Ophiolites

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The crust of the earth under the oceans is different from the crust of the continents. Ophiolites seem to be fragments of oceanic crust on land. They are thus clues to how oceanic crust forms and spreads

by Ian G. Gass

Plate-tectonic theory proposes that oceanic crust, which forms some 70 percent of the earth's solid surface, has been and is being constantly created at the axes of oceanic ridges and rises. Thereafter, by the processes of sea-floor spreading, it moves away from these axes and ultimately plunges into the earth's interior along subduction zones. Since the oceanic crust has this built-in self-destruct system, no part of the present oceanic crust is much more than 200 million years old. In contrast, the continents, being lighter than oceanic crust, are not easily subducted and move passively over the face of the earth in response to sea-floor spreading and plate-tectonic processes. Indeed, continental rocks preserve evidence of earth history going back almost four billion years.

Occasionally a fragment of oceanic crust, instead of being subducted, is preserved at the leading edge of a plate that rides over a subduction zone. To describe this process Robert G. Coleman of the U.S. Geological Survey has coined the term obduction: the reverse of subduction. Coleman has also calculated that less than .001 percent of all oceanic crust has been obducted and remains on dry land. Small though these remnants are, they provide unique information on the processes currently operating under the axes of oceanic ridges and rises. They also yield clues to the evolution of ancient oceans, the mechanisms of collisions between plates and the position of ancient destructive plate margins, and they strongly suggest that plate-tectonic processes have been active for at least the past billion years. These on-land fragments of oceanic crust are known as ophiolites.

Like many other geological terms "ophiolite" has since the advent of plate tectonics taken on a new meaning and significance. Even before this latest revolution in earth science, however, the meaning of the term evolved with changes in the understanding of geological processes. The term first appeared in the geological literature in the 1820's, when Alexandre Brongniart of France coined it to describe rocks also known as serpentinite or serpentinized peridotite: a type of igneous rock usually found in areas deformed by tectonic processes. "Ophiolite" is derived from the Greek *ophis,* meaning snake or serpent; therefore it has the same meaning as serpentinite. Both terms are appropriate only in that both the rocks and some reptiles have a mottled green appearance. Other than demonstrating the addiction of European geologists to the classical languages, "ophiolite" had little significance and was used in an ad hoc way throughout the 19th and early 20th centuries to describe serpentinized peridotites and the rocks commonly associated with them.

In the 20th century there were two major changes in the usage of the term. In 1906 Gustav Steinmann of Germany noted the close association of serpentinized peridotite with other igneous rocks and deep-water sediments (such as radiolarite) in the Alpine fold mountains around the Mediterranean. Later, in honor of this outstanding geologist, the association of serpentinite, radiolarite and pillow lavas (lavas erupted under water) became known as the Steinmann Trinity. Then, through common usage, "Steinmann Trinity" and "ophiolite" became synonymous. In other words, "ophiolite" no longer referred to one kind of rock but to an assemblage of related rocks.

Steinmann particularly emphasized the association between deep-water sediments and the serpentinite and the pillow lavas. Others developed this lead and proposed that ophiolites were masses of igneous rock emplaced in geosynclines: huge linear depressions in the earth's crust that become filled with sediments. Some workers believed the igneous rocks were intruded into the layers of sedimentary rock as sills (horizontal intrusions); others saw them as immense balloons of magma (molten rock) erupted onto the surface of the sediments along the flanks of the geosyncline.

It was visualized that once the balloon had erupted its skin chilled and fractured and was invaded by dikes (vertical intrusions) from the balloon's still-molten interior. Thereafter pillow lavas erupted onto its surface. As the molten interior crystallized, the heavier minerals settled to produce layered peridotites and overlying layered gabbros.

Here I must pause briefly to define what is meant by terms such as "peridotite" and "gabbro." In this context they apply to the rocks of the oceanic crust and the underlying uppermost part of the earth's mantle. The uppermost part of the mantle is thought to be formed of peridotite, a rock that consists almost entirely of the magnesian minerals olivine [$(Mg,Fe)_2SiO_4$] and pyroxene [$Ca(Mg,Fe)Si_2O_6$]. Also present, however, is dunite, a rock that consists almost entirely of olivine.

The oceanic crust is formed of rocks, such as basalt and gabbro, that are somewhat richer in silica (silicon oxides). Basalts are fine-grained; gabbros, having crystallized more slowly, are coarse-grained. Both, however, consist

OPHIOLITE ON THE ARABIAN PENINSULA is represented by the dark-colored mountains running from the upper left to the lower right in this Landsat picture of northern Oman. The body of water at the upper right is the Gulf of Oman, which connects the Persian Gulf and the Indian Ocean. The mountainous area is known as the Samail nappe. Light-colored area to the left of the dark-colored ophiolite is continental rocks, mainly limestones; they are underlain by granitic rocks of the Arabian continental plate. The dark color of the ophiolite results from the abundance of basalts, gabbros and peridotites, rocks characteristic of the oceanic crust and the underlying mantle of the earth. The small patches of red along the coast and in other areas are vegetation, which appears red because of the arbitrary color coding of the wavelengths detected by the sensors carried on the Landsat satellite. The Landsat image data have also been further processed by computer in order to enhance the image. The processing was done by the Earth Satellite Corporation. The field of view in the picture is 130 kilometers across.

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of the same minerals: olivine, pyroxene and plagioclase ($NaAlSi_3O_8$–$CaAl_2Si_2O_8$). Basalts form the upper one to 2.5 kilometers of the oceanic crust (exclusive of the overlying sediments), gabbros the lower 3.5 to 6 kilometers.

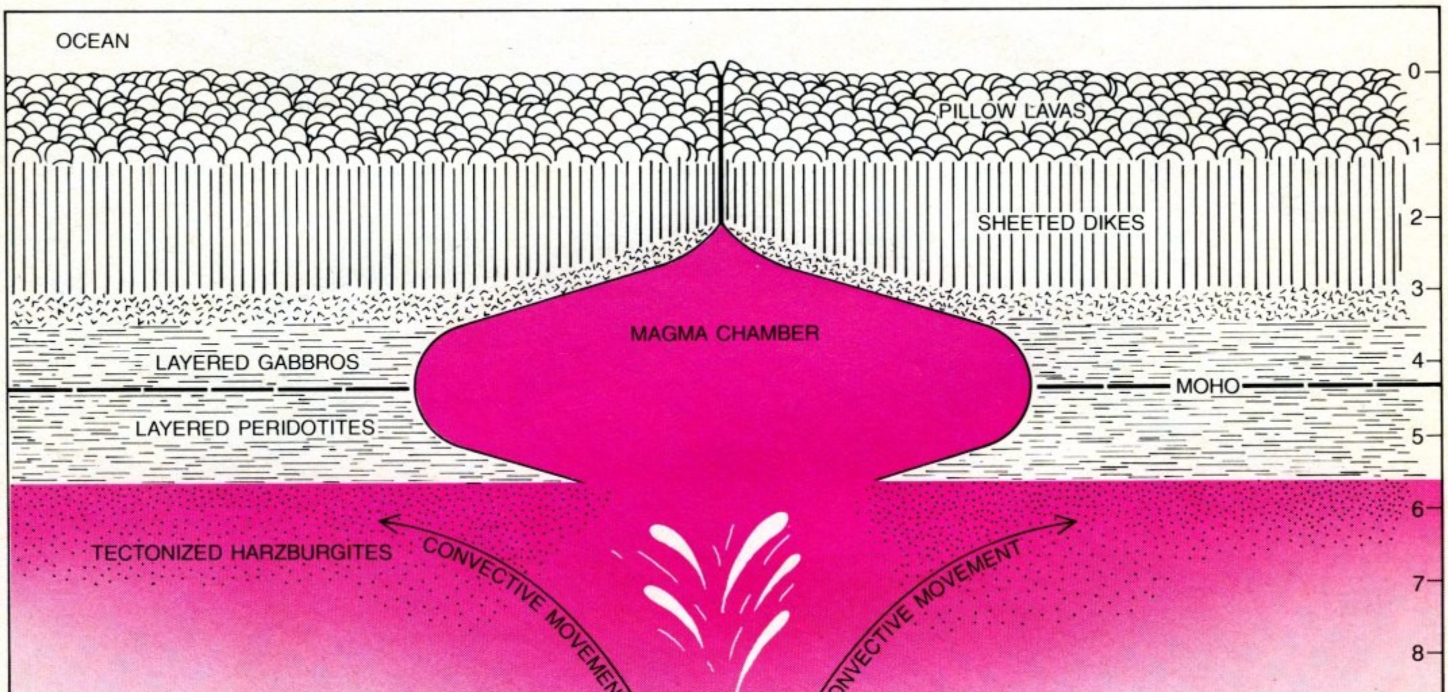
To return to the geosyncline model of ophiolites, it developed in the 1930's, 1940's and early 1950's and remained the consensus among geologists until the mid-1960's. The essence of the model is that ophiolites were interpreted as being the result of magmatism during the initial stage in geosyncline development. They were therefore in situ (autochthonous) igneous rocks and, whether they were intruded as sills or erupted, they were interleaved with the sedimentary rocks of the geosyncline. It is this basic concept that has changed. Today almost all ophiolite masses are regarded as being allochthonous, that is, they were formed elsewhere and were transported tectonically to their present position.

The model now widely accepted is that an ophiolite is a fragment of oceanic crust formed at the axis of an oceanic ridge or rise, moved across the ocean floor by sea-floor spreading and finally lifted above sea level. Concurrently with this switch from an in situ to a transported origin for ophiolites the concept of the geosyncline, which once dominated the geological literature, has been virtually abandoned.

The complete change in ideas on the origin and significance of ophiolite complexes was brought about by a variety of investigations. First it was demonstrated that virtually all ophiolites are allochthonous, having been brought in contact with the adjacent rock formations by tectonic processes. Second, detailed studies of ophiolites in the eastern Mediterranean, particularly the Troodos massif on the island of Cyprus, showed that their internal structure was not compatible with their having been formed in situ in a geosyncline; it could be realistically explained only on the basis of magmatic processes operating at oceanic ridges and rises, where new oceanic crust is generated. Third, it was noted that in each of the eastern Mediterranean ophiolites the same rock sequence could be recognized and could be compared with layers in the sea floor deduced from geophysical evidence. Fourth, it was shown that ophiolite rock types were similar to those of rocks that had been dredged from the deep-sea floor.

The similarity of ophiolite sequences to one another and to oceanic sequences and the comparability of oceanic and ophiolitic rocks (demonstrated by Nikolas I. Christensen of the University of Washington and Matthew H. Salisbury, now at the Scripps Institution of Oceanography) led to the general acceptance of ophiolites as fragments of oceanic crust formed at oceanic ridges and rises. Since then it has been common practice to use ophiolite data to clothe the necessarily meager skeleton of oceanographic data on oceanic-ridge-and-rise structures. This view became widely accepted in the 1970's, but even so when those attending the Geological Society of America's Penrose Conference on ophiolites undertook to redefine the term in 1972, they stressed that it should be applied only to a particular rock association and should not have any connotations of origin.

A complete ophiolite, such as the relatively undeformed ophiolite of the Troodos massif of Cyprus, is an orderly sequence of rock types. In most instances the processes of obduction have disrupted the originally coherent mass and have spread parts of the ophiolite over a large area. The component parts of such a dismembered ophiolite can often be fitted back together by unraveling the tectonic jigsaw puzzle. It is easier, however, to study relatively undeformed ophiolites such as the Troodos



SCHEMATIC CROSS SECTION OF OCEANIC CRUST is based on ophiolite studies. In the middle is the axis of an oceanic ridge or rise. At the top of the crust (except for a thin layer of sediment that is not shown) are pillow lavas: lavas that have flowed out onto the ocean floor from a high-level magma chamber. Below the pillow lavas are sheeted dikes: vertical slabs that were originally intruded at the axis of the ridge or rise and were then moved outward along with the spreading sea floor. Below the sheeted dikes are coarse-grained, unstructured gabbros representing melts that crystallized against the roof of the magma chamber. Crystallizing within the chamber are layered gabbros and peridotites; the "Moho" (for Mohorovičić discontinuity) is the boundary between them. Below the layered peridotites are tectonized (deformed) harzburgites. As the pressure decreases upward the peridotite of the mantle begins to melt and the basaltic liquid so formed collects into balloonlike masses called diapirs. As the diapirs rise with the convecting mantle the mineral olivine precipitates out of them, but the liquid remaining in the melt escapes upward to replenish the magma in the high-level chamber.

massif and the Samail nappe in the Sultanate of Oman on the Arabian peninsula. Therefore it is on these studies that much of the following generalized description is based.

Starting from the top and going down, most ophiolites are overlain by marine sediments. In some instances, as with the Cyprus and Oman ophiolites, the sediments are deep-water ferromanganoan mudstones or radiolarites. In others the sediments are similar to those on continental shelves or adjacent to arcs of volcanic islands. Therefore they indicate that the oceanic crust, from which the ophiolite was derived, must have been near the margin of a continent or of an island arc at some stage of its history. More than anything else these sediments provide evidence on the environment of the ophiolite within an ocean basin before it was lifted above sea level; in this regard studies such as those of Alistair Robertson of the University of Edinburgh and Alan Gilbert Smith of the University of Cambridge have proved particularly valuable.

The top of the ophiolite proper consists of extruded basalts. Many of these rocks have the pillow forms characteristic of lavas that have erupted under water. Indeed, such lavas have been filmed in the act of formation by divers during a submarine eruption off Hawaii. Pillow lavas have also been repeatedly identified by manned and unmanned submersibles investigating the floor of the axial rift of the Mid-Atlantic Ridge and the axial zone of the East Pacific Rise.

Some lava pillows are nearly spherical; others are more elongated and might better be termed bolsters. The form of the pillows probably depends on the configuration of the sea floor onto which the lava is erupted. On steep slopes the melt forms globules that roll down the slope and accumulate at the base. The elongated pillows probably form on gentler slopes, where the lava flows downslope for some distance before solidifying. When the lava is erupted in hollows or on flat surfaces, it is unlikely to be pillowed, and unstructured layers of varying thickness seem to form.

Pillow lavas are known to form in very deep water, in shallow water and even where lavas erupted on land flow into water. How much water was above them at the time of their formation is indicated by their content of gas vesicles, or bubbles. Such vesicles are formed when the gas dissolved in a molten rock separates from the melt as the pressure is lowered. If the pressure of the overlying water is sufficiently high, however, the gas does not separate and no vesicles form. By measuring the vesicularity of basalts from known depths James G. Moore of the U.S. Geological Survey has shown that there is a crude

PILLOW LAVAS are seen in the Wadi Jizzi of the Samail nappe in Oman. These elongated pillows, which are more like bolsters, were probably erupted over a gentle slope on the ocean bottom and flowed for a short distance from the top right to the bottom left before solidifying.

SHEETED-DIKE COMPLEX is seen in the Samail nappe. Each dike, originally an intrusion of molten rock, is a vertical sheet of rock. Each was intruded upward along the axis of an oceanic ridge or rise. The outward convective movement of the underlying mantle (*see illustration on opposite page*) produces tension, and when a tension crack opens, magma from the chamber escapes upward and another dike is formed. The dikes are on the average one meter thick. Therefore the sea floor spreads in one-meter jumps every 50 to 100 years rather than in the smooth one to two centimeters per year visualized in the models of theoretical geophysics.

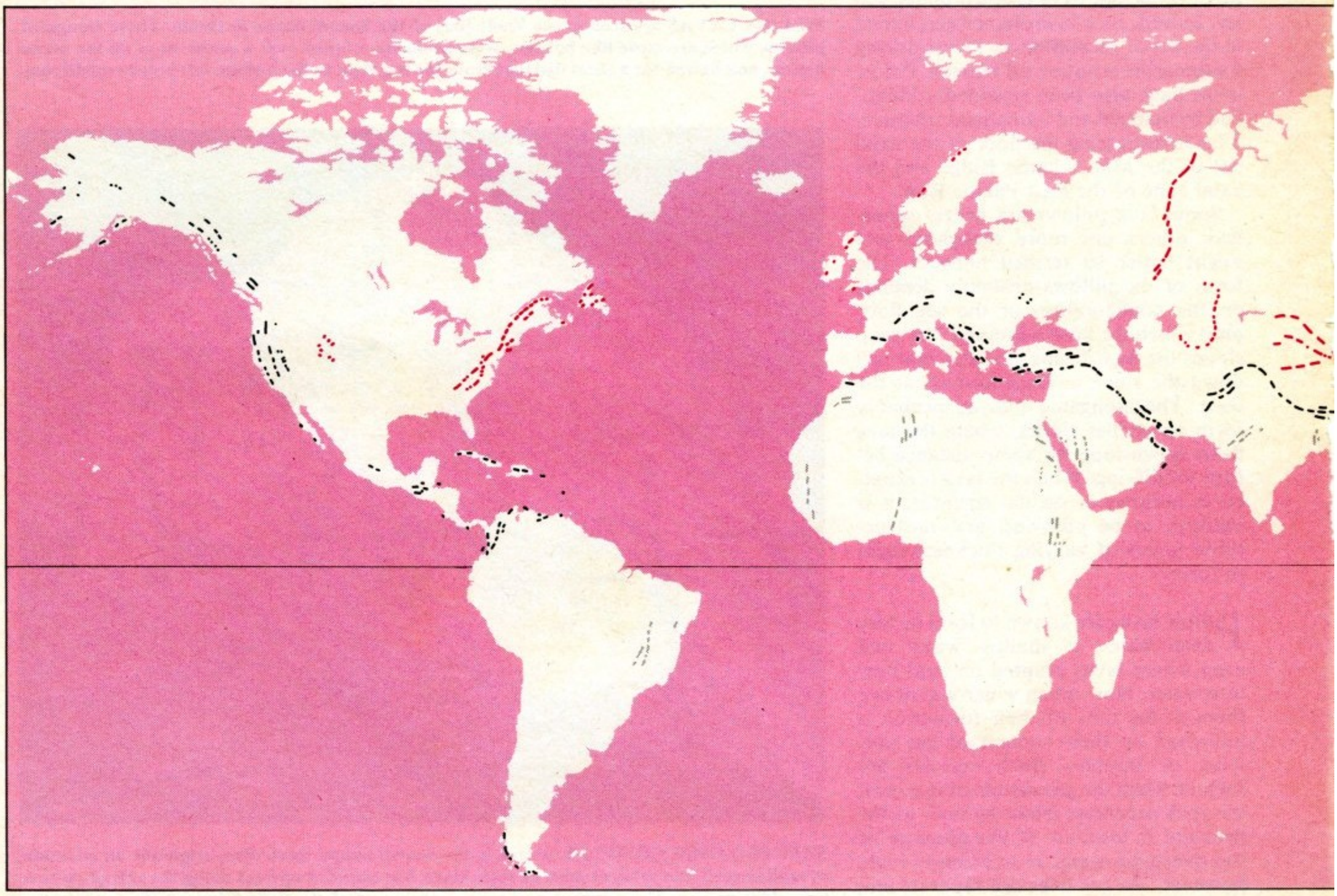
correlation between the depth below the surface of the water at which a lava was erupted and the vesicularity of the lava; with increasing depth (pressure) the vesicularity decreases. This can give only an approximate estimate of the depth because the abundance of the gas in the magma varies. Moreover, sea-floor spreading can move a lava to a depth other than the one at which it was erupted. Still, vesicularity is a further clue to the origin of ophiolites at oceanic ridges and rises.

Most of the lavas in ophiolites are basalts, similar to those dredged from present-day oceanic ridges. In Oman, however, it is only the lower part of the pile of lavas and the dikes under it that resemble the oceanic-ridge basalts in chemical composition. The upper part of the lava sequence differs geochemically from the lower, and Julian A. Pearce and Tony Alabaster of the Open University in England have convincingly demonstrated that these upper lavas were erupted in an island-arc environment later than the main event of sea-floor spreading. In Cyprus all the lavas have a composition comparable to that of volcanic rock erupted above a subduction zone.

The top of the lava pile consists entirely of extruded rocks. Farther down dikes become increasingly numerous. Many of the dikes are sinuous and seemingly had to wriggle their way upward through the lava pile. The thickness of the lava pile varies, but in the Troodos massif it is about one kilometer and in Oman it ranges between .5 kilometer and 1.5 kilometers. Near the base of the sequence the ratio of dikes to lavas is about 1 : 1; then, within a downward distance of 50 to 100 meters, the abundance of dikes increases from 50 to 100 percent and there is little or no lava between them. Moreover, the disposition of the dikes is not sinuous but a regular and often almost vertical array. Indeed, this part of the ophiolite has been likened to a pack of cards standing on edge. It has been termed the sheeted-dike complex.

In the 1950's, before the advent of plate tectonics, it was the sheeted-dike complex that presented the main conceptual problem in ophiolite studies. Nowhere else had a rock complex consisting entirely of dikes been found. In classic fossil volcanic areas such as the Hebridean province of northwestern Scotland the abundance of dikes with respect to the total outcrop is less than 10 percent. Therefore the search was always on for the host rock in which the dikes had been emplaced. Any rock that looked slightly different was studied in detail; the commonest contenders as host to the dikes were structureless flows of basalt. No one, as far as I am aware, then thought of the possibility that there was no host rock at all. Only after the 100 percent dike structure of the sheeted-dike complex had been demonstrated in the undeformed and well-exposed Troodos massif was it sought and identified in more deformed masses.

When the plate-tectonic model was proposed, it was quickly realized that the axis of an oceanic ridge or rise was just the place where a 100 percent dike complex would form. The current concept is that most of the dikes are injected along a narrow zone, no more than 50 meters wide, at the axis of the ridge or rise and that the dike material is moved away from the axis by sea-floor spread-

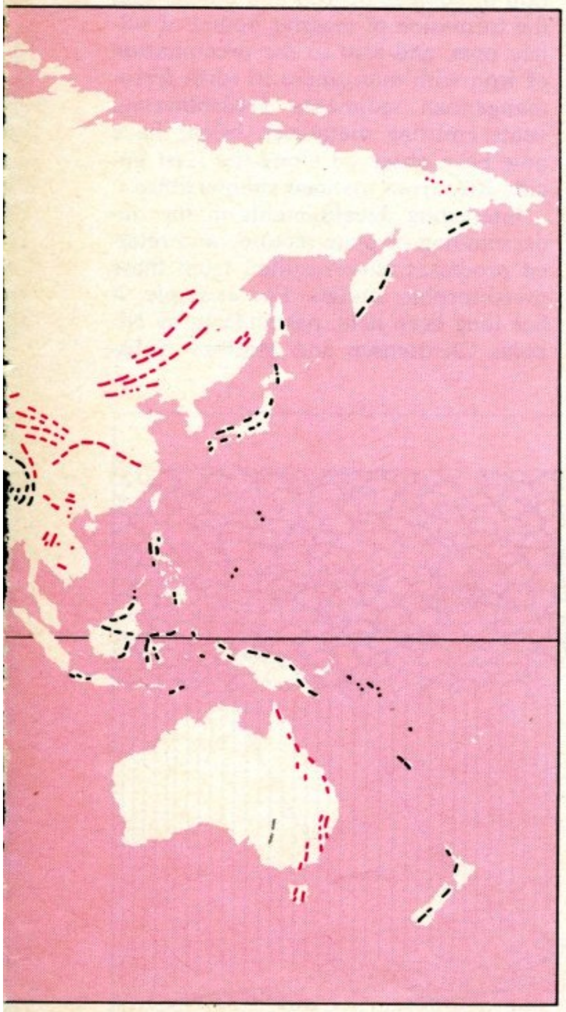


WORLDWIDE DISTRIBUTION OF OPHIOLITES is given on this map. The lines in black are ophiolites less than 200 million years old. The lines in color are ophiolites between 200 and 540 million years old. The lines in gray are ophiolites between 540 million and 1.2 billion years old. The younger ophiolites are those related to the present cycle of plate tectonics. They include the ophiolites emplaced around the Pacific, and all are close to the sites where oceanic crust is being subducted. The next-oldest ophiolites (running along the Appalachians, north into Nova Scotia and Newfoundland and continuing into Ireland, Scotland and Norway) mark the closing of the Iapetus Ocean

ing. Recent studies of sheeted-dike complexes, unencumbered by preconceived geological ideas, show that this part of an ophiolite complex does consist of 100 percent dike.

Johnson R. Cann and Rupert G. W. Kidd, working at the University of East Anglia, identified within the dikes the phenomenon of one-way chilling, which can be explained as follows. Magma being injected into a fissure in cold rock will form a dikelike body. The melt will cool most rapidly, and will therefore form the finest-grained rock, where it is in contact with the cold host. Cann and Kidd recognized that in the Troodos massif many dikes, instead of having two chilled margins, have only one. In addition, more of the chilled margins were on one side of the dikes than the other; this is the phenomenon of one-way chilling.

Cann and Kidd proposed that at an oceanic ridge magma would tend to be injected along the still liquid or softer axis of an earlier dike and so would split the two halves of the earlier dike, with one half moving in one direction and the other half in the opposite direction. On each side of the ridge the dikes would show a preferential one-way chilling on the side farther from the ridge axis. On this basis it has been inferred that the oceanic ridge where the north-south dikes of the Troodos massif formed lay to the west of the present-day outcrop. It should be emphasized that the statistical excess of one-way chills in one direction over those in the other is small and also that continuous outcrops with a statistically valid number of dikes are found only rarely. One-way chilling is an attractive concept and one that seems intuitively acceptable, but it is by no means proved.



in the Paleozoic era. The ophiolites in the U.S.S.R. also mark a Paleozoic plate-collision suture. Not all the ophiolites marked have been positively identified. For example, most ophiolites in China are not well described.

Although the sheeted-dike complexes are the best evidence that ophiolites formed along zones of tension in oceanic ridges and rises, such complexes are not always present. For example, in the Voúrinos ophiolite in Greece, as it has been described by Eldridge M. Moores of the University of California at Davis, sheeted dikes are poorly developed. It has been suggested that sheeted-dike complexes form only when sea-floor spreading is slow enough to allow a dike to solidify before the next one is injected. Since oceanic crust cools rapidly and seawater is percolating through all this material, the explanation is questionable. Moreover, the Oman ophiolite, the fossil of an oceanic ridge where the sea floor spread in both directions at the high rate of two centimeters per year, has a superb sheeted-dike complex. Although the absence of sheeted-dike complexes from some ophiolites remains a geological problem, it is worth noting that many ophiolites originally described as being without a sheeted-dike complex have been found on closer examination to have one.

The dikes of a sheeted complex must have come from an underlying source of magma. It is therefore not surprising to find that with depth the basaltic dikes give way, over a distance of between 10 and 100 meters, to gabbroic rocks that have a similar composition but a markedly coarser-grained texture. Detailed mapping of these plutonic complexes (igneous rocks formed well below the surface) suggests that the uppermost gabbros, which form a layer between 10 and 300 meters thick, were formed by the melt cooling and crystallizing against the roof of a chamber from which the magma flowed toward the surface. Below this layer the gabbros and the underlying peridotites, if there are any, are markedly layered. Until recently it had been widely accepted that the layering was the result of the minerals' crystallizing out of the melt and then settling to the bottom of the magma chamber.

Alexander R. McBirney and Richard M. Noyes of the University of Oregon have proposed an alternative mechanism as a result of studying the classic layered gabbros of Skaergaard in eastern Greenland. They suggest that gradients of chemical composition and heat cause minerals to crystallize out of the melt along horizontal planes within it; no movement of the crystals is needed to account for the layering. Whether the crystals settle or form layers in place, however, the inference of the layered plutonic rocks is that there is a large body of magma below the surface along the axis of an oceanic ridge or rise. Work on the Troodos massif by Cameron R. Allen of the University of Cambridge has suggested that along this slow-spreading (one centimeter per year) axis there were numerous magma chambers four or five kilometers in diameter. For the faster-spreading (two centimeters per year) Oman ophiolite the magma chambers seem to have been some 20 kilometers in diameter.

The evidence of these layered plutonic rocks is that below the axis of the oceanic ridges there were magma chambers whose dimensions depended essentially on the input of heat into the ridge from the underlying mantle of the earth and on the rate of cooling brought about by sea-floor spreading. But do these layered rocks represent a single body of magma crystallizing completely or, as seems intuitively more likely, was the magma body fed periodically from below? Studies by E. Dale Jackson of the U.S. Geological Survey on the Voúrinos mass in Greece, by Cameron Allen on the Troodos massif and by John D. Smewing and Paul Browning of the Open University on the Samail nappe in Oman show that in all these ophiolites the melt was periodically replenished by new batches of magma.

These workers, analyzing separate ophiolites, have shown that the layered sequences consist of repetitive cycles starting with dunite and giving way upward to peridotites and then to gabbros. The cycle starts again and is repeated many times throughout the layered sequence. The inescapable conclusion is that the composition of the melt in the main chamber was reset periodically by a fresh influx of magma.

At the base of all complete ophiolite sequences is a tectonized (deformed) peridotite consisting almost entirely of the minerals olivine and orthopyroxene [$(Mg,Fe)SiO_3$]. Peridotites of this composition are called harzburgites, and so they are described as tectonized harzburgites. The chemical and mineralogical homogeneity of the tectonized harzburgites suggests that they represent material of the uppermost part of the mantle from which basaltic liquid has been extracted. This proposal is supported both by the presence within the harzburgites of gabbro pods that are best explained as batches of basaltic melt that crystallized before they could escape from the mantle and by localized patches of peridotite of a different composition (lherzolites) that probably represent remnants of mantle from which little or no basaltic magma had been extracted.

Most workers accept that the tectonized harzburgite represents depleted mantle, the residue from which basaltic melts have been extracted to form the overlying rocks: from the bottom up the layered plutonic rocks, the sheeted-dike complex and the sequences of lavas. The model proposed to explain these features is that at depths of 25 or 30 kilometers basaltic magma first separates from the mantle. The two components, the magma and the harzburgite, move upward under the influence of convection in the mantle.

The rising magma collects into balloonlike bodies called diapirs, one kilometer to five kilometers in diameter. The diapirs move upward with the ascending mantle material, and as they do so olivine crystallizes out of the melt to form a crystal layer at the bottom of the diapir. The melt escapes into the main magma chamber but the olivine remains in the mantle as lenses of dunite within the tectonized harzburgite. Although the harzburgite is hot, it remains solid. Therefore it is deformed as it moves upward and then outward under the axis of the oceanic ridge or rise.

The available evidence suggests that the newly formed oceanic crust is transported by this convective movement in the underlying mantle. Detailed investigations, particularly those of Adolphe Nicolas and his colleagues at the University of Nantes, support that view. They also demonstrate that the deformation took place at about 1,000 degrees Celsius and imposed a linear fabric, perpendicular to the orientation of the overlying ridge axis, on the tectonized harzburgite.

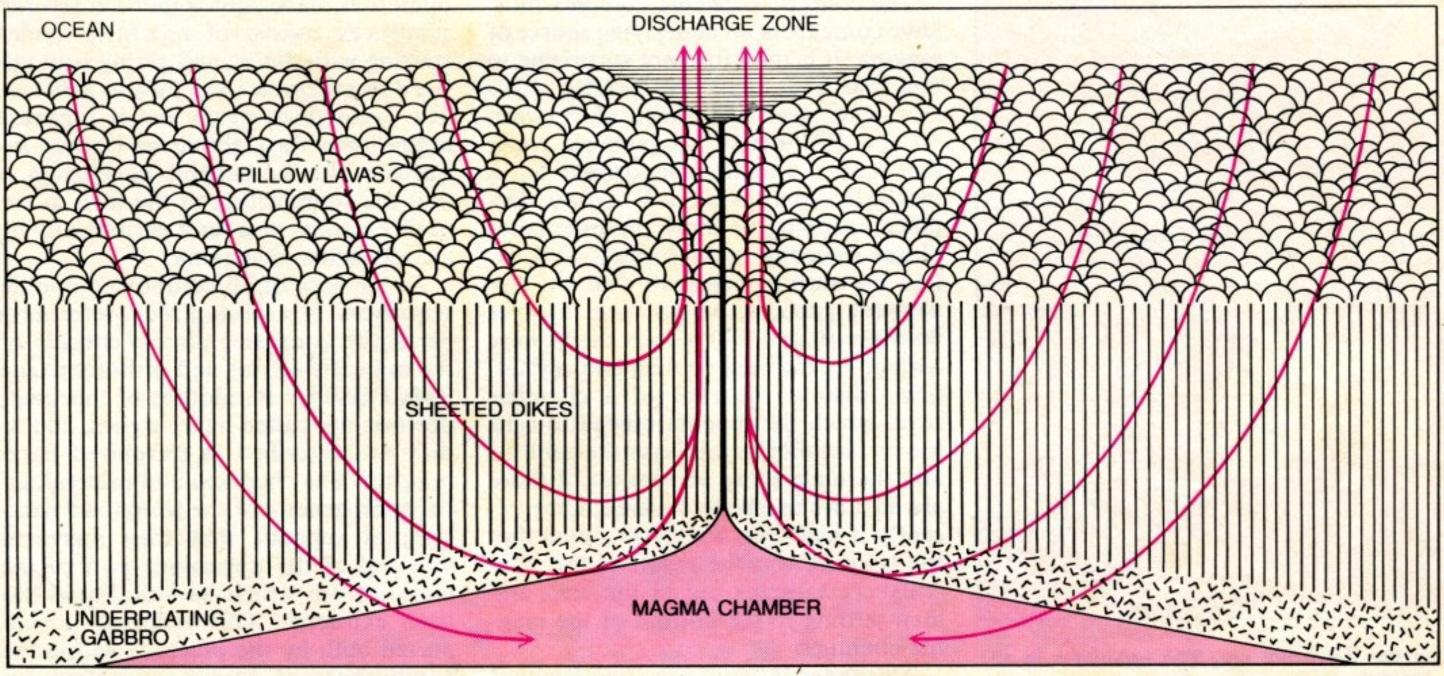
Ophiolite studies have thus revealed much about the structural and magmatic features at fossil oceanic ridges and rises. What else do they reveal about the oceanic crust? Oceanic ridges and rises are repeatedly (on the average of every 30 kilometers) offset by fractures. These fractures, known as transform faults, make it geometrically possible for rigid plates to move over the face of a nearly spherical earth. Even if ophiolites represent only .001 percent of the subducted oceanic crust, one of them, if it preserves more than 30 kilometers of oceanic ridge, is also likely to preserve a transform fault. Indeed, transform-fault structures have been investigated on Cyprus by my former colleague Kapo Simonian, on Masirah Island in Oman by Ian Abbott and Frank Moseley of the University of Birmingham and in western Newfoundland by John F. Dewey and his colleagues at the State University of New York at Albany. The features displayed by these structures at various levels revealed by erosion enhance the understanding of present-day transform faults.

Another feature of ophiolites also relates them to oceanic crust: their metamorphism, that is, the fact their rocks have been greatly altered since they originally formed. Virtually all igneous rocks dredged or drilled from oceanic crust away from the axes of oceanic ridges and rises have been metamorphosed. These oceanic metamorphic rocks, unlike most continental metamorphic rocks, show no directional fabric. Therefore they were altered without the deformation that commonly accompanies continental metamorphism.

Since the metamorphic processes operated while the ophiolites were part of the oceanic crust, and since there are no directional fabrics, the main agent of metamorphism must have been heat. The main source of heat is the underlying magma. The metamorphic processes involved the circulation of seawater through newly formed, still-hot oceanic crust with a thermal gradient in excess of 150 degrees C. per vertical kilometer. The water is believed to circulate by convection in a single-pass cycle, with the permeable rocks of the oceanic crust being recharged with water continuously over a wide area and discharging water above thermal highs.

The convecting seawater leaches metals out of the oceanic crust and also redistributes silicon and other elements. In returning to the surface the metal-enriched fluids are channeled along faults, and so the emission of the fluids into seawater is localized. In favorable sheltered locations, such as depressions in the sea floor, chemical reactions between the hot, metal-enriched brines and the seawater lead to the precipitation of sulfides of iron and copper and the formation of massive bodies of sulfide ores, and also to the precipitation of iron with manganese to form ferromanganoan sediments. Hydrothermal vents emitting metal-rich brines have now been observed along the East Pacific Rise from manned submersibles.

Interesting developments in the understanding of plate-tectonic and related processes have resulted from these metamorphic studies. For example, it has long been held, particularly by Nikolas Christensen and Matthew Salis-



SEAWATER INFILTRATES HOT SEA FLOOR in the immediate vicinity of the spreading axis. The water is heated as it moves through the newly created oceanic crust and incorporates those elements that go readily into solution. The hot and now enriched brines return to the surface of the ocean bottom along fracture zones. The dissolved elements are precipitated out where the hot water reenters the ocean.

bury, that the horizontal layering in the oceanic crust, identified through the velocity of earthquake waves, is a metamorphic phenomenon and that the change from the velocity characteristic of the second layer from the top (5.07 kilometers per second) to the velocity characteristic of the layer below it (6.69 kilometers per second) represents the change from one type of metamorphism to another. Certainly in ophiolites the change from the dike complex to gabbros occurs at about the same level as a change in the type of metamorphism. Both changes could influence the earthquake-wave velocities of the oceanic crust.

So far we have been concerned with the structure, composition and metamorphic features of ophiolites and what they tell us about oceanic geology. There is a separate question raised by ophiolites. If they represent oceanic crust formed at oceanic ridges and rises, how are they emplaced near the destructive plate margins adjacent to continents and island arcs? It is to this process that the term obduction is applied. The actual processes of obduction are poorly understood, and further consideration of the term and its implications is needed.

Almost as soon as the processes of plate tectonics were proposed the term subduction came into the geological literature. The word is from the Latin *sub,* under, and *ducere,* to lead. Hence "subduct" literally means "to lead under." "Ob-" rather than "sub-" implies that the movement is in a direction or manner contrary to the usual one. Therefore obduction implies a movement contrary to subduction, a movement over rather than under. It also implies an upward movement of the oceanic crust, and just how this movement comes about is a puzzle.

The simplest explanation of the on-land presence of ophiolites is to regard them as fragments of oceanic crust attached to a continent or to an island arc. As a result of the subduction of oceanic crust seaward of the eventual ophiolite, both the continent or island arc and the oceanic crust attached to it are underlain by a subduction zone. For the oceanic crust to be exposed as an ophiolite it must be lifted above sea level. This can happen in any one of several ways.

If the subducting plate is oceanic, it will take water down into the mantle in water-bearing metamorphic minerals such as zeolites and amphiboles. On being subducted these minerals will be heated and will release water, which will convert some of the peridotite in the overlying mantle into serpentinite. The serpentinization of the peridotite increases its volume and makes it lighter, so that it tends to rise. The process contributes to the uplift of the overlying crust and mantle.

Alternatively, if the potential ophiolite is underthrust by continental crust, the presence of lower-density continental rocks at depth will upset the normal equilibrium and cause uplift. In 1963 David Masson-Smith of the Institute of Geological Sciences and I, investigating variations in gravity over the Troodos massif, proposed that this ophiolite was lifted above sea level by the underthrusting of continental crust. The process was intensified by the rise of a mass of serpentinite under what is now the center of the massif. Similar mechanisms involving the underthrusting of an eventual ophiolite by an oceanic plate are favored by my Open University colleagues working in Oman to explain that ophiolite and by Daniel E. Karig of Cornell University to explain the Zimbales ophiolite in the Philippines.

Support for the underthrusting mechanism comes from the study of the metamorphic rocks under ophiolites. Many ophiolites, notably those of Newfoundland and Oman, are underlain by a thin layer of metamorphosed rocks separating the ophiolite from the underthrusting material. These metamorphic rocks were formed in a zone where the temperature was highest (about 600 degrees C.) immediately adjacent to the overlying ophiolite. The temperature diminished rapidly with depth, so that only a few hundred meters below the top of the zone the rocks are unmetamorphosed. The metamorphic agent here is probably a combination of heat emanating from the overlying slab of oceanic crust and frictional heat generated by the downward movement of the subducting plate. In these instances the assemblages of metamorphic minerals and their disposition are best explained by the continuous subduction of an oceanic plate.

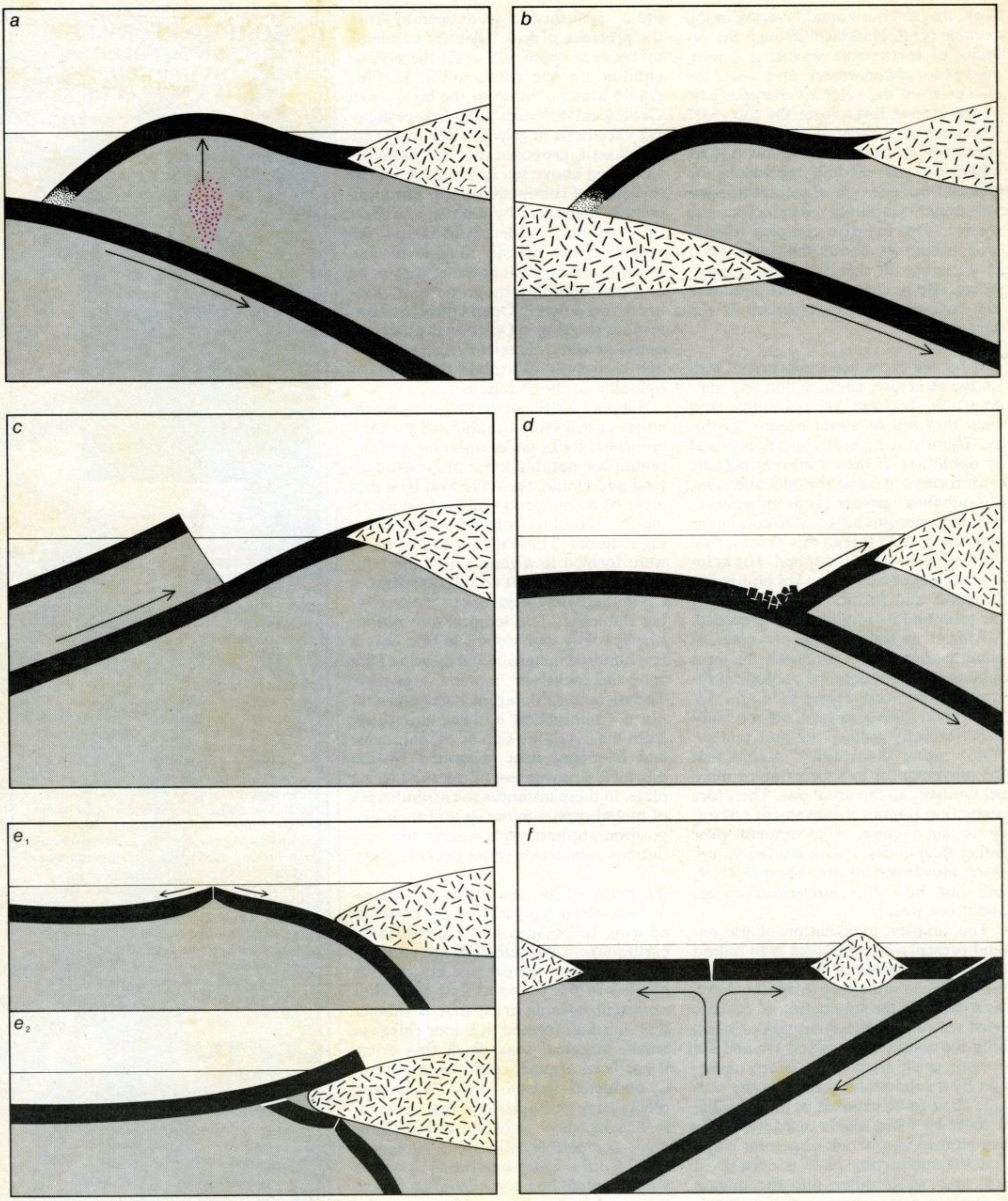
In many of the less deformed ophiolites the rock layers that are correlated with the oceanic layers identified by earthquake-wave velocities are markedly thinner than the oceanic layers. This has led to the proposal that ophiolites represent oceanic crust that is thinner than normal, formed at minor ridges in small, marginal seas. Such thin crust, it has been argued, could be more easily obducted. Indeed, Julian Pearce and others have demonstrated that ophiolitic basalts show geochemical features most compatible with their being derived from a water-bearing melt whose water content had come from an underlying subduction zone. Moreover, the age of an ophiolite and the time of its emplacement are commonly very close together, and so it has been suggested that the oceanic crust formed first gets emplaced as an ophiolite before the conveyor belt of the subduction process gets well under way. This too could explain the thinness of an ophiolite layer.

Other factors, however, are not easily compatible with this simple model. There is no doubt that most ophiolites are in contact with underlying rocks of continental origin. In some instances it can be proved that it is the fragments of oceanic crust that have moved over the continental rocks. A classic case is the emplacement of the Papua–New Guinea ophiolite, which, as it has been described by Hugh L. Davies of the Australian Bureau of Mineral Resources, Geology and Geophysics has been emplaced southward along a thrust zone inclined to the north. This zone, unlike all others around the Pacific, is inclined seaward; it is one of the few cases where the term obduction may be appropriate.

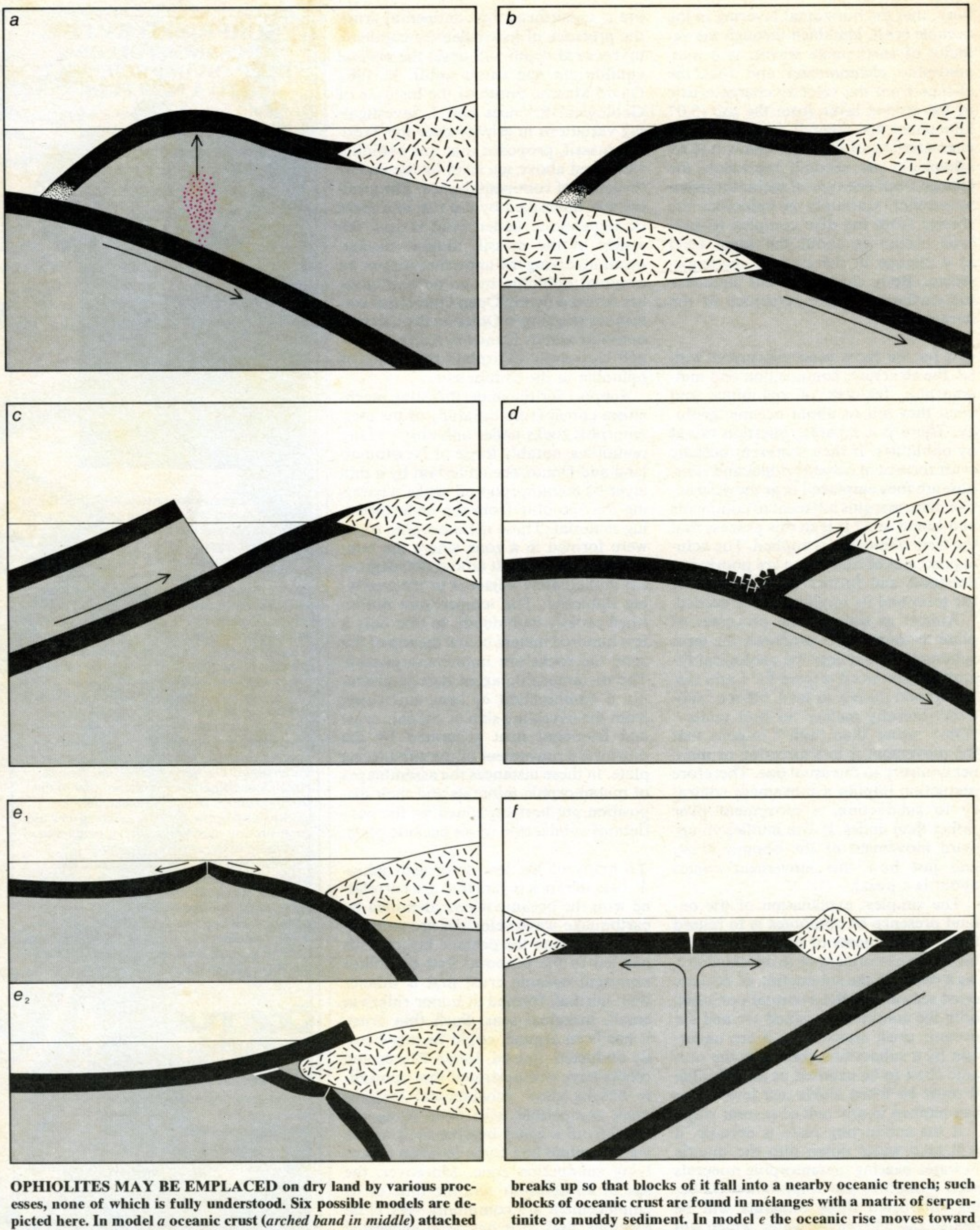
In other instances blocks of oceanic crust, often many kilometers across, are found in a mélange, embedded in a matrix of serpentinite or muddy sediment. In these instances it seems most likely the blocks of oceanic crust were detached as the oceanic plate buckled and fractured before it was subducted. The blocks detached by the process fell into an adjacent deep oceanic trench. Such trenches are the main surface indication of a subduction zone.

The term "obduction" is therefore a troublesome one. It is nonetheless useful as long as the complexities involved are kept in mind. What may be more to the point is that in the present cycle of plate tectonics (there have been other cycles in the past) ophiolites are found mostly at or near subduction zones. Hence their presence can be taken to indicate the proximity of fossil destructive margins. This association has been applied successfully in geological reconstructions of Mesozoic and Lower Palaeozoic terrains by Robert Coleman, John Dewey and Alan Gilbert Smith, among others.

"Ophiolite" too is a somewhat troublesome term for on-land fragments of oceanic crust. Certainly the term has changed its meaning. In geology before the emergence of plate tectonics an ophiolite was associated with the initial stages in the development of a geosyncline; it consisted largely of serpentinite and had been metamorphosed in the course of a cycle of mountain building. The Troodos massif shows none of these features, and in the 1950's, when it was first being studied in detail, it was not even considered an ophiolite. Then by the early 1970's it became apparent that there were enough structures like the Troodos massif for them to need a collective label. Many of the complexes that were already called ophiolites turned out on reexamination to have the same structure; hence it was perhaps inevitable that the label ophiolite was retained. The term was, however, given a new and far more precise meaning. Today most earth scientists accept that ophiolites are on-land fragments of oceanic crust formed at oceanic ridges or rises, and with this consensus the time seems ripe to accept the term ophiolite, however inappropriate it may seem.



OPHIOLITES MAY BE EMPLACED on dry land by various processes, none of which is fully understood. Six possible models are depicted here. In model *a* oceanic crust (*arched band in middle*) attached to a continent or to an island arc (*lens-shaped body at right*) has been uplifted when other oceanic crust is subducted under it. Water from the subducted oceanic crust alters the mantle material (peridotite) above it into one that is less dense and therefore lifts up the overlying oceanic crust. In model *b* continental crust is subducted under oceanic crust; since the continental crust is lighter than the overlying material, it tends to rise and in so doing lifts anything above it. In model *c* oceanic crust moves upward (*arrow*) along a zone inclined away from the continental mass. In model *d* oceanic crust fractures and breaks up so that blocks of it fall into a nearby oceanic trench; such blocks of oceanic crust are found in mélanges with a matrix of serpentinite or muddy sediment. In model *e* the oceanic rise moves toward a subduction zone (e_1). Since the crust is thin over the magma chamber (*see illustration on page 110*), the part of the crust away from the subduction zone (to the left of the spreading axis), instead of being subducted, is sufficiently buoyant to ride up over the continental margin (e_2). In model *f* a more regional picture is depicted. It is believed most ophiolites represent oceanic crust produced by sea-floor spreading in a marginal sea above a subduction zone. Emplacement of the ophiolite at the margin of a continent or an island arc could result from any of these processes or a combination of them.



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Ian Gass at retiral Symposium,
Walton Hall, 20 Apr 1991.
OUGS Member #1

(Photo by Bill Marshall-Roberts, Student A004115X, OUGS Member #13)

THE INDEPENDENT
Saturday 17 October 1992

OBITUARIES

Professor Ian Gass

THE SCIENTIFIC revolution completed at the close of the 1960s transformed dull and boring Geology into dynamic Earth Sciences. In Britain, the coincidental setting up of the Open University provided Ian Gass with the clean slate he needed to found a department of world renown, in both teaching and research.

Based at Walton Hall in Milton Keynes, the heart of the UK's largest and most distinctive university, the Department of Earth Sciences reaches out to an entirely part-time, adult undergraduate student body scattered the length and breadth of Britain, Northern Ireland and, increasingly, beyond. It was Gass's department until he stepped aside in 1982 and, having survived problems of health which would surely have defeated lesser mortals, he finally succumbed to another stroke just one year after his retirement from a Personal Chair in 1991. He was Emeritus Professor in Earth Sciences at the time of his death.

Born in Gateshead in 1926 and educated first at the Royal Grammar School, Newcastle upon Tyne, and then in Huddersfield, Ian Gass always maintained that his ancestral home was a pile of crumbling stones somewhere in Perthshire. After service in the Army towards the end and in the aftermath of the Second World War, he entered Leeds University, where he graduated BSc in 1952. His principal mentor there was W.Q. Kennedy, famed for his fundamental geological work in the Scottish Highlands and who provided inspiration and vision for a succession of students. Gass subsequently graduated MSc 1955, PhD 1960 and DSc 1972, all at Leeds University.

Thus encouraged by Kennedy, Ian Gass joined the staff of the Sudan Geological Survey in 1952, moving to the Cyprus Geological Survey in 1956 where he served until 1960. His years as a survey geologist laid the foundation for his remarkable achievements in later life as a teacher and researcher, as it did for Kennedy and has done for so many other notable geologists. Specifically, the island of Cyprus caught his imagination and enabled him later to formulate his ideas, first published in *Nature* in 1968, that there is to be seen in Cyprus a fragment of old ocean floor, caught and pushed up between the colliding continents of Africa and Eurasia to the north. Many of Gass's scientific publications, around 100 in total, concern the intriguing rocks to be found in the ancient oceanic crust, collectively termed ophiolites, and with which his name will always be associated.

Leaving the life of a survey geologist, Ian Gass had the great good fortune to spend a year as Assistant Lecturer in Geology under Peter Sylvester-Bradley, F.W. Bennett Professor in the infant University of Leicester. He thus came under the spell, albeit briefly, of one of the most remarkable heads of department ever to grace the university scene. Attracted back to Leeds by Kennedy, Gass spent the 1960s first as Lecturer, then Senior Lecturer in Geology.

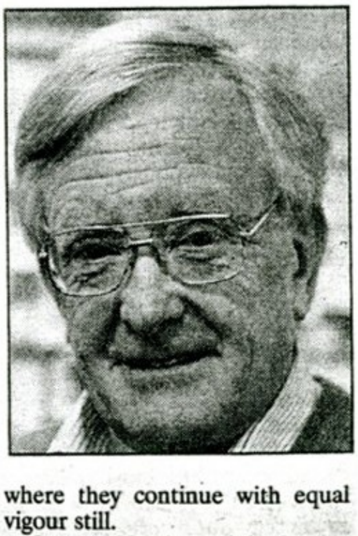
At Leeds, Kennedy had established in 1955 a Research Institute of African Geology which he directed until his retirement in 1967, when he was succeeded by Robert Shackleton. The 1960s were thus productive years for Gass in his research effort, no doubt fuelled by his common cause with both Kennedy and Shackleton. In 1962, he led the Royal Society expedition to Tristan da Cunha, following the eruption and subsequent evacuation of the tiny population on that remote outpost in the South Atlantic earlier that year. In 1970 was published a major text of 461 pages, *African Tectonics and Magmatism*, co-edited with Tom Clifford.

The story of the conception and birth of the Open University is now well known. Following Harold Wilson's public utterance in Glasgow in 1963 and Jennie Lee's role as political midwife, Walter Perry, then Vice-Principal of Edinburgh University (now Lord Perry), was appointed as the Vice-Chancellor and other foundation posts were quickly filled. Fortunately for science, Mike Pentz, a larger-than-life character if ever there was one, was chosen to be Dean and Ian Goss as foundation professor designate of Earth Sciences. By this time, April 1969, it should be noted that the decision had already been taken at Leeds University to change the name of the Department of Geology to the Department of Earth Sciences, the first in the UK so to do.

Gass launched himself and the people he appointed as colleagues into a fury of activity in temporary accommodation on a building site at Walton Hall. The faculty's Science Foundation Course was delivered on time in 1971, comprising Earth Sciences along with Physics, Chemistry and Biology. Even the lengthy postal strike that year failed to stop delivery of that innovative course in mass scientific higher education. Between March and December 1970, Ian Gass, Peter Smith and Chris Wilson conceived, edited and produced *Understanding the Earth*, a text of 355 pages which was to have a major impact round the world. It seems astonishing now to recall that this "little book" published by Artemis Press and so described later by the physicist P.M.S. Blackett (Lord Blackett), was designed as an accompanying Reader to the Science Foundation Course.

Gass immediately adapted to the new teaching environment of the Open University. As well as in written course-materials, he excelled as a teacher on television. His love/hate relationship with the BBC became legendary but he inspired confidence through the medium of television, bringing a subject of enormous interest and fascination in to the homes of many. Geology is not an easy subject to convey to others, but his television programme on the Tertiary Central Igneous Complex of the Isle of Skye, for example, won major awards.

Right from the start, the Open University decided to hold residential, one-week Summer Schools for all students in host institutions around the country. There are no prizes for guessing the location of the first, 1972, Summer Schools in Earth Sciences to form part of the then new second-level Geology course. The Leeds-based Summer Schools continued for six years until transferred to Durham University, where they continue with equal vigour still.



Gass ruthlessly exploited every possible avenue of funding for research which a new organisation allowed, with spectacular results. Seizing the opportunity to acquire a permanent brick building at Walton Hall when Open University Educational Enterprises moved off campus, he set about consolidating his department's position. Building extensions housing modern, costly equipment produced results with major research projects round the world being set up. He personally supervised the work of many research students. It was natural and to be expected that the main expertise to be developed would be in so-called hard-rock geology (volcanology, geochemistry, etc) but Gass encouraged a broad spectrum of scientific interests.

Gass found time to serve on many important committees, notably as President of the International Association for Volcanology & Chemistry of the Earth's Interior (IAVCEI) in 1983-87. Among many distinctions, he was elected a Fellow of the Royal Society in 1983, serving on its Council and as Vice-President, 1985-86. The Geological Society of London awarded him its Prestwich Medal in 1979 and its Murchison Medal in 1988.

Ian Gass was a warm-hearted product of Tyneside with an earthy style and sense of humour. Others, especially outside the geological community or his own immediate sphere of interest, may have found him somewhat abrasive at times, but he was always courteous, especially to subordinates, even if direct. He had an uncanny knack of surrounding himself with colleagues with whom he did not necessarily agree. He clearly loved a good fight.

Norman E. Butcher

Ian Graham Gass, geologist, born Gateshead 20 March 1926, staff Sudan Geological Survey 1952-55, Cyprus Geological Survey 1955-60, Assistant Lecturer Leicester University 1960-61, Lecturer / Senior Lecturer Leeds University 1961-69, Professor of Earth Sciences and Head of Discipline Open University 1969-82, Personal Chair 1982-91, Emeritus Professor 1991-92, FRS 1983, Honorary Visiting Professor Leeds University 1992, married 1955 Mary Pearce (one son, one daughter), died Bedford 8 October 1992.