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SYMPOSIUM ON THE EXPLORATION AND EXPLOITATION OF THE SEA-BED AND ITS SUBSOIL

(STRASBOURG, 3 - 5 DECEMBER 1970)

SUBJECT No. I

Location and evaluation of the mineral resources of the sea-bed and its subsoil

STRASBOURG

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Location and evaluation of the mineral resources of the sea-bed and its subsoil

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REPORT

prepared at the request of the Organising Committee of the Symposium

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SUMMARY

I. CONFIGURATION AND TOPOLOGY. DEFINITION OF MORPHO-STRUCTURAL UNITS OF THE SEA-BED

First, a few basic figures on the area of the oceans and seas (according to Menard and Smith, 1966; the southern ocean, often listed separately, is here shared out among the others):

	million km^2
Pacific and bordering seas	181,344
Atlantic and bordering seas	93,932
Indian Ocean and bordering seas	74,118
Arctic Ocean (including the sea of Norway and the Baltic)	12,639
Total	362,033

This total covers 71% of the earth's surface. The average depth of oceans and seas is 3,730 m.

As a result of the tremendous amount of submarine research that has marked the period since the second world war, a number of basic units of the sea-bed can now be defined according to their morphological and structural characteristics.

The existence of most of these units has been known for some time, but we now have far more detailed knowledge than forty years ago. These units are: the continental margin, the abyssal plains and hills, the mid-oceanic ridge, trenches, aseismic ridges and fracture zones, seamounts, and shallow banks in the deep sea. The characteristics of these units are given below; the percentage of undersea surface occupied by each type of unit is based on Menard and Smith, who specify previous estimates.

CONTINENTAL MARGIN. The continental margin is the part of the sea-bed bordering the continents. It covers 20.6% of the sea-bed, and may be divided into the continental shelf, continental slope, and continental rise (the rise alone covering 5.3% of the sea-bed). At the Rome Symposium on the International Regime of the Sea-bed (July 1969), the following definitions of these three sub-units were proposed by a group of geologists and geomorphologists (Emery, Gaskell, Guilcher and Niino). The definitions may be regarded as the latest in this field.

Continental shelf: The zone around the continent extending from the low-water line to the depth at which there is usually a marked increase of declivity to greater depth. Where this increase occurs, the term shelf edge is appropriate. This shelf edge ranges in depth from less than sixty to more than five hundred and it averages 130 m. Where the zone below the low-water line is highly irregular and contains depths well in excess of those typical of continental shelves (as off southern California), the term continental borderland is appropriate.

Continental slope: The zone bordering the continental shelf that extends seawards from the shelf edge at declivities that average about 4°15' down to the depths of 1,200 - 3,500 m.

Continental rise: The zone that borders the base of many continental slopes and has a smooth declivity that averages 30' to depths of 3,500 - 5,500 m.

The combined continental shelf and continental slope (15.3% of the sea-bed) are sometimes called the continental terrace.

Very large islands such as Greenland, New Guinea and Madagascar have a continental margin in the same way as the continents proper. These islands may be described as island-continents.

The continental margin varies considerably in a breadth in different parts of the world. It is very wide in areas where emerged relief is low, such as western Europe, north-east America, northern Siberia and north-west Australia, and narrow or very narrow adjoining mountainous regions, such as south-east France, and the west of South America. In spite of its variability, the continental margin has certain general structural characteristics. Geophysical prospecting has now proved that it usually has a covering of sediment resting on a crystalline basement. The thickness of the covering varies considerably according to the region, ranging from almost nothing to over 5 km, and sometimes over 10 km. Generally, this covering becomes thicker further out to sea, while it may be lacking on the innermost part of the margin, e.g. directly adjacent to the Armorican Massif. It is generally thickest under the continental slope and the continental rise: beyond this, towards the deep sea-bed, the thickness falls off rapidly and substantially. It sometimes happens that the increase in thickness away from the continent is irregular, and that the basement outcrops on the continental slope, at least in areas where the slope is grooved by submarine canyons (see submarine canyons below). Sedimentation may also occur behind natural dams which may be tectonically-raised parts of the basement, organogenic reefs, or diapiric salt domes, to which we will return later. Our knowledge of the subsoil structure of the continental margin is based not only on continuous seismic profiling, now widespread in the most varied regions of the world, but also on deep-boring, which has begun on the eastern margin of the United States, and is to spread elsewhere in the near future.

On the continental shelf, the consolidated rock sometimes outcrops. This occurs in regions with strong tidal currents which hinder sedimentation, as in the central English Channel. Usually, however, the rock is covered by unconsolidated sediments, of which there are two kinds. Some of these were deposited during an earlier part of the quaternary period, when the general sea level was lower than today as a result of repeated expansion of icecaps in regions, leading to retention of some of the ocean water. It may thus be established that some 20,000 years ago the general sea level was 100 to 130 m lower than at present. At depths over 100 m, the shelf deposits formed at the time of this lower sea level are therefore continental and not marine deposits: river alluvion, often coarse because the solid transporting capacity of water courses was greater than today; off some countries which are now temperate, such as western France (Normandy, Brittany), there are periglacial deposits, linked with the cold climate without glaciers then prevalent in the area; there are also glacial deposits, in places where icecaps extended over the continental shelf, as in the Irish Sea, off the New England (USA) coast, or around the Antarctic continent. In general, these relict deposits, bearing witness to earlier conditions, are found mainly on the outer part of the continental shelf. This has been demonstrated by Emery in very different regions: east of the United States, the Chinese seas, western Europe, etc. This means that the outer parts of the shelf often contain coarse and not fine sediment, since the sediment laid down in that earlier age was coarse. As far down as at least 100 m we find the remains of former coastlines, now no longer functional because entirely submerged, consisting of beaches of shingle or sand, coastal calc concretions, and sometimes traces of lagoons: these may be found in the Bay of Biscay and off the coast of Provence. The continental shelf also has submerged fluviatile valleys, drowned karsts (calc relief), etc.

Other loose formations of the continental shelf are even now being deposited and shaped by the sea. These are found mainly, although not only, on the inner parts of the shelf, near the present coastline. Such formations include sandbanks like submarine dunes, frequently found in the waters off the British Isles, the Netherlands, Belgium and the Armorican Massif. Tidal currents play an important part in shaping these formations. Fine deposits of silt are also building up on the shelf. The origins of these deposits are various, and sometimes still controversial. Big rivers sometimes play a substantial part, but even the deposits of water courses as vast as the Mississipi, the Irrawaddy and the Amazon are not sufficient to cover the entire shelf around the river mouth, and earlier residual deposits are still found on the surface relatively short distances away.

Thus, the loose sediments of the continental shelf do not, in their present form, represent a system of equilibrium. Such a system no doubt existed in the course of past geological ages, as in the cretaceous age on the east coast of the United States; but during the quaternary, variations of sea level have been too frequent for such a system to become established. The pattern is a patchwork, influenced by local conditions. The loose sediments, whether contemporary or surviving from the past, are generally no more than a few dozen metres thick, often far less, and occasionally more. It all depends on the quantity and stability of the sediments.

On the slope and the rise, the main morphological feature consists of submarine canyons, found in many parts of the world in all latitudes. These are steep-sided valleys several hundred metres deep, often branching, and ranging from a few kilometres to several hundred kilometres in length. The longest known submarine canyon is the Bering Canyon in the sea of the same name, which is 400 kilometres long; not far away is the Pribilof Canyon, with a volume of 8,500 km^3. The usual volume of large canyons is less than 500 km^3. Off the coasts of Europe, these canyons are most numerous and characteristic in the Bay of Biscay and off the coast of Portugal and in the Mediterranean, off the coasts of Languedoc, Provence, the Nice region and Corsica.

It is possible that some canyons may be subaerial valleys swallowed up as a result of tectonic folding, as in the case of the canyon that penetrates the mouth of the Congo. But this hypothesis can certainly not be generalised, and the most widely-held opinion at present is that submarine canyons are formed and kept clear by slumping and sliding and by turbidity currents (one or other of these processes, or a combination of the two). Turbidity currents are presumed to be caused by the suspension of sediments in the water, particularly as a result of submarine earthquakes, which are thought to be the cause of high-speed flows of water which is dense because heavily loaded with sediment, and capable of causing erosion. While there is no doubt that submarine sandfalls have been observed in the Californian canyons, no real high-speed turbidity currents have yet been observed, and indeed any such observation would be impossible with present techniques, since the submarine observation equipment would certainly be carried away by the current and destroyed, together with its occupants. But the frequent existence of delta-form deposits at the mouths of canyons on the rise, as well as the channels with lateral levees that extend the lower part of the canyon over the abyssal bottom, are weighty arguments in favour of turbidity currents. Other arguments put forward are the sandy, sometimes coarse, deposits alternating with layers of silt in the canyons, especially in the Bay of Biscay. It is not known, however, whether these canyons are simply kept in being by such currents (which is easy to accept), or whether they have been dug out entirely by this means (which seems acceptable in the case of fairly friable sedimentary formations, but hard to believe in the case of granite, in which some canyons are found). It is possible that the location of many canyons was originally due to tectonic dislocation, submarine erosion subsequently setting in on the existing outline. Slumping and sliding may cause rough cavities which are later formed into valley networks by means of turbidity or other currents. However this may be, it has been found that the continental slope and rise are characterised by massive sedimentary movements, in contrast with the outer part of the continental shelf, which has recently been an area of great stability.

ABYSSAL PLAINS AND HILLS. According to Menard and Smith, this important unit covers 41.8% of the sea-bed. It is found between about 3,000 and 6,000 metres. It is the largest region of all, and one which differs fundamentally from the continents in its structure. The top of the mantle rocks under the earth's upper crust, a zone where the velocity of seismic waves is 8.1 km per second, lies some 7 km below the ocean and 30 - 40 km below the continents. Not only is the oceanic crust less thick than the continental crust, but it is also denser and less variable in composition. It contains three layers, increasing in density from top to bottom, and thus increasing in velocity of transmission of seismic waves. Layer 1 has an average thickness of 450 metres and a velocity of some 2 km/s; the Layer 2 is 1.75 km thick, with a velocity of 5 km/s; and Layer 3, 4.7 - 4.9 km thick with a velocity of 6.7 km/s. Layer 1 is almost certainly composed entirely of unconsolidated or very slightly consolidated sediments, dating from the lower cretaceous age or later, i.e. mainly tertiary; Layer 2 probably consists of basalt, perhaps with some consolidated sediment from the jurassic or earlier in certain parts; Layer 3, which forms over two-thirds of the crust, is composed either of peridotite or of basalt which is more metamorphic than that of Layer 2. Thus, the actual ocean bed should generally have only a very thin layer of sediment, unlike the continental margin, and there is dense eruptive rock directly below this sediment. There are two reasons why this sedimentary layer is so thin: these beds are relatively new, not very old; and the speed of sedimentation is far slower than on the continental margin. These two points are explained in greater detail below.

The abyssal plains are exceedingly flat stretches with a slope of less than 1:1,000. The plains alternate with undulating hills, ranging from a few metres to several dozen metres in height. These are found in all oceans, and in deep seas such as the Gulf of Mexico, the North Polar Sea and the Mediterranean. There are isolated hills on some abyssal plains, as for example in the Gulf of Mexico. The abyssal plains sometimes communicate by gaps linking one with another, as in the case of the plains of Biscay and Iberia, off the Iberian peninsula. The plains and hills occupy vast depressions known as oceanic basins (or sea basins, in the case of seas such as the Mediterranean).

The flatness of the abyssal plains is due to the sedimentary coating which has covered former irregularities, which may once have been abyssal hills. There are two kinds of sediment: turbidites and pelagic sediments.

Turbidites are sediments thought to have been laid down by turbidity currents, this belief being due to their structure (graded bedding, i.e. a relatively coarse lower layer followed by finer and finer layers, and repetition of the same sequence, each couplet being due to a particular turbidity current). Since turbidity currents are born on the continental slopes and the rises that follow them, abyssal plains with turbidites must be in topographical continuity with these slopes, or with the insular slopes that function in the same way as the continental. Thus in the Indian Ocean the abyssal plains of the Indus and Ceylon must be undergoing sedimentation by turbidites from the rivers Indus and Ganges, which have built up deep-sea cones at the edge of these plains. Turbidites may spread from one abyssal plain to another if these plains are interlinked (plains of Biscay and Iberia). Leveed channels, such as exist at the mouths to submarine canyons, run across certain abyssal plains, and are thought to feed these plains periodically with turbidites. In the

North Pacific, present deposits of turbidites are located in the trenches (see below), as well as off the Hawaiian Islands, and particularly in the Tufts Abyssal Plain, off the coast of Washington and British Columbia; to the north of this region, the Aleutian Abyssal Plain contains no turbidites, at least in its upper sediments, but only pelagic deposits, because it is cut off from the Aleutian Islands by the Aleutian Trench.

Pelagic sediments are those caused by the showering on the bottom of fine particles suspended in the sea. These consist either of organic particles, calcareous as with Globigerina ooze, or siliceous, as with Diatom ooze, or of mineral particles, still finer than the above, the red clay of the ocean floor. The distribution of calcareous and siliceous particles depends on the distribution in the ocean waters of organisms whose skeletons fall to the bottom after death: Diatom ooze is found in high latitudes. Red clay is found in the deepest parts, from 4,000 to 4,800 metres down, because at these depths calcareous test (the most common) dissolve before reaching the floor. Red clay, which contains 70% to 80% silica and alumina, is thus a residual deposit of sedimentation; where the depth is not so great, it is diluted with organic particles. It consists of the finest mineral particles from the continents. It covers an area of some 100 million square kilometres, 70 million of which are in the Pacific. The boundary between the two kinds of deposit is known as the compensation depth. Pelagic deposits also often contain numerous manganese nodules, which will be discussed in connection with mineral resources. These nodules, sometimes weighing over 100 kilograms but generally smaller, are scattered over the sediment surface. It appears that pelagic deposits build up most rapidly in the basins of the western parts of the oceans, where they are encouraged by deep oceanic circulation, intensified in these parts.

The average accretion rate of pelagic sediments is certainly very low, but it is naturally even lower for mineral red clays than for organic particles, since the former are residual of the latter. For the former, the figure of 1 mm per 1,000 years has been put forward, and for the latter, 1 cm per 1,000 years. In the case of turbidites, the accretion rate is certainly higher since these are fed from the continental slope, but the rate varies according to supply. In the Indian Ocean, it is reckoned that 40% of sedimentation is formed by the deep-sea cones of the Indus and the Ganges alone (see above).

In the Antarctic Polar regions and in certain Arctic regions, e.g. off Greenland and Labrador, the deep sediments contain coarse particles from melting icebergs. These are known as glacio-marine elements, and are also found on the continental shelves and slopes of the same regions.

MID-OCEANIC RIDGE. This unit covers 32.7% of the sea-bed, and is thus the second largest in area, after the abyssal plains and hills.

The mid-oceanic ridge is the longest and broadest mountain system in the world. It was first discovered in the Atlantic, but it extends into the other oceans over a length of 60,000 km. It stretches from Iceland (its largest area above sea level) in the Atlantic to the southern ocean, rounding the south of the African continent, and forming an upside-down Y in the Indian Ocean, one of its branches penetrating the Gulf of Aden, while the other stretches south of Australia and New Zealand into the Pacific where, with the name of East Pacific Rise, it finally links up with the California coast of North America. From the north Atlantic it enters the Norwegian Sea by way of Jan Mayen Island, then crosses the North Polar Sea, ending up at the Lena Delta in Siberia. Over the whole of its length, its general elevation above the surrounding oceanic basins ranges from 1,000 to 3,000 metres, and its breadth from 1,000 to over 2,500 kilometres. Apart from Iceland and Jan Mayen Island, the ridge appears above sea level at Ascension Island and Easter Island, but almost all of it remains submerged.

Throughout its length, the ridge is accompanied by shallow earthquake epicentres. Also, in the Atlantic and Indian Oceans, it is accompanied in its axis by a 25 - 50 kilometre-wide rift, 1,000 to 2,500 metres below the adjacent peaks, which does not seem to be present in the Pacific Ocean. It has long been known that East Africa has two sub-parallel rifts running north to south, and it is thought that these are a continuation of the Indian Ocean median rift, via the Gulf of Aden and Ethiopia. The seismicity of the ridge is especially centred in the median rift.

The topography of the ridge is very rugged, and one major feature is a complete or almost complete lack of sediments, at least on its median part; away from the axis towards the basins, the sediments are slightly more abundant and slightly less recent.

The mid-oceanic ridge also differs in structure from the adjacent basins. The Layer 3 of the oceanic crust is missing, at least in the Atlantic, instead of which we find, only 2 or 3 km below the ocean floor, rocks with a velocity of 7.1 to 7.5 km/s, a velocity between that of the Layer 3 and that of the normal mantle rock. In the Pacific section the anomaly is not so great, consisting rather of a flattened bulging of the layers.

These and other factors, in particular those connected with changes in the earth's magnetic field over the ages, are now interpreted by the theory of the spreading sea-floor, which is the one most likely to correspond with reality. The mid-oceanic ridge is seen as the rising place of sub-crustal materials, which then expand laterally, transporting with them the sea-bed. This may be seen as a modern version of the continental drift theory, put forward by Wegener in the first decades of this century. But the motor of the whole system is now sought in the ridge. The continents follow the movement of the sea-bed. By examining positive and negative magnetic anomalies, in a pattern parallel to the ridge, we can even draw up a chronology and suggest figures for the spread of the sea floor in different places: this spread is not everywhere the same, and even appears to have stopped in certain places. For example, there must once have been a branch of the mid-oceanic ridge in the axis of the Labrador Sea; this branch must have been long inactive in view of the low seismicity of the area. In the south-east Pacific, the Chilean Ridge, which links Chile with the mid-oceanic ridge, has seismic activity like the latter, and, also like the latter, is a site of an expansion of the sea-floor. It is thought that the Bay of Biscay was opened up by the separation of Armorica and Galioia, but this movement is believed to have stopped by the lower Miocene. The structural differences between the ridge in the Pacific and the ridge in the Indian and Atlantic Oceans suggest two different stages of development, or perhaps two different kinds of spreading. The rate of spread is a few centimetres per year: 1 to 2.25 in the Atlantic, 1 to 3 in the Indian Ocean, and 2 to 6 in the east Pacific ridge. Some authorities believe that there are periods of arrest and periods of renewed movement.

At the point where the east Pacific ridge reaches the North American continent, it must have raised the borderland of the continent and caused fragmentation into floating blocks which migrated westwards.

Menard has suggested that before the development of the east Pacific ridge, another enormous ridge, which he calls the Darwin ridge, had developed in the centre of the same ocean, and that its subsequent depression, taking with it the mountains of the ridge, led to the formation of numerous atolls (see below).

This would be a rational, if not a certain, explanation of the thickness of the sediments, which is nil or almost nil on active ridges, and slight on abyssal plains and hills.

TRENCHES. These long narrow depressions (over 1,000 km long, but only 50 to under 5 km wide at the bottom), the deepest in the world, are usually associated with island arcs. These units cover only 1.7% of the sea-bed, including the narrow ridges which bear the island arcs. This feature is most developed in the Pacific. There are trenches along the whole western side of this ocean, generally situated on the outer, i.e. the eastern, side of the island arcs. These trenches are, from north to south, the Aleutian, Kuril, Japan, Marianas, Admiralty, Vityaz, Tonga and Kermadec Trenches. Between Japan, the Philippines and the Marianas, there are other parallel trenches on the eastern side of other island arcs: the Philippine Trench, and the Ryukyu. There are three characteristic trenches in Melanesia, on the inner, western, side of the island arcs or the Bismarck Archipelago, Bougainville, the Santa Cruz Islands and the New Hebrides. There are also one or two trenches on the inner side of the Indonesian Islands.

There are other trenches in the Pacific along the mountains of western North and South America, off the coast of Lower California, Guatemala, Peru and Chile. In these cases, the continental mountains take the place of the island ridges.

Outside the Pacific, there are other trenches accompanying the Antilles (Puerto Rico Trench) in the Atlantic, the Java Arc in the Indian Ocean and the Scotia or South Sandwich Arc in the southern ocean. All these trenches are normally situated on the outer side of the island arcs.

Depths of 11,022 m have been measured in the Marianas Trench, over 10,000 m in the Kuril and Japan, Philippine, Tonga and Kermadec Trenches, and over 8,000 m in several others, notably in the Chile Trench. Ocean depths of over 8,000 m form only 0.04% of the total area of oceans according to Menard and Smith (0.14% consists of depths greater than 7,000 m), which points up the highly exceptional nature of these trenches.

Trenches are associated with seismic epicentres, as is the mid-oceanic ridge; but a great many of these epicentres are situated at depths greater than 200 km, which is far more peculiar to the trenches; the epicentral plane, instead of being vertical, slopes towards the continent, so that the deep-seated epicentres are either under the bordering seas of eastern Asia or under the American continent, in the case of the foci linked with the Chile-Peru Trench. The epicentral plane certainly corresponds to vast oblique faults, which have opened up over several hundred kilometres inside the earth, and reach the ocean bed in these trenches.

Various explanations have been put forward at different stages as to the origins and workings of the trenches. The favourite explanation at present is linked with the theory of the spreading sea-floor mentioned above. According to this theory, the trenches would be the ocean-edge terminal of the sea-bed originating from the central scar of the mid-oceanic ridge and spreading out on either side like a conveyer belt. The sea-bed would go down towards and under the continent along the oblique fault. This conveyer belt theory is generally satisfactory. However, it is still open to question why there are not trenches at the edge of every ocean opposite the mid-oceanic ridge, and why there are almost no trenches at the edges of the Atlantic. Were there perhaps once trenches, now filled with sedimentation? Under the continental margin of the east coast of the United States and Canada, the upper surface of the layer with a velocity of 5.6 km per second is as deep as 12 km in some places, forming a buried furrow from the north of the Bahamas to south-east Newfoundland. But it is not accompanied by seismic epicentres. Another explanation is the "plaques" theory: the Americas form one plaque with the west Atlantic, and Africa and Europe with the east Atlantic, so that there are no scars where they meet the ocean.

Although the trench bottoms are narrow, they are often flat and covered with recent sediments, even away from the possible filled-in trenches in the Atlantic. The thickness of unconsolidated sediment in these great trenches varies. In the Japan Trench, for example, the outer slope is formed of sediments which are acoustically transparent and can thus be geophysically observed; these sediments are several hundred metres thick, and have been affected by a series of step faults. Geophysical investigations have also shown that the southern part of the Peru-Chile Trench has been completely filled in by sediment over two kilometres thick; farther north, between 32° and 8° S, the thickness of the sediment is less than 500 m; still farther north, it increases again to 1,000 m. Trench sediment is no doubt largely furnished by turbidity currents originating on the slope of the associated island arcs (or on the continental slope, in the case of the west American trenches). This explanation is supported by the fact that coarse stones and gravel have been dredged up from a depth of 10,190 m at the bottom of the Philippine Trench. In spite of their great depth, these trenches are not without life, since down to the very bottom their waters contain oxygen, which shows that they are renewed.

ASEISMIC RIDGES, FRACTURE ZONES, SEAMOUNTS AND SHALLOW BANKS IN THE DEEP SEA. Leaving aside the fracture zones, which are superposed on the mid-oceanic ridge, these units together occupy the remaining 3.1% of the sea-bed.

The oceans contain many ridges which, unlike the mid-oceanic ridge, are not seismic. These ridges are far shorter, although some are over 2,000 km long. There are the Lomonosov Ridge and Mendeleev Ridge in the Arctic, the Ninetyeast Ridge and the Mascarene Plateau in the Indian Ocean, and the Walvis Ridge and Rio Grande Ridge in the south Atlantic. All of these border basins with abyssal hills and plains; apart from the Mascarene Plateau, none has any emergent point. Aseismic ridges are most numerous in the Pacific. Most of the Pacific ridges lie north-west - south-east, or approximately: the Hawaiian Ridge, the Line Ridge, the Marshall Ridge, the Gilbert and Ellice Ridge, the Phoenix and Tokelaw Ridge, the Samoa Ridge, the Tuamotu Ridge, the Society Ridge, the Cook and Austral Ridge. All these ridges are volcanic, and active colcanism has migrated from one extremity to the other (in general from north-west to south-east) in the course of time. Volcanism is still very active today in the Hawaii and Samoa Ridges. Ridges have generally evolved over tens of thousands of years.

Fracture zones are vast, elongated structural disturbances, consisting of a combination of escarpments, asymmetrical ridges, troughs and seamounts, stretching for over one thousand kilometres, and sometimes for several thousand kilometres, in the Pacific, Atlantic and Indian Oceans and in the Norwegian Sea. They transect the mid-oceanic ridge with which they are associated, causing lateral displacement. For instance, in the north Pacific the Mendocino Fracture Zone displaces the sea-bed to the north of it 1,000 kilometres westwards. Other fracture zones include the Murray, Clarion, Clipperton, and Easter Fracture Zones in the Pacific; the Rodriguez, Amsterdam and Owen Fracture Zones in the Indian Ocean; and the Romanche and Vema Zones in the Atlantic. The development of fracture zones has been linked with the spreading of the sea-floor.

There are numerous seamounts scattered over the sea-bed. These are almost always volcanoes, some associated with seismic or other ridges, and others independent. According to Menard, there must be ten thousand volcanoes rising at least one kilometre above the sea-bed in the Pacific Ocean alone. Submarine volcanoes fall into two groups. The first, which have never emerged, have retained the original conical shape. The others have built up to the sea surface and been truncated by marine erosion after ceasing to be active; they have subsequently subsided, and now form truncated cones at varying depths. Many such mountains are known in the mid Pacific, by the Marshall Islands and further north. These are called guyots.

Where volcanoes in tropical waters have followed the same course of development as these guyots, and where subsidence has been sufficiently slow, the coral reefs growing there have offset subsidence by simultaneous growth, forming atolls. The subsidence of the Darwin Ridge (see above) in the mid Pacific has led in some cases to guyots and in others to atolls, which exist side by side in the Marshall Islands area. The formation of atolls takes millions or tens of millions of years.

Finally, there are various areas of shallow banks, rising out of the abyssal depths. This occurs in the Coral Sea between Australia, New Guinea and New Caledonia; in the South China Sea; the Indian Ocean, north-east of Madagascar (Chagos); in the Caribbean Sea; in the tropical Atlantic, north of Cuba and Haiti; and in the north-east Atlantic, between Ireland, Scotland and Iceland. Some of these banks have islands or islets, such as Chesterfield in the Coral Sea, the Paracels in the China Sea, Rockall in the north-east Atlantic, and the Bahamas in the tropical Atlantic; others have no islands, as in the case of Rosalind Bank in the Caribbean Sea, and Lousy Bank and Bligh Bank in the north-east Atlantic. The origin of these banks varies. They may be volcanic (Rockall), or built up by prolonged calcareous sedimentation (Bahamas), or they may be the remains of continents as isolated rafts in the ocean following expansion of the sea floor (the Seychelles Bank).

The different units comprising the sea-bed thus vary considerably in area. The three largest units, the continental margin (20.6%), the abyssal plains and hills (41.8%), and the mid-oceanic ridge (32.7%) alone cover over 95% of the sea-bed; the others may, however, be of interest in spite of their relatively small area. Since oceans and seas cover 362 million square kilometres, even a unit of only 1/100 of this area would still be six times as large as France, or larger than one-third of Europe.

The proximity of the continental margin to dry land, its continental type structure and its comparative shallowness obviously make this unit of particular interest from the practical point of view.

II. MAIN MINERAL RESOURCES AND THEIR LOCATION IN RELATION TO THE UNITS OF THE SEA-BED

This report is confined to the resources as such, leaving aside questions of potential exploitation or economics, i.e. whether extraction from the sea-bed is technically feasible and economically competitive with extraction from dry land. These problems are obviously crucial, but will be dealt with in other reports to the symposium.

HYDROCARBONS. These are liquid fuels and natural gas, and are the most valuable resources in the sea-bed, at least at our present stage of exploitation of natural resources. In 1968, according to Emery, 3.9 thousand million dollars' worth of crude oil and gas were extracted from the sea-bed, out of a total value of 4.43 thousand million dollars for all submarine mineral resources extracted that year. In the same year, total crude oil and gas production (continents and sea-bed) was 26 thousand million dollars. Submarine production at 15% of this total is thus far from negligible.

Submarine oil and natural gas is probably mainly located inside the continental margin. Indeed, until very recently it was thought that this was the only unit of the sea-bed containing these resources. This assumption was due to the similar structure of the margin and the continent, which hence contain the same kinds of products. Hydrocarbons are found in sedimentary rocks. They are formed by the decomposition of living creatures away from the air, probably mainly in stretches of shallow water. After they have been formed, hydrocarbons can migrate into rocks, and accumulate in permeable rock-stores, e.g. limestone or sandstone. They accumulate especially in domes or anticlines covered with an impermeable layer which prevents their escape. Hydrocarbons are often found in salt domes, which have risen through other rocks because of the low density of salt, and the discovery of salt domes or diapirs is always seen as a favourable sign in oil prospecting, although not a sure sign of oil or gas.

Offshore oil prospecting is therefore carried out on those parts of the continental margin which are not composed of crystalline rocks. Prospecting takes place mainly on the shelf, but it is possible that the continental slope and even the rise may contain hydrocarbons, since these too are sedimentary, and if no oil has been found here so far, this is no doubt mainly because investigations have concentrated on shallower waters at the outset.

Two kinds of methods are used in prospecting. Geophysical methods - surveys of magnetic field and gravitational field, and seismic reflection and refraction - rapidly establish the main structural outlines. Domes and anticlines, possibly saliferous, may be found in this way. Once this has been done, drilling must be carried out at places thought to be favourable. Drilling is far more costly than geophysical prospecting, and results are never certain: out of all the possible places, there will always be only a minority which prove productive. In the shallowest waters, drilling platforms are built resting on the sea-bed. In deeper water (in general, once the water is more than 50 to 60 metres deep) floating or semi-submersible rigs are used, and for very deep prospecting (over 500 metres), "dynamic positioning" derricks, kept in position by a system of propellors operating in different directions. The technical problems are similar for exploration and exploitation, but exploitation also poses other problems beyond the scope of this report.

Since it is already possible to drill to great depths, prospecting has been carried out on the Sigsbee Abyssal Plain (Gulf of Mexico), at a depth of 3,600 metres, under the American JOIDES project. Drilling was carried out on the Challenger Knoll which rises slightly above the plain, and showed that there might be oil outside the continental margins.

Drilling showed that the hill was in fact a salt dome, inside which a limestone reservoir of oil and gas was discovered. The salt dated from the middle Secondary. Exploitation of these hydrocarbons in the foreseeable future is out of the question, since it would not be an economic proposition, but the discovery is of the greatest scientific importance, since it has proved the existence on an abyssal plain of rocks which it was thought could not exist in the deep sea-bed beyond the continental margin. Other research bodies have also recently discovered, by geophysical methods, structures which appear to be salt domes in other abyssal regions, such as the western Mediterranean, and the Atlantic off the north-west coast of Africa. This has not been confirmed by drilling in either place, but the Challenger Knoll shows that it is not impossible. The Challenger Knoll may be part of the same general structure as the saliferous basin of the Tehauntepec Isthmus (Mexico). The most puzzling question at present is how these saliferous rocks, usually formed by evaporation in lagoons, have been formed in places such as these. It is conceivable either that these are not "true" abyssal regions, but parts of continents or continental margins which have subsided to great depths (this is quite plausible in the western Mediterranean region) or that the salt in this case was not formed by evaporation but accumulated by some other process, still to be determined (however, the salt of the Challenger Knoll is similar to the evaporites known around the Gulf of Mexico).

To sum up, hydrocarbons, the main known mineral resource of the sea-bed, are, as far as we know, mainly found on the continental margins. They may also exist in salt domes on the abyssal plains, but it would be very surprising if this second kind of deposit were anything like as widespread as the first.

RESOURCES MINED FROM GALLERIES. Since the 19th century, mineral resources have been mined through shafts sunk beneath the adjacent land. These resources were an extension of those previously discovered under dry land. Thus, certain British coalfields extend under the sea, and have long been successfully exploited. Mining of this kind takes place on an even larger scale in Japan. This kind of mining does not depend on oceanographic progress, but is a direct extension of continental mining. Emery reckons that submarine coal-mines produced 335 million dollars' worth of coal in 1968 (2% of total world production), and submarine iron-mines 17 million dollars' worth of ore. It is unlikely that there will be any substantial increase in this kind of production, in view of the slackening interest in coal, and the operation of vast high-grade iron ore mines, frequently open-cast workings, in various new countries. We shall therefore mention this subject only briefly.

SAND GRAVEL. Sand and gravel are submarine resources with a great future, on the other hand. It has been estimated that 160 million dollars' worth of these minerals was extracted in 1968, which puts them in third place, after hydrocarbons and coal. Their value is reckoned to be 8% of that of dry land sand and gravel production. Emery estimates that two-thirds of the ocean-floor production is from off the United States, and the remaining one-third mainly off England. Developments in western France, and especially Brittany, are also worth mentioning. The world's continental shelves certainly contain vast quantities of these materials, which may be used either for soil correction if they are calcareous, or, more generally, for concrete production. The growth of modern coastal cities will require increasing quantities of these materials. Exploitation has so far been confined to the shallowest parts of the continental shelf lying nearest to dry land. Perhaps even more than with other resources, shallow water is a crucial factor. Thus off the coast of Brittany sand is collected from waters up to or barely exceeding 10 metres in depth. But it is important to draw up an inventory of resources on deeper parts of the shelf, and it is in this light that work has begun on detailed cartography of the sediments on the inner part of the French-Atlantic shelf. It would be valuable to extend such cartography to other similar parts of the world.

METALS OTHER THAN THOSE CONTAINED BY MANGANESE NODULES. There may be many kinds of useful or precious metals on the sea-bed, but one of these, tin, is of particular importance because it is found in a concentrated alluvial form which may have been transported by watercourses to certain parts of the continental shelf during low sea-levels of the quaternary. At least 5 million dollars' worth of such tin was extracted in 1968 (in comparison with 455 million dollars' worth from dry land). Ocean-floor production might expand. It has been suggested that stanniferous alluvia might be found on the continental shelf of the Armorican Massif, as a continuation of those already discovered and worked in the subaerial valleys of Brittany. These hopes have not been fulfilled to date.

Shortly after 1960, hot brine pools were discovered in certain deep depressions of the Red Sea. Shortly afterwards, mineral deposits rich in zinc (2.6% to 3.4%), copper (0.9% to 1.3%), lead (0.10%), silver (0.005%) and gold (0.00005%) were discovered under these hot brines, with an estimated total value of 2 thousand million dollars, not counting exploitation costs. The above figures are merely an indication of scale. Actual exploitation would be difficult, because these deposits are separated from the sea-bed by an unproductive layer of 5 to 10 metres, under 2,200 metres of water, and because the nearest coastlines, some 60 to 80 kilometres away, are deserts without industrial infrastructure.

DIAMONDS. Diamonds are found on the continental shelf of south-west Africa, an extension of the continental diamond deposits. These are worked in shallow waters, near the coast, but extraction is difficult, especially because of the heavy swell in this area. Four million dollars' worth of diamonds were extracted in 1968 (1% to 2% of world diamond production). Such production is not very profitable, although it seems to have become a little more so in 1970.

PHOSPHORITES. Phosphorites, used mainly as fertiliser, are now extracted mainly from a fairly small number of subaerial sources (Florida, Idaho, Morocco, Algeria, Tunisia, USSR and island atolls in the Pacific and Indian Ocean). But there are also marine phosphorites at depths of up to 3,500 metres. Some of these sites are on the continental shelf, the upper part of the continental slope, and the tops and sides of submarine banks. Phosphorites are found as nodules, in sands, muds and certain semi-consolidated sediments. They date from the tertiary or quarternary age (especially the tertiary). They are particularly associated with upwellings along certain continental west coasts in tropical and sub-tropical regions, where the waters have a high phosphate content, and where the phosphate tends to be precipitated in colloidal form in surface waters. It then conglomerates into nodules on the bottom. The structure of these nodules varies. Usually they are irregularly shaped fragments, ranging in thickness only from a few millimetres to a few centimetres, without any concentric arrangement of elements. There is also a far smaller quantity of concentrically structured oolitic phosphorites. The best known marigenous phosphorites are those of southern California. The $P_2 O_5$ content ranges between 22% and 29%, while that of land phosphorites is usually from 30% to 33%.

MANGANESE NODULES. These are probably one of the most plentiful sea-bed resources, along with hydrocarbons, sand and gravel. Manganese nodules are a deep sea deposit, generally found at depths of 3,000 to 5,000 metres, i.e. on the abyssal plains and hills. As mentioned above, they are associated with pelagic deposits of organic particles and red clay. They are even more varied in structure than marigenous phosphorites. The nodules are conglomerated around a core which may be formed of any hard object lying on the sea-bed: cinders or volcanic bombs, sharks' teeth, otoliths, cetacean bones, and siliceous or calcareous sponges.

The form is often influenced by the core, and the structure is often concentric. The average size of nodules is 3 cm; they commonly range from 0.5 to 25 cm, although one has been found weighing 850 kg. They are more frequently found in association with red clay than with globigerina ooze, but often in association with radiolaria ooze, another pelagic deposit. It is not yet known exactly how they are formed. It has been suggested that they may be caused by deep currents, submarine volcanic eruptions, submarine springs, or the alteration of igneous formations on the sea-bed. The speed of formation seems to vary in different places, depending on the available manganese and iron, and the properties of the waters and the surface of the core. Estimates ranging from several centimetres per hundred years to one millimetre per hundred thousand years have been put forward for different places. Estimates of about 1 mm to 0.1 mm per thousand years may be regarded as average. At a rate of 0.1 mm per thousand years, six million tons of nodules would be formed each year on the bed of the Pacific Ocean alone.

The composition of these nodules is obviously a crucial factor when considering possible exploitation. The useful minerals they contain include manganese, cobalt, nickel and copper (iron is also present, but is of no interest because far more common). According to Mero, who has conducted a careful study of available data, the analysed content of these minerals is as follows:

	Pacific			Atlantic		
	maximum	minimum	average	maximum	minimum	average
Manganese	41.1%	8.2%	24.2%	21.5%	12.0%	16.3%
Cobalt	2.3%	0.014%	0.35%	0.68%	0.06%	0.31%
Nickel	2.0%	0.16%	0.99%	0.54%	0.31%	0.42%
Copper	1.6%	0.028%	0.53%	0.41%	0.05%	0.20%

The average composition of the nodules is thus considerably more favourable in the Pacific than in the Atlantic, but there are, of course, great regional differences within each ocean. The ratios of the four most useful minerals, and also the manganese-iron ratios, vary according to area, and Mero has attempted to chart these variations in the Pacific.

There is no point in mentioning the extraction of sea salt in this report, except as a reminder, nor the extraction of certain other dissolved substances, since this symposium is dealing with the resources of the sea-bed and not those of the waters.

III. REGIONAL LOCATION OF RESOURCES

Certain regional factors have been mentioned above, in connection with sand and gravel production, metalligerous concentrations in the Red Sea, and diamonds off the south-west African coast. This section will therefore be confined to hydrocarbons, tin, phosphorites and manganese nodules.

HYDROCARBONS. Four of the world's continental shelves are already important sources of oil and/or natural gas: the Gulf of Mexico off the Mississipi Delta, the Maracaibo Lake (Venezuela), the Persian Gulf and the North Sea. In these four regions, substantial resources have been discovered under parts of the shelf that are fairly shallow (less than 100 m), or not far from dry land, or both. Other regions of considerable interest, where exploration is now at different stages are the borderlands of California, Western and South-East Australia, New Zealand, Nigeria, Indonesia, Alaska, Thailand, South Korea, Aquitaine and Italy. In many of these regions extraction is planned shortly or has already begun (e.g. Nigeria). The location of hydrocarbons on the continental margin is not confined to a small number of regions, but is widespread over the whole of this planet. It is still to early to pinpoint regions where the supply is plentiful or meagre. Even in the case of continental exploration, it is still rash to state that a certain sedimentary region is not rich in hydrocarbons. The only regions that can be counted are those formed of crystalline and metamorphic shields, either above or below sea level.

TIN. Submarine tin placers have been found on the continental shelves of Indonesia and Thailand, where their links with subaerial, alluvial deposits are obvious, both kinds coming from local parent-rocks. These placers are worked at depths down to 30 or 40 metres. Unlike hydrocarbons, submarine tin is not produced in many areas, and it is to be presumed that fuller knowledge will not reveal plentiful deposits in places where tin is not already found on adjoining dry land.

PHOSPHORITES. Apart from the continental borderland of southern California, mentioned above, places where these deposits are found include banks off the coasts of Peru and Chile, southern Africa, the south-eastern United States and, no doubt, north-west Africa. The link with upwellings is noteworthy in many places, but does not seem to be always present. Mero reckons that 10% of the world's continental shelves may hold phosphorites. This mineral would thus be far more widespread in submarine deposits than in subaerial deposits, which may prove to be of economic or political interest.

MANGANESE NODULES. These nodules are generally present in all oceans, and the Pacific seems to be particularly rich (it has been seen that the metal content of these nodules is also higher in the Pacific than in the Atlantic). The central Pacific takes first place, followed first by the western and, closely after, by the eastern Pacific. The nodule concentration is thought to be between 0.05 g and 3.8 g per cm^2 in the Pacific, with an average of 1.45 g in the centre, 0.86 g in the west and 0.78 g in the east. However, these estimates are based only on a hundred or so measurement using samples or photographs of the sea-bed, and may be subject to major correction. Far fewer measurements have been made as yet in the Atlantic and Indian Oceans, and it would be wiser not to put forward any specific figure. Whilst manganese deposits seem less abundant here than in the Pacific, there may be certain areas of high concentration, as on the Blake Plateau off the Carolina and Florida coast, where, according to Mero, the Gulf Stream may speed up accumulation.

IV. ESTIMATED QUANTITIES

This attempt to estimate quantities is confined to a few mineral resources, and based mainly on the work of Mero.

HYDROCARBONS. As on the continents, absolute evaluation of hydrocarbons is very risky and subject to frequent correction. It is perhaps safer to put forward estimates in relation to the known continental resources at a given period. In 1951, Pratt thought that marine hydrocarbon resources might be equal to land resources. In 1969, Gaskell thought that the continental shelves might well contain at least one quarter of the world's oil resources. Such estimates can be based only on impressions or bold extrapolations. It may be suggested that the resources of the shelf are fairly similar in quantity to those of the continents not substantially less but certainly not substantially more. The potential resources of the continental slopes and rises are completely, or almost completely, unknown, and this applies even more to the resources of the abyssal regions. If annual oil production is to double by 1980, rising to four thousand million tons, we may venture to predict that offshore production will triple over the same period. But it all depends on what oil discoveries may be made in continental and marine fields, and this brings us back to questions of economics, which we have decided to leave out of this report.

SAND AND GRAVEL. Although there is still a sad lack of accurate submarine sedimentological maps, it may be assumed that there are at least several hundred thousand million tons of these resources in the world, even confining ourselves to sand and gravel at depths of less than 40 or 50 metres, i.e. the most easily accessible. This resource is very widespread, although the inner parts of certain continental shelves are very muddy, and coarser sediments are found only further out. This applies to the north-east coasts of South America and the German coasts.

PHOSPHORITES. On the basis of the presumed extension and characteristics of phosphorite deposits in southern California, where they are better known than elsewhere, Mero estimates that the total world tonnage is 300 thousand million, one-tenth of which could be extracted.

MANGANESE NODULES. The same author has attempted to estimate the tonnage of manganese nodules in the Pacific Ocean alone, certainly the most plentiful source. His estimate is 1,656 thousand million tons, 900 of which in the central region, 406 in the western region and 350 in the eastern region. A Soviet estimate in 1961 was one-twentieth of this figure, still a vast amount in absolute terms.

We may thus conclude that the sea-bed contains practically inexhaustible reserves of several mineral products of primary importance. But it has still not been established whether exploitation of these resources will be competitive in the near future.

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