The Earth's crust, according to the broadly accepted postulates of plate tectonic theory, is divided into about a dozen major and as many minor blocks. These blocks—or plates—float like rafts on the denser, hotter, more fluid rock below. The boundaries along which plates meet are areas of intense geological activity. One type of boundary, called a diverging boundary, is generally located along submarine mountain ranges. There lava from deep within the Earth oozes up through fissures at the crest. It forms new oceanic crust moving out in both directions from the spreading center, carrying the continents and ocean beds along at rates of a few centimeters a year.

Over geologic time, the plates have moved vast distances, giving today's globe a far different look than it had 200 million years ago, when all land was in one supercontinent formed by an earlier tectonic cycle.

At the leading edges of the plates, called converging plate boundaries, the plates collide. In many such regions, called subduction zones, one plate dips under the other, forming a deep oceanic trench as crustal material returns to the Earth's hot interior. The rates at which crust is created and destroyed are presumed to be roughly equal; otherwise the Earth's diameter, which appears measurably constant, would be altered radically.

Early in the discovery and exploration of this process, in the last decade or so, the interactions between plates were recognized as the source of such phenomena as mountain building, continental drift, volcanism, and earthquakes. Indeed, the locations of earthquakes have been used to define plate boundaries. There are other reasons for studying plate boundaries, past and present, converging as well as diverging. Tectonic processes at these boundaries are now known to be associated with the origins of metal and hydrocarbon deposits; their study promises valuable clues to the location of the Earth's mineral riches. Metals can serve both as tracers of tectonic processes and as a good in themselves; tectonic research has become an attractive mix of basic and applied studies.

**Metallogenesis, the geostill...**

Worldwide, only a relatively small portion of the ridge structures that spawn the Earth's crust have been studied. This is hardly surprising since the ridges wind their principal way some 65,000 kilometers through all the major ocean basins of the world. As a consequence, much of the early metallogenic information has come not from the ocean floor but from studies of such places as the Troodos area of Cyprus. The Troodos massif has been famous for its mineral wealth, especially copper, since the time of the Phoenicians. It is also a submarine geophysical laboratory delivered to the surface: an unchanged slice of oceanic crust thrust out of the sea. Troodos geology is considered characteristic of formations found at the oceanic ridges at tectonic spreading centers. And Troodos may not be unique; mineral deposits similar to those of Troodos are found in the northeastern United States, eastern Canada, and many other presently non-oceanic parts of the world.

A second major type of mineral deposit is commonly associated with those converging plate boundaries at which oceanic crust is subducted under a continent. These large bodies of low-grade ores are known as porphyry copper; they account for more than half the world's supply of minable copper. The majority of these deposits are found in a ring around the Pacific Ocean, along the mountain belts of western North and South America, and in parts of the Alpine belt of Europe. Still other mineral deposits, characteristic of phenomena at those convergent boundaries where oceanic crust plunges under island arcs, are found in Japan.

Efforts to understand the metallogenic consequences of the birth and death of the Earth's crust were stimulated in the early 1970's by proposals often attributed to Richard Sillitoe of the Royal School of Mines in London and Frederick Sawkins of the University of Minnesota. Their proposal for a metal-generating phenomenon is called the "geostill."

In very general terms, the still-formative concept holds that, as lava rises out of the Earth's mantle at the mid-ocean ridges, it cools and cracks. Sea water, infiltrating the fractured lava under conditions of heat and pressure, dissolves trace concentrations of metals in the lava. The hot, metal-rich brines that result are driven upwards by convection. At the surface, with temperatures and pressures reduced, metals precipitate out, producing a mud in which both sediments and liquids are en-

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**Minerals from Mantle to Mine**

The formation of metal and petroleum deposits in the Earth appears strongly linked to tectonic processes. Can geophysics tell us where to search?
riched with metals. Thus, the process apparently responsible for concentrating ores initially is hydrothermal rather than—as geologists thought before plate tectonics—a process occurring in molten rock.

Operation of the hydrothermal refining process has been observed in the Red Sea, which is the product of what might be construed as an intracontinental spreading center—another could be Africa's Great Rift Valley—just developing between the African and Eurasian plates; the end result of the process can be seen in Troodos, on Cyprus. Brines as hot as 60° C have been sampled near the floor of the Red Sea. Three small basins in the sea contain sediments 100 meters thick that are saturated and covered with salty brines enriched with iron, zinc, copper, lead, silver, and gold. Were this resource on land, it would be of estimable value. Buried under some thousand meters of water, its exploitation is not feasible at present, though the muds of the Red Sea are regarded as a potential bonanza to the countries on its borders as ore deposits on land give out.

In the second stage of the geostill process, the new crust formed at the mid-ocean regions is gradually covered by sediments, forming the new ocean floor which is carried out from the rift in both directions by the moving plates. After a journey of several thousand kilometers, lasting millions of years, the sediments reach a subduction zone such as the Peru-Chile Trench at the rim of the Nazca plate off western South America. Descending hundreds of kilometers into the trench to regions of high temperature and pressure, the sinking oceanic crust is partially melted. The metals boil off one at a time as depth and pressure in the trench increase. Ore deposits originate from the metal-containing concentrates and rise in the overriding plate. Often, the deposits of a single metal are elongated, approximately parallel to the plate's margin, with metals deposited in a predictable sequence related to distance from the margin, density, and melting temperatures: iron, copper, lead, zinc, and finally tin.
...and hydrocarbons

An association is also beginning to emerge between plate boundaries and accumulations of hydrocarbon deposits—oil and gas. At converging boundaries there are island arcs, located between subduction boundaries and the continents they border. These arcs divide the ocean into smaller basins, resulting in conditions that favor accumulations of sediment and organic matter, the conversion of organic matter to petroleum, and the trapping of the petroleum in pockets. Converging boundaries also favor development of hydrocarbon resources extending from the continental shelves into nearby ocean basins—off Chile and Southern California, for instance.

Knowledge and payoffs

Numerous studies of the resource implications of plate tectonics have been supported by the National Science Foundation as part of the International Decade of Ocean Exploration: Project FAMOUS—the joint French-American Mid-Ocean Undersea Study—in 1974 undertook a systematic investigation of the Mid-Atlantic Ridge, making a detailed study of an area of emerging crust 300 kilometers southwest of the Azores. Another, longer term project has been focusing on the Nazca plate, an active metallogenic site bordering the western shores of South America. Three of its edges are diverging boundaries; the fourth is a converging boundary where the plate is plunging under South America. The Nazca plate project covers plate evolution, from birth at a mid-ocean ridge to death at a subduction zone, and offers clues to metallogenesis at a variety of stages.

Another group of scientists is concentrating on the Galapagos spreading center at the northern boundary of the mineral-rich Nazca plate. Evidence collected during the Nazca plate study, as well as from other research, suggests that this area holds a special promise for the discovery of a hydrothermal vent, a hot and active area of the kind found in the Red Sea, where metallogenesis begins. The vent has proven elusive; locating it would yield direct and dramatic evidence of the initial stage of the geostill process in operation.

But earlier payoffs are likely to emerge at the other end of the process—in the areas of plate convergence and subduction where crustal material returns to the mantle and where ores purportedly concentrate and emerge as minable deposits. Sillitoe, Sawkins, and others proposed more than five years ago that, in western South America and Bougainville and Taiwan in the western Pacific, for instance, deposits may well be still forming beneath active volcano chains as a consequence of plate subduction. Older deposits, it was proposed, might be explained (and new ones pinpointed) in such places as Puerto Rico, southeastern Europe, and the western United States, as a consequence of tectonic cycles earlier in the Earth's history than the present one.

Similar present or historic conditions, Sillitoe proposed, point to likely prospects in the Aleutian Islands, Izu-Bonin, the Sumatra-Java area, Banda, the North and South Celebes, New Hebrides, and Fiji, as well as the Lesser Antilles island arc, Asia's Kamchatka Peninsula, Burma, Thailand, Japan, and New Zealand.

The Southeast Asia project

Prospects such as these have understandably created some interest; governments in several parts of the world have begun to look to the resource implications of tectonic theory as a possible way to identify and locate potentially exploitable metal and hydrocarbon lodes.

This interest has led to what is currently the heaviest focus of geophysical research, in an area of Southeast Asia where three major plates (Pacific, Indian-Australian, and Eurasian) and several minor ones converge. Geophysical evidence indicates that either continuous or episodic convergence has been taking place there for at least 200 million years. Much of the region now lies under water. This prevents extensive land studies of the boundaries and multiplies the cost of field work. Yet the numerous islands, surrounded by depths of water from shallow to the deepest known, are fertile territory for relating marine and land geology. The complexity of the area might be counted as a drawback in terms of deriving simple solutions from complicated and interrelated systems. Nevertheless, it does offer unique opportunities for carefully coordinated studies that might be able to separate and assess some of the geological and tectonic variables affecting the genesis of metallic and hydrocarbon deposits. The Philippines, for example, is already the world's seventh largest producer of copper; other metals are also produced, and petroleum resources are being rapidly developed in the region. Many of these known and potential resources are apparently related in locale and genesis to plate convergence.

Because of this, and hard on the heels of the assessment by Sillitoe and others of the region's potential, Indonesia, Malaysia, Korea, the Philippines, and other Southeast Asian governments asked, through the United Nations, for help from the West in a coordinated study of their region—a study with both scientific and economic implications. The National Science Foundation's International Decade of Ocean Exploration program was asked specifically to contribute a program that would relate the area's present and past tectonic activity to the potential occurrence of petroleum and metal deposits.

The result of the request was SEATAR, a multinational Study of East Asia Tectonics and Resources, that grew out of a 1973 workshop on the subject convened in Bangkok under United Nations auspices. The workshop recommended a research program to determine the location, characteristics, and significance of the principal tectonic features of the area and to relate them to the genesis of metals and hydrocarbons.

SEATAR evolved as a cooperative project. Scientists, mostly from East Asian government agencies, are carrying out detailed field geological investigations on land; responsibilities for large-scale complementary work at sea and in laboratories have devolved upon U.S. and European scientists. Scientific teams from the Federal Republic of Germany are carrying out both detailed studies of offshore mineral deposits and large-scale marine tectonic investigations. Japan is also contributing to both land and marine studies. In some cases Japan is engaged both in the search for specific resources and in large-scale studies of tectonic patterns.

The United Kingdom's Institute of Geological Sciences is conducting a five-man, five-year study of Sumatra in an effort to outline that island's mineral resources. (Sillitoe had led a similar effort in the Chilean Andes, where he made the observations that led to the geostill concept.)

For the United States, a steering committee headed by Dennis Hayes of Columbia University's Lamont-Doherty Geological Observatory was set up in 1974 to develop a research program for
Shifting plates. The dynamics of plate tectonics provide a new window to the mechanisms by which exploitable mineral deposits form. The schematic below represents the kind of situation found in Indonesia.

this country within the general guidelines of the plan set forth at the Bangkok workshop. Hayes and his colleagues recommended a comprehensive five-year program involving a half dozen institutions, at least for a beginning, focusing on geological and geophysical processes and structures typical of the area. Following the committee's lead, the U.S. teams are attacking basic problems that would, nevertheless, have a high probability of practical economic results within a reasonable time.

The Bangkok workshop had recommended that, wherever practical, studies be concentrated along six major transects. The U.S. program initially is limiting its efforts to the southern half of the study area: the Sunda, Philippine, and Banda transects. Each is the conspicuous victim of intense tectonic and volcanic activity in response to plate collisions, and each is the subject of hydrocarbon exploration in the shallow water regions nearby. The transects provide good examples of contrasting subduction margins, and considerable work has already been initiated offshore to complement geological and geophysical studies on land.

Geological atlas

A large body of geological data exists for many of the land areas of Southeast Asia; much of this has been assembled in past geological compendia. Geological and geophysical data for the offshore regions are also extensive, although there are serious gaps in coverage, both in location and type of data. Much of this information is in the files of oceanographic institutions around the world. Consequently, one of the first tasks of the U.S. SEATAR program was to inventory the offshore data. Compilations made by a number of scientists in the program identified obvious gaps in existing data; some were filled by short-term field projects. Hayes and others at Lamont-Doherty then examined the results in great detail, a time-consuming undertaking that involved considerable
The geostill. The genesis of copper deposits occurs both at the spreading centers where crust is formed and the converging margins where it returns to the mantle.

rethinking of the raw data and reconciling of the many conflicts in the data. Out of this effort will come a working atlas of marine portions of Southeast Asia.

The atlas, to be published this summer, includes maps showing gravity, depth, surface sediment, seismic refraction, magnetic, heat flow, and thermal conductivity data. It will serve as a base for current and long-range planning during the life of the U.S. SEATAR program. It will also identify and assess additional data gaps that must be filled. A revised atlas with explanatory material will be published at the end of the program. The tectonic processes revealed by the atlas could help disclose the origins of existing hydrocarbon and metal resources in the area, and point to promising locations for new exploration.

Another project involving the entire area is well under way at Cornell University, where Bryan Isacks and Richard Cardwell are preparing detailed maps of earthquake activity. Earthquakes represent fractures in the earth and denote the stresses to which a region is subjected. Hence, they indicate a continuing tectonic activity, while they also suggest the tectonic processes that operated in the past; it is likely that the same processes now in operation also played major roles in the geological evolution of much of the region.

In general, shallow earthquakes (down to 100 kilometers) define present plate boundaries at the surface; deeper ones are like a dipstick that defines the path of the subducting plate. Subduction is understood only in the most general terms. Plates descend at different rates and angles, sometimes breaking into segments. At the fractures between segments, the processes that mobilize metals into ore deposits apparently operate at higher than normal rates. Hence, understanding the anomalies of a subducting plate may help predict the metal anomalies on land.

Previous tectonic studies of the Southwest Pacific, parts of broader studies of the entire Southeast Asian or western Pacific regions, have tended to concentrate on the more well-defined plate boundaries. In addition, they have usually focused on one type of data—for example, the distribution and frequency of large earthquakes. The work of Isacks and Cardwell, which is similar to work they are doing with French scientists in the Tonga-Fiji-New Hebrides region, involves collecting all available data on earthquake location. Analysis of the data is expected to define as precisely as possible the geometry of the earthquake zones.

The Cornell scientists, integrating the earthquake data with marine geological and geophysical data, hope to be able to define and disentangle the region's many earthquake zones as a key to the rapidly changing systems of subduction that appear to have marked both the past and present tectonic activity of the area. Cornell's maps will represent the best knowledge available on earthquakes in the region, and will be of additional value to local governments in their attempts to cope with their earthquake problems.

Sunda transect

The Sunda transect cuts through Sumatra, the second largest island of Indonesia. Included in the transect are excellent sites for mapping the geology of an active island arc system. Daniel Karig of Cornell has been studying the islands, attempting to lay out the spectrum of geologic events that mold the arc system, and attributing each event to a point in space and time within the arc framework.

Once the process is understood in an active arc system, it might be possible to establish diagnostic criteria by which the process' end result can be recognized when it is found.

Karig's work has the advantage of observing the process directly in an oceanic setting, where the geology is much simpler. It started on Nias, the largest island in the chain lying west of Sumatra. Arriving in Indonesia for his field work, Karig ended up in Nias because it was a suitable site and was served by a more-or-less scheduled boat. Many of the islands are uninhabited, accessible only by chartered vessel, and nearly impossible to move about on.

Nias, in the island arc framework, is an area behind the subduction zone where material scraped off the descending plate is added to the arc. Normally, such an area is below water. Nias is exposed, constituting a sort of "window" into an oceanic process. It also exposes one flank of a little-explored and little-understood type of marginal trough that appears promising for economically significant accumulations of oil. (A geologically similar example is the area off the southern coast of Alaska that is now being leased for oil exploration.)

Although accessible by boat, Nias is far from hospitable. Logistics are difficult. The pace is leisurely. Jerry-built local buses sometimes run; just as often they don't. The climate is hot and wet; 200 inches of rain falls in an average year.

For one field tour, Karig opted for the "dry season," only to find that that meant cloudbursts every three or four days, rather than the more gentle daily rain that characterizes the wet season. The local diet, largely rice, tubers, and vegetables, is debilitating. Trying on his other foods to supplement local supplies.

For his research in the remote areas of
SEATAR. Areas of exploration, or research transects, cutting across geophysically important Southeast Asia, are marked by bands on this map of an area where several plates collide in a complex tectonic pattern.
Nias, Karig prefers to travel alone, relying on his rudimentary Indonesian to get him by. He always takes the precaution of leaving his schedule at his base of operations in Nias. Frequently the research requires working along jungle streams, which not only provide the easiest access to remote areas but also the most favorable locations for outcrops of original rock unmodified by vegetation and weathering.

On his most recent trip to Nias, graduate student Gregory Moore slipped while crossing a stream and broke an ankle. Fortunately he was not traveling alone. His helper and local inhabitants rigged a sedan chair; it took six people to carry him out over six kilometers of rough, muddy, and densely vegetated terrain. Earlier, on his first trip to Nias, Moore contracted malaria.

Karig returns to the Sunda transect this year, both to finish the land work and to investigate the submarine area west of Nias. Working off the research vessel Thomas Washington, he and Joseph Curray of the Scripps Institution of Oceanography plan to gather the marine data that will cover other events along the island arc system. They also hope to collect data from a number of oil companies drilling in the area.

**Banda transect**

The Banda transect, which extends northward from Australia, covers perhaps the most complex and least understood of the three regions in the U.S. SEATAR program. It has the tightest curvature of any island arc, apparently because three large plates interact there, and the Banda arc, caught in the middle, is buffeted by at least three sets of relative motions. Because the marine portions are such an unknown, the first U.S. SEATAR work is a geophysical reconnaissance of them. The Indonesian and Australian governments are conducting coordinated research on land. The intent of the work is to decipher the stages in the formation of marginal (inland) oceans and to investigate the possibility that the Australian continent is being swallowed—though slowly—by the Banda island arc.

These marginal oceans are regarded as promising sites for hydrocarbon deposits because of the burden of sediment they carry.

In the fall of 1976, Carl Bowin of the Woods Hole Oceanographic Institution and George Shor of Scripps obtained several structural profiles across the Banda Sea. They used two techniques—seismic reflection and seismic refraction. In the first, sound waves are sent vertically into the ocean. Their reflection provides detailed information on the upper layers of the ocean floor. On the Banda field trip, the Woods Hole research vessel Atlantis II carried a multichannel reflection system that simultaneously records each reflected sound at six locales, providing better resolution and hence finer detail.

In seismic refraction studies, the sound is sent at greater angles. It penetrates to greater depths, traveling down through the sediments and the oceanic crust, even, Bowin reports, through the thicker crust of the Australian continental margins. The velocity with which the sound travels through the various layers depends on composition. The Thomas Washington was also on the Banda cruise, permitting two-ship seismic refraction measurements, which gather data from still greater depths. The fine detail from seismic refraction measurements and the depth information from seismic refraction measurements combine to give the most comprehensive picture to date of the structure and composition of the seabed in the Banda transect.

The research vessels gathered other types of geophysical data, including gravity, magnetic, and heat flow. The magnetic data disclosed anomalies or stripes not previously recognized in the south Banda basin and indicating an origin of the basin by sea floor spreading. The anomalies were found to be similar to patterns found in the Indian Ocean, suggesting the possibility that the Banda Sea is a part of the primordial Indian Ocean, trapped by later formation of the eastern Indonesian arc.

Bowin and Shor also collected piston cores in soft sediments 40 feet deep. After their thermal conductivity has been measured for calculation of heat flow, the cores go to I. R. Kaplan at the University of California, Los Angeles for analysis of the amounts and composition of organic compounds. Later, Kaplan will simulate conditions at depth to see what products might be formed from the organics present in the sediment.

**Philippine transect**

The metallogenic phase of the U.S. SEATAR program is largely confined to the transect that cuts across the Philippine Islands. The islands have exposed rock units and a tectonic history that make it well suited for testing the relationship between plate convergence in a subduction zone and the development of metal deposits. The rocks are only a few million years old, young in geological terms, and hence promising research targets.

These studies of metallogenesis focus on three phases of the process: the source materials of ore deposits, how metal-containing materials are transported, and how metals are finally concentrated into minable ore deposits. The marine phase of the studies is already under way. In late 1976, Dennis Hayes and Roger Anderson surveyed the west Philippine basin using a 24-channel seismic reflection system. These data, coordinated with reflection data, can identify critical structures and characteristics deep in the crust. Hayes and Anderson made two profiles across a presently inactive portion of the northern Philippine Trench and two across the ridge-arc system that extends northward from Luzon. This combination should give the first continuous deep-penetrating seismic profile across an arc with active or recently active subduction boundaries on opposing sides.

The data gathered for the SEATAR program were closely coordinated with data taken on the same cruise under the International Project of Ocean Drilling, which is the continuation of the Deep Sea Drilling Project. IPOD plans a series of deep drill holes along the transect. Because the typical basalt layer at the top of the oceanic crust is exceptionally thin and the topography smooth, the prospects are good for drilling through the basalt and into the unknown lower portions of the oceanic crust.

The land phase of the Philippine transect studies has been slower getting under way because of the problems of correlating directly events taking place in the sea with what is found on land. However, the Philippines are rich in a wide variety of metals, both of the Troodos type and porphyry copper. Moreover, the processes that formed both could be actively under way. Thus, the area offers exciting research opportunities. Nevertheless, the geology is so complex that it has proven easier to gather data than to develop hypotheses that can be tested—a necessity if the time and space relationships among rock units involved in the evolution of ore deposits are to be understood. Land-based studies,
expected to be included in later stages of the program, should help close the gap between data and theory.

Industry efforts

Research under NSF's program is not intended to duplicate the geological mapping usually done by local governments. Nor does it duplicate efforts of the oil and mining industries. Rather, NSF-supported research seeks to understand the basic processes and structures from which prospecting techniques would be developed. These techniques would probably be applied first to the location of new resources on land; later, as land resources are depleted, the more elusive resources of the sea will become prime targets.

Industry is becoming more receptive to the resource implications and ideas of plate tectonics, the oil industry perhaps more so than the mining industry.

Taking readings. Dennis Hayes (left) and Roger N. Anderson at a 12-channel seismic amplifier used in recording shots from sonobuoys and in measuring two-ship refraction signal arrivals.

Throughout its long history, the mining industry has always relied on prospectors who, hit or miss, found metals at the surface of the continents. Those deposits are fairly well exploited by now. The much younger oil industry, on the other hand, has grown up having to look below the surface, and in the past five years a number of companies have organized research groups that take a global look at oil resources on the basis of plate tectonics. In addition, industry representatives have attended meetings of some SEATAR groups, have helped review proposals, and have been observers of such specifically relevant work as Karig's on the Sunda transect.

The old model of a static Earth had little to say concerning the origins and distribution of resources. But that is not true of the dynamic picture plate tectonics paints of the geologic history and continuing evolution of the planet. However, that picture is still so broad-brush that it is of little immediate practical value. For instance, ores are concentrated only in occasional "pods" in the thousands of miles of the Andes along the South American coast, and the location of similar deposits cannot be predicted from present knowledge. The relationship between plate tectonics and resources must be understood in much finer detail before it can serve as a predictive tool. That understanding may well grow out of research on the island arcs of Southeast Asia.

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