delicate extrusive forms had been destroyed, the flows were sliced and offset by numerous faults, and the surfaces were reduced to broken, jumbled lava blocks and extensive talus fans at the base of fault scarps.

Preliminary petrographic study and analysis of rock glasses by electron microprobe have shown considerable variation in composition of the lavas, which can be related to their apparent age and position within the median valley. Table 1 shows examples of the more extreme compositions. The analysis shown in column A is typical of recent lavas from Mt. Pluto on the central volcanic axis and closely resembles that of the unusual low-TiO_2, high-MgO glass reported from DSDP sites 3-14 and 3-18 (*4*). The analysis in column B is typical of lavas on the east and west flanks of the valley, as well as of older flows near the central axis that have not been covered by the younger extrusions. This composition is more typical of basalts reported from other parts of the ocean ridge system. The regional variation in percentage by weight of SiO_2 is shown in Fig. 4; a similar variation can be demonstrated for most of the other oxides of major elements, as implied by the data in Table 1. Especially notable are the increases in FeO/MgO, TiO_2, and K_2O from the center to the margins of the median valley.

The slight asymmetry in the compositional distribution is consistent with the bathymetric asymmetry and differences in spreading rates and suggests that all of these features reflect operation of common processes at depth. The chemical variations, although subtle, are matched by distinct differences in liquidus mineral phases (microphenocrysts). As SiO_2 increases, olivine becomes less abundant, chrome spinel disappears, plagioclase becomes more abundant, and pyroxene appears. The chemical and petrographic variations are similar to those observed previously only over distances of hundreds of kilometers along the length of the Mid-Atlantic Ridge (*5*). It seems unlikely that these variations, which we observe over a distance of a few kilometers, can be related to separate mantle sources or to deep mantle processes, although transition element geochemis-

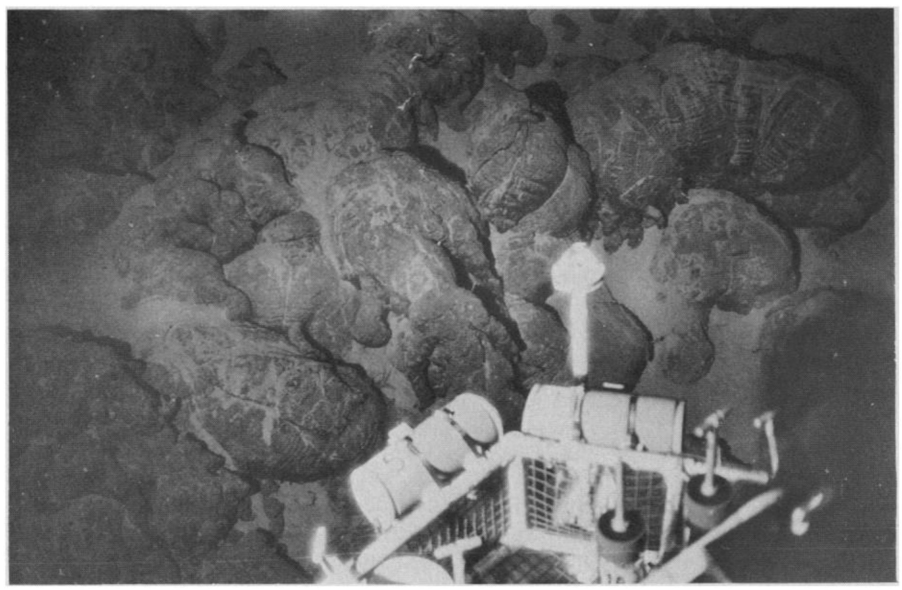


Fig. 2. Elongated bulbous and bun-shaped lava pillows. Note multiple fracturing of crust due to expansion combined with surface quenching.

Fig. 3. Layered interior of lava tube exposed at the top of the wall of a tensional fracture.

try implies separate magma types in the R.V. *Charcot* dredge samples from the FAMOUS area (*6*).

Preliminary dating of lavas based on measurements of manganese and palagonite crusts, along with our impressions of outcrop freshness based on direct observation of sediment cover and faunal abundances, indicates that at least some of the apparently differentiated flank lavas are of about the same age as lava from the central valley, although the flank eruptions are much less voluminous. This differentiation between central magma and contemporaneous flank magma is well known at Kilauea volcano (*7*) and implies the existence of a shallow, compositionally zoned magma chamber beneath the median valley (*8*). Calculations indicate that simple fractional crystallization of olivine and plagioclase, as suggested by the petrographic data, can account for most of the major element variation, although serious discrepancies remain for TiO_2 and alkalies. Frey *et al.* (*4*) showed that TiO_2 and FeO/MgO are apparently the most critical major element parameters in sea floor lavas, and any process proposed to account for compositional differences in lavas across the median valley will have to account for the simultaneous variation in these parameters.

Tectonics

In contrast to recent volcanic activity, which appears to be concentrated in a narrow central zone, recent tectonic movement is evident throughout the entire width of the inner rift valley floor. Faults and fissures are numerous, striking 020° parallel to the rift axis (Fig. 5). Locally, faults trend perpendicular to the axis, but these are few in number and are truncated by the more dominant 020° structures.

The dominance of tectonic activity is reflected in the fine-scale geomorphology of the central valley. From the west wall across the central depression between Mt. Venus and Mt. Pluto to the first major step fault of the east wall is a predominantly block-faulted terrain. Normal faulting is common, and when combined with tensional extension it yields open fissures with differential movement between the two walls. Dips range from 45° to nearly vertical, with 70° to 80° common on smaller faults. Displacements vary from less than 1 to more than 100 m, 10 to 20 m being the most common. The faulted blocks are back-tilted 5° to 7° and in some instances have rotated away from one another, producing a rubble-filled V-shaped notch.

Observations in the region of Mt. Pluto agree with those of the French on Mt. Venus to the north, that the morphology of the central topographic highs results from constructional volcanic processes, but the remainder of the inner floor to the east and west is in part shaped by tectonic forces. Even in the central region of Mt. Pluto, small postvolcanic tensional fissures occur. South of Mt. Pluto, one scissors fault was traced with displacement down to the west at its northern end and down to the east at its southern end.

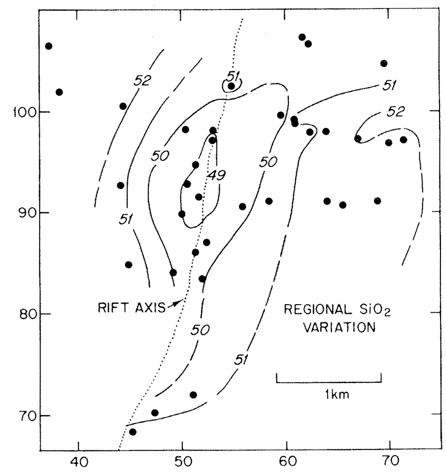


Fig. 4. Regional variation in SiO_2 content of rock samples recovered by *Alvin*. Dots are station locations for which data are available. These stations are located along the dive tracks shown in Fig. 1. Numbers are percentages of SiO_2 by weight.

The nature of fissure development was varied. The most typical feature in the central volcanic zone was a small crack 2 to 4 cm wide with no vertical displacement, striking 020° across otherwise undisturbed volcanic terrain. Small cracks traced over the young sediment-free central region may extend 50 to 100 m before being offset in an en echelon pattern. To the east and west the fissure widths vary, show vertical displacement, and may show considerable variation along strike. Beginning as 1-m openings 10 m deep, they may then be completely filled with rubble or divide to form two fissures isolating a down-dropped block. Farther to the east and west vertical fault scarps predominate over open fissures.

Table 1. Electron microprobe analyses of basalt glasses. The analysis in column A is from the west flank of Mt. Pluto, dive 525, station 5, sample 2. That in column B is from the east flank of the median valley, dive 527, station 6, sample 3.

Constituent	Percentage	
	A	B
SiO_2	48.9	51.1
TiO_2	0.84	1.42
Al_2O_3	16.1	14.9
FeO	8.74	10.1
MnO	0.15	0.18
MgO	10.5	7.89
CaO	11.8	11.8
Na_2O	2.41	2.46
K_2O	0.09	0.21
Cr_2O_3	0.09	0.08
Totals	99.62	100.14

Proceeding from the central valley toward the walls, the submarine typically passed over a series of outward-dipping faults with displacement down toward the valley walls. This outward and downward displacement is maintained even though the general bottom gradient is upward. The structure of the central valley is thus a horst with a central sag. Beyond the marginal graben, the normal faults increase in throw and become inward-dipping, as exemplified by the scarps forming the main east and west walls.

One of these inward-dipping faults was investigated during four dives on the west wall. Here, the displacement observed on two of the dives was at least 300 m, from the top of the scarp to the top of the talus. The upper 130 m of the scarp consisted of truncated lava tubes and pillows lacking any intercalated sedimentary material. These grade through an interval of 30 to 50 m into a more massive outcrop characterized by a blocky, angular surface without the elliptical outlines and radial joint patterns typical of truncated pillows. Lenticular intrusions 20 to 30 cm wide and more than 2 m long strike obliquely across the exposed surface; they are most common 15 to 50 m below the top of the massive outcrop. The total number of dike-like or sill-like intrusions observed on three dives, however, was surprisingly small—on the order of a dozen or so.

The nature of the fault zone on the west wall was strikingly different from that of the faults in the inner valley. The latter were generally clean, fresh, and free of fault breccia and fault gouge. On the lower west wall, on the other hand, the fault zone was 100 to 150 m wide, and exposed alternating, subvertical shells of fault breccia and massive basalt, dipping parallel to the face inward toward the inner rift valley floor at about 80° (Fig. 6). Elsewhere the west wall appears to have been uplifted along a series of parallel normal faults, with individual displacements of less than 100 m showing exposures only of truncated lava. The upper surfaces of these fault slices form structural terraces capped by primary volcanic material which are back-tilted 5° to 7°. Major talus fans develop at the base of these scarps and, in many cases, on the back-tilted surfaces of the fault blocks.

The faulting appears to be a continuing process with repeated episodes of displacement. Narrow fissures cut across individual pillow forms with no disruption oth-

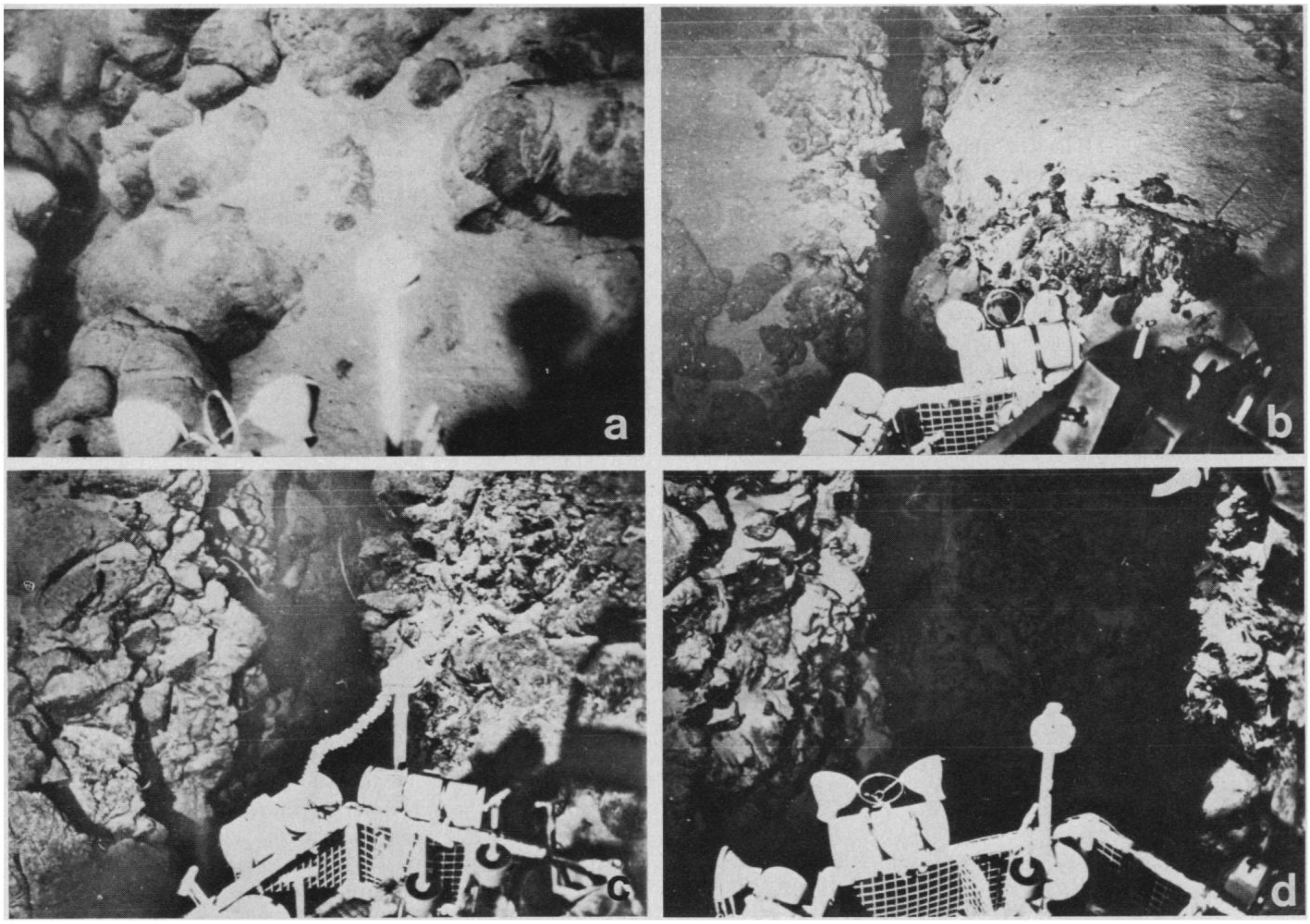


Fig. 5. Varieties of minor and major tensional fractures, increasing in size from (a) to (d). In (d), the submarine is about 8 m into the fracture.

er than a single plane of failure. Broken pillows on opposite sides of fissures up to 1 to 2 m wide can usually be visually matched, and indicate mainly dilation with minor vertical displacement. Coherent pillow forms preserved in the fault scarps sometimes made it difficult to determine whether the slope was a fault scarp or a primary flow front. Renewed tectonic activity along older fault planes is indicated by faulted lithified calcareous sediments, a few centimeters to a meter in thickness, overlying the older pillow surfaces.

During the diving operations, more than 50 fault scarps were inspected. In no instance were sediments found interbedded with the igneous rocks. It was common, however, to see sediments accumulated in open fissures. Since tectonic activity dominates in the older flanking region, where sediments have had a greater time to accumulate, open fissures may represent the primary avenue by which sediments enter the geologic section.

Two dives on the north and south sides of the active transform section in Fracture Zone B encountered heavy sediment cover in the topographic trough and on its walls. This cover consisted of a semiconsolidated blanket of calcareous sediment draped over the terrain, with only local exposures of weathered basalt talus or greenstone. On the north side of the transform, there was minor shearing and tilting of sediment and igneous rocks. No mafic or ultramafic rocks were recovered, although dredging on the topographic saddle to the south has recovered serpentinite, pyroxenite, and veined greenstone. No thermal anomalies were observed from the submarine, although many of the dredged greenstones are strongly fractured and brecciated, and are traversed by vuggy veins containing both calcite and aragonite which may be due to hydrothermal circulation.

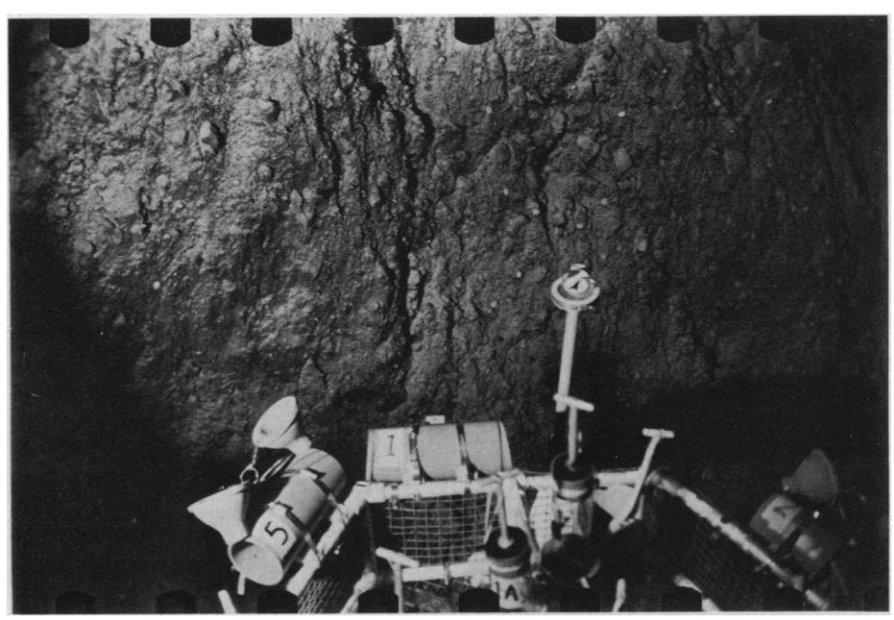


Fig. 6. Brecciated and vertically striated basalt on the west wall of the median valley.

Summary

Lava forms resemble those observed on terrestrial pahoehoe lava flows; the features that appear in truncated fault scarps as circular or elliptical pillows are elongated, tubular forms in three dimensions. Detached, subspherical pillows are very rare. The lavas show systematic chemical and mineralogical variation, with the olivine basalts associated with the central volcanic highs and plagioclase-pyroxene basalts being typical of the west and east walls. Active volcanism is mainly restricted to a narrow (0.5 to 1 km wide) central zone in the median valley.

The central valley has a horst-like structure which is bounded by graben at the base of the east and west walls. Intrusive sills and dikes are exposed only at the base of one 300-m scarp on the west wall. Most fault displacements are less than 100 m and expose only breccia, truncated lava pillows, and tubes.

In general, faulting appears to be a continuing process, while volcanic activity is episodic. Structural deformation rapidly degrades the primary volcanic morphology typical of the central highs, although volcanic features are locally preserved on the wider structural terraces on the west and east flanks of the median valley. Dives in Fracture Zone B revealed minor deformation of recent sediment cover, but there was no evidence of recent volcanic or hydrothermal activity.

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Transform Fault and Rift Valley from Bathyscaph and Diving Saucer

Observations by earth scientists at the bottom of the sea shed new light on the geology of plate boundaries.

ARCYANA

The FAMOUS (French-American Mid-Ocean Undersea Study) program was designed to conduct an integrated and detailed geological, geophysical, and geochemical study of a portion of plate boundary where new oceanic crust is generated and where some processes leading to the formation of the oceanic lithosphere may appear more clearly (*1*). The originality of the program was to include the use, for the first time, of precisely navigated, manned research submersibles in the latter phases of the work at sea and thus enable methods of classical field geology to be applied to the study of the deep ocean floor. Collection of data on a scale ranging from centimeters to kilometers was demanded by the narrowness of the surface expression of the plate boundary.

The study area lies along the boundary between the North American and African plates, southwest of the Azores archipelago in an area where a segment of rift valley 40 km long, 30 km wide, and 1.5 km deep, oriented approximately 020°, is offset by two active fracture zones (transform faults) striking east-west. It had been demonstrated before the first dives were made that the deepest part of the rift valley or inner floor accommodates along part of its length an elongated hill or central high 200 m high and 1 km wide (Fig. 1), and it was suggested that the central high, although not necessarily an entirely constructional feature, was the major locus of the most recent accretion of new surface crust (*2*). The purpose of the first diving phase, which was undertaken with the bathyscaph *Archimède* in 1973, was to test this hypothesis and to show that useful geological mapping from submersibles was possible even in the very rough terrain of the rift valley (*3*).

The second phase of diving was carried out in the summer of 1974 with *Archimède* and the diving saucer *Cyana* and had three main objectives. The first was to extend the 1973 survey in order to map and sample across the transition from features near the axis of the inner floor, which we knew to be at least partly attributable to primary volcanism, to the deepest features of the walls flanking the inner floor, which we presumed to be essentially of tectonic origin (box I, Figs. 1 and 2). This structural and petrological section of the inner floor of the rift valley was to be compared with a section investigated by the American team immediately to the south, in a location where no clearly developed central high was present.

Although transform faults are satisfactorily explained on kinematic grounds, their morphology and geology, which provide important constraints for ridge crest mechanical models, have not been adequately described. Therefore, the second objective of the dives was to study the median portion of transform fault A, which offsets the rift valley segment about 20 km in a dextral sense. There, according to magnetic anomalies (*2*), crust on either side of the valley should be about 1 million

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ARCYANA is a collective name, based on the names of the submersibles *Archimède* and *Cyana*, for Jean Francheteau (geophysicist), Roger Hékinian (petrologist), Xavier Le Pichon (geophysicist), and David Needham (marine geologist), Centre Océanologique de Bretagne, B.P. 337, 29273 Brest; Pierre Choukroune and Paul Tapponnier (structural geologists), Laboratoire de Géologie Structurale, Université des Sciences et Techniques du Languedoc, Place Emile Bataillon, 34000 Montpellier; Gilbert Bellaiche (marine geologist), Laboratoire de Géologie Dynamique, Centre National de la Recherche Scientifique (CNRS), La Darse, 06230 Villefranche-sur-Mer; and Jean-Louis Cheminée (volcanologist), Laboratoire de Géologie Dynamique, CNRS, 4 Place Jessieu, 75230 Paris-Cedex 05.