Journal of the Minnesota Academy of Science

Volume 32 | Number 2 Article 12

1965

Marine Geology

Preston E. Cloud Jr.
University of Minnesota

Follow this and additional works at: https://digitalcommons.morris.umn.edu/jmas

Part of the Geology Commons

Recommended Citation

Cloud, P. E. (1965). Marine Geology. *Journal of the Minnesota Academy of Science, Vol. 32 No.2*, 109-116. Retrieved from https://digitalcommons.morris.umn.edu/jmas/vol32/iss2/12

This Article is brought to you for free and open access by the Journals at University of Minnesota Morris Digital Well. It has been accepted for inclusion in Journal of the Minnesota Academy of Science by an authorized editor of University of Minnesota Morris Digital Well. For more information, please contact skulann@morris.umn.edu.

Marine Geology[1]

PRESTON E. CLOUD, JR.

Department of Geology and Geophysics, School of Earth Sciences, University of Minnesota

Were the average temperature of the earth a few tens of degrees less than it is, ice would be the most common crustal rock. The fact that it occurs in its liquid phase over 71 per cent of the earth's surface should not obscure the fact that the oceans are geologic features, particularly in their substructure, their boundary relations, and their history.

History

Scholars, millenia ago, reflected on and made observations of phenomena that are now properly considered as marine geology, although there was, then, no organized body of knowledge in this field. Democritus, Aristotle and Plato were expressing fairly modern ideas about marine sedimentation and sorting around 400 B.C., and a passage in the *Critias* from Plato's dialogues contains the germ of the supposedly recent concept of gravity mass movement in deep-water sedimentation. Polybius, who lived between 204 and 122 B.C., wrote on the sedimentary regimen in the shallow sea of Azov. Posidonius, a couple of generations later, announced, without saying how he knew, that the sea around Sardinia was 1,000 fathoms deep — a record that was to stand for almost 2,000 years. And Seneca, a Roman contemporary of Jesus, formulated essentially modern concepts of the gross weathering properties of water.

Albirouni, who lived about the year 1,000, described the mechanical grading of water-borne sediment; and Leonardo da Vinci wrote, in the fifteenth century, of the bottom of the sea becoming filled with sediment until, finally, it became the top of the mountains. Nicolaus Cusanus, a contemporary of Leonardo, invented a sphere with a detachable weight for sounding great depths — the precursor of later models by Hooke and Brooke — and embodying the time-lapse principle of modern echo sounding. The fact is, however, that until fewer than 200 years ago, water was pretty much something one sailed on and stayed out of if one could. Apart from the desultory efforts mentioned, few persons before the late eighteenth and early nineteenth centuries even tried to find out how deep the sea was, let alone what was beneath it, unless they were concerned with some menace to navigation.

For all practical purposes, margine geology as an organized scientific discipline really began with the first Challenger Expedition, 1872 to 1876; all that is worth knowing until then is summarized by Murray and Renard in the front part of their classic report on the deep-sea sediments collected during that expedition. Much of what we know to this very day about the broad distribution patterns of marine bottom sediments is attributable to the Challenger Expedition, which was also the prelude to a number of excellent geodetic and hydrographic surveys, some important studies of reefs and bottom samples, and beautiful work by a succession of French investigators on sedimentary-ecologic facies in shallow marine waters.

The most noteworthy advances of the last half century that apply primarily to the geology of the sea floor were the development and perfection of continuous echo sounding, during the 1920's, and the invention by C. S. Piggott in the mid-1930's of an explosive coring device. By means of the so-called "Piggott gun," operated from the Western Union Telegraph Company's cable ship *Lord Kelvin*, the first deep-sea cores attaining penetrations of more than about five feet were obtained. Eleven cores, averaging 7 feet long and reaching penetrations of as much as 9½ feet, were taken from depths of 4,000 to almost 16,000 feet along a single traverse between Newfoundland and Ireland.

Modern marine geology may be said to have begun with the analysis of these cores by W. H. Bradley, M. N. Bramlette and others, published in 1942 as Professional Paper 196 of the U.S. Geological Survey. Here we are unequivocally introduced for the first time to the concept of long-distance mass transport of sediments by deep-flowing density currents, and to the most comprehensive sequence then known in depth, time and climatic evolution of deep-sea sediments. Here we see the germ of the intensified geological exploration of the deep sea that was to flourish so vigorously after the second great war, and even during it as inspired "civilian sailors," such as Admiral Harry Hess of Princeton University, piled up fathograms wherever they cruised and applied other new recording devices to the collection of oceanographic data.

To almost everyone's surprise, cruising funds, ships and equipment have continued to be available, culminating in the present oceanographic boom in which geology necessarily plays an important part. It is high time, too, for many of our questions about the major features of the earth and the processes that created the geological record can be answered only beneath and in the sea.

Some inkling of the results to be obtained is suggested by a half-dozen well confirmed postwar discoveries that are revolutionizing our concepts of the oceans and, with them, the earth. (1) The depths of the sea are not featureless abyssal plains, as was once supposed, but are quite as varied as comparable expanses of dry land, and

[1] This paper was first presented at Charlottesville, Virginia, by invitation of the University Center of Virginia and the Virginia Academy of Sciences in the fall of 1960, and was subsequently given as one of the lectures in the Visiting Geoscientist program of the American Geological Institute in the spring of 1961. It is published in response to continuing inquiry about its general availability in published form, and without the formal documentation normally included in a scientific paper.

have even greater and sharper relief features owing to the weakness of erosive forces at depths below wave base in the sea. (2) Gravity mass movement by sediment flows and turbidity currents is turning out to be a sedimentary mechanism of major importance in the marine realm, carrying sediments rapidly from shallow to deep water to fill basins, bury hills or spread over abyssal plains of vast extent. (3) The differences between continents and ocean basins are not as sharp in some respects as we once believed, but are sharper in others; contrary to all predictions, the flow of heat from the interior of the earth is about the same for ocean basins as for continents, yet some types of earthquake waves will apparently not cross from oceanic to continental rocks. (4) Heat flow, moreover, is relatively high from the mid-ocean ridges and rises, and low from the trenches at continental margins, giving new impetus to the persistent theory that convection cells within the earth's mantle are somehow involved in the differentiation of continents and ocean basins, with mountain building as a by-product. (5) These same midocean ridges, commonly with central rifts, have been mapped with increasing detail along the geographic centers of various ocean basins beginning with the work of the John Murray Expedition in the middle 1930's; they appear to compose a complex and more or less continuous 40,000-mile scar around the globe, with an area above the surrounding basins equivalent to all the dry lands of the earth. (6) Fast, east-flowing counter-currents are found below the Pacific and Atlantic equatorial currents, and other deep-flowing counter-currents exist below parts of the western boundary currents in the Atlantic and Pacific Oceans. Sediments of unusual types related to such currents may give us clues to past equatorial positions, contributing to a solution of the persistent problems of polar migration and continental drift.

By no means all important discoveries in aquatic geology and oceanography are as spectacular as these, but they suggest the order of magnitude of advances still to be made in the more general realm of marine geology.

Nature of the World Ocean

According to dictionaries consulted, the ocean is a great body of water that covers 71 per cent of the globe, and I have had far too little success with lexicographers on better grounds to argue that definition. The ocean is where it is, however, because of the substructure of the earth's crust and mantle; its characteristics are strongly dependent on its atmospheric superstructure and its boundary relations with continents and other parts of the lithosphere; and time and sedimentary relations are also essential to our understanding of the hydrosphere or any of its parts as a geological entity. Indeed, the ocean is nothing more than the interconnected low places on the earth occupied by H_2O in the liquid state. During the differentiation of the earth's lithosphere, its crustal rocks have become segregated into light sections that are thicker and higher than the rest (the continents), and heavy sections that are thinner and lower (the ocean basins), thus preserving the general balance of gravity — the principle of isostasy. To people only a fathom tall, the mountainous heights and oceanic depths seem relatively great, but on a global scale the ocean basins are merely shallow, somewhat misshapen and overfilled saucers, from which a little water spills over the edges to flood the continental shelves.

How do we go about studying the make-up of these saucers: their composition, the bumps and ridges on their bottoms, their cracked and crazed edges, and the characteristics and movements of the salty broth that overfills them?

Methods of Study

Problems in marine geology, as in other fields of science, may be approached by three main routes: empirical, experimental and theoretical. The scale, nature and state of the understanding of geological problems is such that the observational or empirical approach is likely to take precedence, supplemented by experiment and theory as we learn to pose the questions on which experiment may shed light and to which theory can give structure and impetus. That neither experiment nor theory is being neglected in this field will soon become evident. The conspicuous feature of modern marine research to be emphasized here, however, is the use of special and often complicated and expensive data-gathering apparatus of various sorts.

Data are collected from oceans and other water-filled basins both by direct and indirect methods. The indirect methods include the use of various sorts of geophysical apparatus that measure differences in rate and nature of transmission, reflection, refraction or absorption of shock, sound, light, heat, electricity or magnetism, both natural and induced. These methods apply to rock, sediment or water, and are implemented by an array of equipment that ranges from the two-ship deep-seismic arrangement, through the sonic apparatus used for measuring depth and structure of sediment and water, to the micro-electrode or thermister that one places in the sediment or in a bore hole to record electrical or thermal data. Details would be meaningless here; the apparatus will all be different a few years hence. The point is, that from measurements obtained by such equipment we can estimate the density and elastic properties, the attraction of gravity, and the magnetic, electrical and thermal characteristics of rocks and sediments beneath thick layers of water; and from such estimates we can draw inferences about the geologic composition, structure and history of the ocean basins.

Some geologists and oceanographers are beginning to feel that we have pushed about as hard as we should with such methods for a while, however, and that we must make a stronger effort to obtain more direct observations. This means the entry of man or his prosthetic devices into the depths of Davy Jones' Locker. It is fun, but it is not enough, to go down a couple of hundred feet with SCUBA gear. We must do more coring and bottom photography; we must build bigger, better and more maneuverable bathyscaphes and mesoscaphes equipped with devices for taking and retaining samples on direction from observers inside; and we need to drill more deep holes like the one that revealed the Darwinian volcanic foundation beneath Eniwetok Atoll barely 15 years ago. We must send remote controlled robots and television cameras to the depths to make observations for us. And we must digest and synthesize the data already available so that we shall know where to look and what to look for. The present great and now well-known adventure in direct observation is the Mohole project — the plan to bore a hole to the Mohorovičić discontinuity where an abrupt increase in the speed of earthquake waves suggests the location of the transition from crust to mantle. Feasibility studies and site selection are now well advanced, and in a few more years we may have a piece of the earth's mantle that lies beneath the crust, and the first set of cores penetrating the whole of the crust itself. Critics of the Mohole need not worry about it being just a gimmick. Even if the mantle were never reached it will be well worth the try for the information on the history and origin of the oceans which will come from studying the fossils that will be found in core samples obtained on the way down.

It is worth emphasizing, too, that an indispensable and often, by far, a larger part of the work in marine geology, as in other fields of science, is done at the laboratory bench or desk: peering into a miscroscope, segregating and preparing samples or data, and reading and writing long after sensible people have gone to bed. This deserves emphasis because it is still not generally appreciated that it may take several times the money and time invested in the cruise itself to bring the results of an oceanographic cruise to published conclusion, or that highly significant contributions have been, and will be, made by people who never set food on a research vessel.

The Oceanic Water-Body and Its Atmospheric Superstructure

Disregarding oceanic substructure for a moment, it may seem obvious that the water in the ocean basins is where it is because water seeks its own level; and you may well ask what this has to do with marine *geology* anyhow. The fact is, questions of enormous geologic importance and interest are vested in the ocean waters. Where did they come from? Did they come from the rather rapid condensation of an original steaming or plasmic atmosphere surrounding a molten infant earth as we once thought, or by a sort of gradual degassing or dehumidification process from the interior of a probably warming and perhaps expanding earth, as there is now increasing reason to suppose? Did the ocean acquire its dissolved salts mainly as a result of leaching by meteoric waters from the rocks and sediments they flowed across and through on their way to the sea, or was the salt mostly introduced along with the juvenile volcanic waters that gradually filled the low places of the earth? Has the saltness of the oceans remained constant, increased or fluctuated through geologic time? What controls the relative proportions of salts in the sea? How and under what conditions are some ions matched and precipitated from solution to form sediments and eventually rocks? What are the depoisoning mechanisms through which lethal and technologically important rare elements like copper, zinc, silver and selenium are removed from the sea? What effects have the varying conditions of the sea on the nature and distribution of organisms and sediments and how can these best be utilized in interpreting the past?

These are all geological questions about present sea waters, the answers to which must come in large part from study of the present hydrosphere; we could and will ask many other questions about the seas of the geologic past. To deal with these questions critically is one of the most exhilarating of intellectual exercises, for to do so we must go not only to the sea, but to the juvenile and meteoric waters of the earth, the thermodynamics and kinetics of chemical reactions and balances, microbiological segregation processes, biogeography, ion exchange and general linkage between hydrosphere and atmosphere, and even to the atmospheres of other planets and the origin of the solar system.

As long as we supposed the earth to have originated by the detachment of an incandescent ball of matter from a parent sun, it was natural to attribute its internal stratification and the origin of the hydrosphere to the cooling of this fiery ball. A different hypothesis is necessitated by the ascendant concept of earth origin through the cold aggregation of planetesimal particles, with internal stratification produced by gravitational-compressive and radiogenic heating. From a study of the dissolved substances in juvenile and oceanic waters W. W. Rubey concluded, in 1952, that the volume of the ocean had increased gradually through geologic time, but that the percentage and proportions of dissolved substances ("salt") had remained about the same. This conclusion is still being tested and modified, but it appears to be consistent with all available evidence. Incidentally, like Ditmar, the founder of chemical oceanography, Rubey never actually worked on an oceanographic vessel.

The internal structure and, therefore, the sediment transporting capacity of the sea, is largely a function of its relation to the atmospheric super-structure. Ocean circulation and thermal structure is controlled by the temperature and circulation of the atmosphere in combination with the distribution of existing lands. Through ion exchange and other forms of chemical and biological reaction, detrital or chemical sedimentary particles are altered as they settle through the water and after they have finally settled across the depositional interface, where the interstitial waters and biotas bring to bear their own peculiar effects. All of these things in their turn are reflected by the kinds, thicknesses and sequences of sediments marine geologists bring to the surface in their core barrels; the distribution of sedimentary ores like phosphate and manganese; and the variety and abundance of the marine life that writes with its preserved hard parts the record of changes in time and environment. A variety of collecting and analytical equipment is available with which to study these interrelated hydrological, meteorological, sedimentological, chemical and biological processes in the modern sea, in depth and space, and in the laboratory as well. In order to interpret both the recent variables and their more ancient records we must find the people and the means to put this equipment to work.

Variations in level of the shore line take place as a result either of changes in volume of the ocean basins or the water in them, or changes in the level of the land. From a study of shore line features related to mechanical, chemical and biological erosion and deposition, geologists can judge whether a particular relative movement of the shore line was local or global. If global, they can infer from correlations with evidence for climatic change whether the shift of water level was a result of change in volume of glacial ice or whether evidence must be sought in crustal movements beneath the sea.

Crustal Substructure

Among the problems that the geologist must go to sea to study are the nature, origin and duration of ocean basins and continents and other major crustal features, such as the great oceanic ridges and fracture zones, the submerged mountains and flat-topped seamounts, and the island arcs and trenches. Apart from what the geologist has been able to deduce from observed rock sequences and structural relations above the sea, to date he has gathered his information about crustal structure mainly by indirect methods. These include the records of natural or artificial earthquake arrival times on seismographs ashore, the record of explosive shock waves deliberately generated at sea, gravity and magnetic profiles at sea and on land, airborne magnetometer profiles, and the records of heat flow and remanent paleomagnetism at selected points of the earth.

Nature, origin, and duration of ocean basins and continents

Many differences have been observed between continents and oceans other than the fact that one is dry and the other wet. The rocks above the Mohorovičić discontinuity, where the speed of earthquake waves increases abruptly downward, are thicker, lighter and more siliceous in the continents than on the ocean floor. The sedimentary blanket over most parts of the ocean appears to be less than half a kilometer thick, in contrast to the very thick sedimentary accumulation on the continents, and the rocks beneath are gravimetrically compensated and appear to be mainly basaltic and ultrabasic. The great majority of the world's earthquakes are located along the boundaries between ocean basins and continents or beneath the island arcs and trenches and the mid-ocean ridges; deep-focus earthquakes are almost restricted to the continents and continental margins. Moreover, it is now known from the work of Maurice Ewing and his associates at the Lamont Geological Observatory that some types of earthquake waves apparently will not pass from oceanic to continental rocks (Sci. Amer., Oct. 1960, p. 95).

On the other hand, the evidence is clear from studies of sedimentary sources and geologic structures that areas now 8,000 feet deep in the Ligurian Sea and down to 24,000 feet in the Indonesian basins were once dry land.

The blunt truth of the matter is that we simply do not yet understand what these facts are trying to tell us. Until about 15 years ago any geologist even casually familiar with the subject would have predicted from known lithologic differences that heat would be lost more slowly from the oceanic than from the continental crust. When the rate of heat flow from the rocks beneath the sea was finally measured by Sir Edward Bullard and by geophysicists from Scripps Institution and other places, however, it turned out to be just about the same as from the continental rocks, with two striking exceptions. The few observations available indicate that under the deep oceanic trenches there is a slower rate of heat loss than elsewhere, and in the mid-ocean ridges it is much faster! This has reinvigorated the hypothesis of convection currents in the crust and mantle as a deforming mechanism and has led physiographer Bruce Heezen of Lamont Geological Observatory to resurrect the hypothesis of an expanding earth first formulated by the British physicist P.A.M. Dirac over a quarter century ago.

Have the ocean basins and continents existed in about their present relations since the first differentiation of the earth's crust? Have they changed places in the whole or part from time to time? Have the continents grown from original plutonic and mainly granitic nuclei by the tectonic welding to their margins of a succession of seaward spreading geosynclines? Have pieces of a primeval megacontinent drifted out into the primeval world ocean or been wedged apart as a result of crustal expansion? Or have continents reformed episodically as a result of the growth and assimilation of the continent-forming sialic rocks through differentiation processes associated with convection currents in the mantle.

The available data can be and are argued both for and against all of these possibilities, which is sufficient evidence that more information is needed, especially from the ocean basins. Paleomagnetic data show that the magnetic poles have migrated systematically through geologic time and that the paths of magnetic polar migration for different continents differ in a way that could be explained by concurrent drifting or wedging apart of the continents, assuming approximate coincidence between magnetic and geographic poles, and provided there was some continental separation to begin with. We have as yet none of the needed paleomagnetic data from the oceans. What the paleomagnetic data may mean in terms of the poles of rotation is also unsettled, but very important for paleooceanography.

Special features of the oceanic crust

The development of continuously recording echo sounding apparatus in the 1920's and 1930's, and its further refinement and wide application during and after the second world war, soon provided us with undreamed of details about major morphologic and structural features of the deep sea floor.

About 1000 seamounts or isolated volcanic peaks standing more than a kilometer above the sea floor have been charted in the central Pacific Basin and W. H. Menard has estimated that there may be as many as 10,000 of them in the entire Pacific Ocean. Some of these seamounts show flat, erosionally truncated tops now thousands of feet below sea level — the so-called Guyots. For these, at depths as great as 6600 feet, E. L. Hamilton of the Navy Electronics Laboratory has described beach eroded pebbles and fossils that lived in shallow sunlit waters somewhat more than 70 million years ago, in Late Mesozoic time. The work of H. S. Ladd and his associates on the U.S. Geological Survey reveals that other volcanic peaks are now buried at depths up to 4000 feet beneath a succession of shallow water sediments that accumulated over the last 60 to 70 million years and that contain fossils signalizing episodes of emergence in the general history of profound post-Mesozoic subsidence of the Pacific Basin. These volcanic undersea mountains, including the ones that are capped by reefs, occur in clusters and alignments that trend northwest-southeast for hundreds of kilometers across the central Pacific Basin, and the volcanic materials that poured from these rifts thickly mantle the ocean floor and are, in some way, related to its subsidence. The many small abyssal hills between and beyond them are randomly arranged and are frequently capped by Tertiary sediments.

No fewer than four great fracture zones 100 km. wide, 2,000 km. long, and faced by towering cliffs with reliefs of thousands of feet extend along great circle arcs into the Pacific Ocean from the Pacific coast of the United States. These enormous cracks in the edge of "the saucer," first found by vessels of the U. S. Navy Hydrographic Office and the Coast and Geodetic Survey about 15 years ago, have been studied in detail by H. W. Menard of the Navy Electronics Laboratory and Scripps Institution of Oceanography, who observed that one runs into a great structural offset just north of Los Angeles and another is continuous with the belt of recent volcanos that crosses Mexico at latitude 19° north. A couple of these east-west cracks impinge on the great transcurrent north-south trending San Andreas fault without offsetting it. As yet no one knows what causes these rifts or how the earth has moved along them beyond the fact (recognized from offset magnetic trends by V. Vacquier and associates in 1961) that there is a large sidewise or lateral component of motion within the East Pacific Basin itself. They may be the tensional manifestations of long-term counter-clockwise rotation of the Pacific Basin, but the data needed to evaluate the problem critically are yet to be gathered. More recently scientists of the Lamont Geological Observatory have shown that there are similar offsets along east-west cracks in the equatorial regions of the Atlantic Ocean.

Consider now the previously mentioned and possibly continuous mid-ocean ridge that divides most ocean basins into two or more subsidiary basins, and whose high heat flow and locally rifted crest has suggested to some geologists that it is currently in the process of being pushed up and torn apart by rising and spreading convection currents in the earth's mantle. Ambiguities in the North Pacific and in western North America suggest to some geologists that here the Pacific basin is being rotationally underthrust beneath the continental rocks, the location of a former "mid-ocean ridge" being indicated by high heat flow and volcanism from Nevada to Puget Sound. Information is insufficient to warrant further discussion here of either ridges or subsidiary basins, beyond remarking that they are surely of profound significance in terms both of global structure and ocean circulation, and that we need to know a lot more about them.

Oceanic Margins

The boundary relations of the oceans with atmosphere and subcrust have already been mentioned. Here may be added a few words about the peripheral relations of oceans with the continents and those pieces of the bottom that rise to the surface as islands.

Continental Shelves

It may seem logical to think of the boundary between continents and oceans as marked by the continental shelves, if not the shore; but the problem isn't that simple. Continental shelves, as practically everyone knows, are wide or narrow, sloping surfaces that pitch gradually seaward from the shore to some depth, commonly 200 meters or so, at which the slope abruptly steepens to great depths. This is the shelf break, and where it faces the sea with no additional complications beyond it may indeed be taken as the edge of the ocean basin. Inasmuch, moreover, as a great deal of important commercial activity is carried out on and over the continental shelves, they are of great human and economic interest. They have, therefore, been extensively charted and dredged and a great deal has been written about them. Still we have relatively little of the kinds of information that we most need about their structure and sedimentary cover, and which it is now possible to get from sonic, electric, magnetic, seismic and gravimetric profiles, or by diving, coring and drilling. It is possible, for instance, to argue from available facts that the continental shelves and shelf break are erosional, depositional, structual or some combination of these things. We know next to nothing, also, of the great intertidal marshes and flats so characteristic of the Atlantic coast of the U.S. south of the Hudson River, beyond the fact that they are fine birding grounds.

Among many interesting features of the continental shelves, the most hotly debated has been the deep undersea canyons that scallop their edges and reach far down into the deep sea. Their "headwater" plans look so much like those of ordinary streams that it was a logical first reaction to attribute them to stream erosion that took place between 10,000 and a million years ago while a large fraction of the ocean was locked up in glacial ice. In 1936, however, the late great Harvard geologist R. A. Daly proposed that the real erosional agent consisted of density currents of water within water, so laden with sediment as to increase its bulk specific gravity and cause it to flow down slope beneath the overlying lighter water. The lively discussion that ensued between the two principal and several minor points of view about submarine canyons was the direct incentive for much of the marine geological research during the following two decades. As a result, we now know (1) that seaward channels of several of the larger and more prominent canyons extend so far and deep that the oceans would have had to be nearly empty for them to be cut subaerially in their entirety, and (2) that other canyons are definitely related headward to streams on the land. As in many disputes, it seems to be a case of the blind men and the elephant. No one now denies that parts of some undersea channels were cut subaerially. Nor do the most ardent advocates of subaerial cutting of the submarine canyons any longer insist either that the volume of Pleistocene ice was really large enough to account for all the water that would have to be removed from the oceans to validate their original views, or that the canyons are evidence of recent very great subsidence. The prevailing view favors complex or multiple origin, with each underwater channel or group of channels (or canyons) considered as a separate problem.

Island arcs and trenches

Out beyond the continental shelves in the western Pacific and northeastern Indian Oceans, and in the Caribbean Sea, are remarkable arcuate island festoons, ridges and trenches that complicate the differentiation of continents from ocean basins and pose their own questions of origin and differences between the different ocean basins. These arcuate systems are characteristically convex toward the sea and show systematic relations between ridges and trenches, to volcanism and to gravity anomalies and earthquake foci. The arcs are nearly perfect traces of the intersection with a sphere of planes that are defined by the locus of earthquake foci and dip steeply toward the continents. The belts of minimal values of gravity in simpler and presumably younger arc systems, like that at the eastern edge of the Philippine Sea, coincide with trenches that curve around the convex outer sides of the island arcs. In more complicated and presumably older arc systems, such as that of Indonesia, however, the low gravity values follow the crest of one of a pair of island arcs and ridges. Arcuate lines of volcanoes appear on the concave or continental sides of island arcs at successively more continent-ward positions, and the andesitic lavas that erupt from these volcanoes are richer in silica and alumina than are the basaltic lavas of truly oceanic volcanoes.

What does all this mean? Some geologists see it as continental accretion in progress, others as the foundering of continental margins, still others as evidence of the creeping or thrusting of continental blocks over the ocean basins or of the basins beneath the blocks. The deficiencies of gravity, low rate of heat loss and commonly thin sedimentary fill of the young trenches reflect some drastic tectonic influence. Is the light crust of the earth being pulled down into the heavy mantle material by descending convection currents? Is it being forced down by the creep of continent over ocean or ocean beneath continent? Does the low-heat flow of the trenches in contrast to the high-heat flow of the mid-ocean ridges mean that the trenches lie over the descending margins and the ridges over the rising centers of convection cells in the earth's mantle? To answer these questions we need a lot more geological and geophysical data about places like the Philippine and Caribbean seas, and Indonesia — including several carefully studied borings through the outer 5 to 35 kilometers of the earth's crust.

Island and reef geology

Of course, the most accessible samples of the ocean bottom are those that we can walk around on and hit with a hammer — the islands. Much of the field work for this kind of marine geology can be done without getting wet or even boarding a ship, and we can and have learned a great deal about the ocean by doing it. It is this sort of geology that has enabled us to draw an approximate petrological boundary — the so-called andesite line — around the Pacific Basin proper, and to work out many details of the record of varying sea level in the recent and ancient past. Further information from selected islands could greatly improve our understanding of the petrography and history of the mid-ocean ridges; of the significance of metamorphic and plutonic rocks, especially those of granitic composition, in the marginal areas; and of the age and paleomagnetic history of the ocean basins. All islands in and bordering the oceans should eventually be studied in detail, if for no other reason than that they are the largest samples of the sea floor that we can observe directly.

Between the tropics, and locally beyond them, the oceanic and shelf islands and even the continental shores are commonly fringed or paralleled by reefs of corals and other organisms. At other places, the submerged sites of former islands are indicated only by capping islands of reef rock or by the lagoon-encircling reefs called atolls. Reefs and reef islands attracted the interest of the earliest mariners not alone because they were hazards to navigation and the homes of nut-brown maidens. They were also the only places where fresh water and nonaquatic provisions could be obtained over great reaches of the tropical Pacific and Indian Oceans; without them neither the European mariners, the nut-brown maidens nor the vegetables would have been able to wander about the way they did! We sometimes signify this romantically by calling the islands "stepping stones."

The origin of these tropical reefs piqued the curiosity and stirred the pens of scientists even before Charles Darwin got around to them on the Voyage of the Beagle in 1832 to 1836, and it has continued to do so since. Darwin noticed that reefs are common within and on the west sides of oceans, but rare on their east sides — a relation that is generally attributed to the cold through nutrient rich waters rising on the lee shores of large land masses in the zone of the easterly trade winds. Darwin also formulated a theory that accounts for reef morphology as a progressive sequence from fringing reef to atoll, brought about by submergence of the reef foundations. Modern reef theory is more complex than this but retains the essential features envisaged by Darwin; and the central Darwinian thesis of great subsidence has been amply confirmed both by Harry Ladd's recent deep boring on Eniwetok Atoll and E. L. Hamilton's Cretaceous shallow water fauna from deeply submerged seamounts.

There are still big problems as well as lots of important little ones about organic reefs, however, that also involve fundamental problems about the oceans themselves. Why are atolls so excessively rare and reef corals so poorly represented in the Atlantic Ocean? What is the relation between the double line of large and complicated atolls in the north-central Indian Ocean and the rifted central ridge of the Indian Ocean? How does the reef building community manage to flourish so vigorously in the centers of the nutrient-poor oceanic "deserts?" What was it doing during the Pleistocene ice ages?

Sedimentary Relations

Turning now to the subject of sedimentation in the aquatic realm, we come at last to something that may sound a bit more like conventional geology. Every particle of solid matter that finally settles from the water column to accumulate beneath the depositional interface, in some way reflects its origin, transportational history and such post-depositional or diagenetic processes as may have affected it between the time of its last coming to rest below the depositional interface and its procurement as a geological sample. Study of such records for individual particles and their ensemble involves the application of all the techniques and equipment of the sedimentological, geochemical, petrological and paleontological laboratories toward the environmental and chronological recreation of its history.

Did this speck of matter precipitate chemically from sea water, or within or about an organism, under physicochemical or biological influences, or was it carried down from the land as a detrital particle of pre-existing rock? In any event, how and where did it start and to what processes was it subjected enroute? Has it always been in the sea or has it moved through fresh or brackish waters or the atmosphere? Has it gained or lost substance by ion-exchange, leaching or addition of matter interstitially? Did it move to its last resting place in suspension, by traction or by saltation, and was this transport all at once or by stages? How old is it—and is the time we date that of the present or an older sedimentational or alteration cycle? What changes affected it after burial? Can we use it for anything, or does understanding it tell us anything about other unsolved sedimentary, diagenetic, biochemical or paleontological problems? These are some of the questions the student of marine sediments must ask and try to answer with all the traditional and new apparatus and techniques he can bring to bear, from naked-eye observation of structure and texture, through simple microscopic and chemical examination, to analysis by means of x-ray diffractometer, mass-analyzer and electron probe. And he must study, experiment with, and compute the thermodynamic properties and interrelations of the superjacent and interstitial water and the pertinent biological fluids, as well as of the sediments themselves.

The marine geologist will be on the lookont, too, for rare elements and potential metallic ores in his samples, because he is aware of the need for geochemical distribution data and he knows already that certain things are characteristic of particular sedimentary environments, such as niobium and manganese in deep-sea sediments, and certain rare earths associated with phosphate in areas of upwelling. As yet, we are uncertain of the quantities, origin, tenor and recoverability of the submarine mineral deposits, but we are sure that phosphate, manganese and, perhaps, other useful substances besides magnesium will some day be recovered commercially from or from beneath the sea. We must also learn to control the circulation of organic nutrients so as to increase the yield of commercial fisheries or even bring them into being where none now exist.

Time Relations

Geochronometry

Geologists are interested in two kinds of time relations in the oceans. They want to date, correlate and work out the environmental history of the most complete sequences they can find and sample at various places beneath the sea. And they want to reconstruct the oceanography of bygone geologic times in as much detail as possible in order to test alternative paleogeographic patterns and polar orientations.

The most satisfactory basis for a system of geochronometry is by correlation with a sequence of events in a still continuing, unidirectional, nonrepetitive process. Organic evolution and isotopic decay are the two processes known to geologists to have these properties and, thus, the processes best suited for and most commonly applied to the measurement of geologic time. Fossils commonly give remarkably refined correlations in a relative time sequence but they are not always available, do not give ages in absolute units of time, and do not ordinarily give a sufficient degree of resolution in the younger deep sea sediments. Thus, for suitable samples of sediments younger than about 40,000 years we employ the radiocarbon method, for the discovery of which Willard Libby received the Nobel Prize. For very old and unfossiliferous rocks the ratios of mother to daughter isotopes in the uranium-lead, strontium-rubidium, and potassium-argon sequences are used. Until very recently, however, there was no suitable method of dating unfossiliferous sediments in the range of about 40,000 to a million years old. Attempts were made using the ratio of thorium^{230} (ionium) to uranium in marine sediments—the so-called ionium method—but this involves unknown factors that make the results highly subjective. In 1957, however, John Rosholt of the U.S. Geological Survey developed a new method that eliminates these difficulties by measuring the ratio of thorium^{230} to protactinium^{231} instead of to uranium. Inasmuch as thorium^{230} and protactinium^{231} are both daughter products of uranium, and exhibit similar geochemical behavior but different half-lives, their ratio should be a function only of the time elapsed since incorporation in the sediment. Recent tests appear to substantiate these assumptions and the method is now being employed and further tested on deep sea samples by Rosholt and associates at the University of Miami Marine Laboratory and elsewhere.

Paleoceanography

Finally, it seems fitting in a discourse on marine geology to introduce a few words on paleooceanography. Paleontologists and stratigraphers have been working out the distributions of ancient oceans and current systems on the basis of regional and global distribution patterns of sediments and fossils for a good many years without any means of testing their inferences. In 1929, however, the Russian, P. Lasareff, developed a stationary model with which he was able to test the evolution of currents for given arrangements of land, sea and wind systems. This has been greatly improved upon by William S. Von Arx, of the Woods Hole Oceanographic Institution, who has constructed a rotating tank apparatus in which he introduces concurrently the effect of the major wind systems and the earth's rotation on hemisphere or regional models of land and sea. With this apparatus, Von Arx has succeeded in duplicating all significant major features of the present ocean currents. It should, therefore, also reproduce the current systems of the geologic past, if we introduce approximately correct models in the right orientation with respect to the axis of rotation and wind systems of the times represented. Alternatively, if we have good reason to believe from the inferred migration routes of fossil organisms that particular current systems prevailed at a given time in the past, we can test the probable orientation of the earth and the apparent arrangement of its lands by finding that under which the preferred current system is best approximated.

Conclusion

It is appropriate to terminate this all too skimpy review of a limitless subject with a quotation from a man whom many regard as the father of modern American oceanography, Henry B. Bigelow (1931, "Oceanography" Chapman and Hall): "In the further development of sea science the keynote must be physical, chemical, and biological unity, not diversity, for everything that takes place in the sea within the realm of any one of these artificially divorced sciences impinges on all the rest of them . . . Our ventures in Oceanography will be most profitable if we regard the sea as dynamic, not as something static, and if we focus our attention on the cycle of life and energy there as a whole, instead of confining our individual outlook to one or another restricted phase, whether it be biologic, physical, chemical or geologic."

Recommended Collateral Reading

CARSON, RACHEL L., 1951. The sea around us: Oxford Univ. Press, 230 p.

EMERY, K. O., 1960. The sea off southern California: John Wiley & Sons, 366 p.

HAMILTON, E. L., 1957. The last geographic frontier, the sea: Scientific Monthly, v. 85, p. 294-314.

HILL, M. N. (editor), 1963. The sea, v. 3, The earth beneath the sea: Interscience Publishers, 963 p.

REVELLE, ROGER, 1955. On the history of the oceans: Journal of the Sears Foundation for Marine Research, v. 14, p. 446-461.

RUBEY, W. W., 1951. Geologic history of sea water: Geological Soc. Amer., Bull., v. 62, p. 1111-1148.

SEARS, MARY (editor), 1961. Oceanography: American Association for the Advancement of Science, Publ. 67, 654 p.

SHEPARD, F. P., 1963. Submarine geology (2d ed.): Harper and Row, 557 p.

VAQUIER, VICTOR, *et al*, 1961. Horizontal displacements in the floor of the northeastern Pacific Ocean: Geological Society of America, Bull., v. 72, p. 1251-1258.

VON ARX, W. S., 1957. An experimental approach to problems in physical oceanography: Physics and chemistry of the earth, v. 2 (L. H. Ahrens *et al.* editors), Pergamon Press, p. 1-29.