

CHAPTER II

The Earth and the Ocean Basins

Figure and Size of the Earth

As a first approximation the earth may be considered as a sphere, but, according to accurate observations, its figure is more closely represented by an ellipse of rotation—that is, an oblate spheroid, the shorter axis being the axis of rotation. The figure of the earth has been defined by various empirical equations, the constants of which are based on observations and are subject to modification as the number of observations increases and their accuracy is improved. The geometrical figures defined by these equations cannot exactly represent the shape of the earth because of the asymmetrical distribution of the water and land masses.

To define the position of a point on the earth's surface, a system of coordinates is needed, and as such the terms *latitude*, *longitude*, and *elevation* or *depth* are used. The first two are expressed by angular coordinates and the third is expressed by the vertical distance, stated in suitable linear units, above or below a reference level that is generally closely related to mean sea level. The *latitude* of any point is the angle between the local plumb line and the equatorial plane. Because the earth can be considered as having the form of a spheroid, and as the plumb line, for all practical purposes, is perpendicular to the surface of the spheroid, any plane parallel to the Equator cuts the surface of the spheroid in a circle, and all points on this circle have the same latitude. These circles are called *parallels of latitude*. The latitude is measured in degrees, minutes, and seconds north and south of the Equator. The linear distance corresponding to a difference of one degree of latitude would be the same everywhere upon the surface of a sphere, but on the surface of the earth the distance represented by a unit of latitude increases by about 1 per cent between the Equator and the Poles. At the Equator, 1 degree of latitude is equivalent to 110,567.2 m, and at the Poles it is 111,699.3 m. In table 1 are given the percentages of the earth's surface between different parallels of latitude.

The line in which the earth's surface is intersected by a plane normal to the equatorial plane and passing through the axis of rotation is known as a *meridian*. The angle between two meridian planes through two

points *A* and *B* on the surface of the earth is the difference in longitude of the two points. In practice, the *longitude* is the angular distance measured in degrees, minutes, and seconds east or west from a *standard*

TABLE 1
PERCENTAGES OF THE EARTH'S SURFACE BETWEEN FIVE-DEGREE PARALLELS

Latitude	%	Cumulative %	Latitude	%	Cumulative %
0°-5°.....	8.68	8.68	45°-50°.....	5.92	76.48
5-10.....	8.62	17.30	50-55.....	5.33	81.81
10-15.....	8.48	25.78	55-60.....	4.71	86.52
15-20.....	8.30	34.08	60-65.....	4.05	90.57
20-25.....	8.04	42.12	65-70.....	3.36	93.93
25-30.....	7.72	49.84	70-75.....	2.64	96.57
30-35.....	7.36	57.20	75-80.....	1.90	98.47
35-40.....	6.92	64.12	80-85.....	1.15	99.62
40-45.....	6.44	70.56	85-90.....	0.38	100.00

meridian plane, generally that of the Royal Observatory at Greenwich, England. Thus, the longitude is measured from 0° to 180° east and west of Greenwich. On the surface of the earth the linear distance equivalent to unit difference in longitude is nearly proportional to the cosine of the latitude.

TABLE 2
SIZE OF THE EARTH
(Fowle, 1933)

Equatorial radius, <i>a</i>	6378.388 km
Polar radius, <i>b</i>	6356.912 km
Difference (<i>a</i> - <i>b</i>).....	21.476 km
Area of surface.....	510,100,934 km ²
Volume of geoid.....	1,083,319,780,000 km ³

The distance between points on the earth's surface and the area represented by a given zone cannot be correctly represented unless the size of the earth is known. The values for the equatorial and polar radii are given in table 2, with other data concerning the size of the earth that can be computed from these values. The values for the equatorial and polar radii are those for sea level. The land masses are elevations upon the geometrical figure of the earth, and the sea bottoms represent depressions.

Measurements of depressions below sea level, to be strictly comparable, should be referred to the *ideal sea level*; that is, to a sea surface which is everywhere normal to the plumb line. In the open ocean the deviations from the ideal sea level rarely exceed 1 or 2 m. The errors that are introduced by referring soundings to the *actual* sea surface are insignificant in deep water, where the errors of measurement are many times greater. In coastal areas where shoal depths represent a hazard to navigation and where soundings can be made with great accuracy, the

effect of tides is eliminated by referring all soundings in any locality to a single reference plane. *Mean sea level* is generally used as the plane of reference for elevations on land, and in the Baltic Sea it is employed as the reference level for depths. More commonly, some other plane of reference, indicated on the chart, is used as the reference level for depths; for example:

Mean low water. United States (Atlantic Coast), Argentina, Norway, Sweden.

Mean lower low water. United States (Pacific Coast).

Mean low water springs. Great Britain, Italy, Germany, Denmark, Brazil, Chile.

Mean monthly lowest low water springs. Netherlands.

Lowest low water springs. Brazil, Portugal.

Indian spring low water. India, Argentina, Japan.

Mean semi-annual lowest low water. Netherlands East Indies.

Lowest low water. France, Spain, Norway, Greece.

International low water. Argentina.

The mean of the heights of low-water spring tides is known as the *low water springs*. *International low water* is 50 per cent lower, reckoned from mean sea level, than *low water springs*. *Indian spring low water* depends upon component tides found by harmonic analysis. Other terms are defined elsewhere (p. 562).

The topographic features of the earth's surface can be shown in their proper relationships only upon globes that closely approximate the actual shape of the earth, but for practical purposes projections that can be printed on flat sheets must be used. It is possible to project a small portion of the earth's surface on a flat plane without appreciable distortion of the relative positions. However, for the oceans or for the surface of the earth as a whole, most types of map projections give a grossly exaggerated representation of the shape and size of certain portions of the earth's surface. The most familiar type of projection is that developed by Mercator, which represents the meridians as straight, parallel lines. Although it is satisfactory for small areas and for the lower latitudes, the size and shape of features in high latitudes are greatly distorted because the linear scale is inversely proportional to the cosine of the latitude. In the presentation of oceanographic materials, this exaggeration is most undesirable and, consequently, projections should be used on which the true shape and size of the earth's features can be more closely approximated.

Numerous types of projections have been developed by cartographers. In some instances, these are geometrical projections of the surface of the geoid on a plane surface that can be flattened out, while in others the essential coordinates, the parallels of latitude, and the meridians have been constructed on certain mathematical principles. Maps and charts

are used for a variety of purposes which require different properties in the projections. Such requirements, incompatible in any single projection, are that the map shall show the features of the earth's surface without distortion of distances, directions, shapes, or areas. The Mercator projection is used for navigational charts because it possesses certain properties that are desirable in navigation. The technique of map making and the properties of the various projections are discussed by Raisz (1938).

In order to show the oceans with the least possible distortion of size and shape, the world maps used in this volume are based on an interrupted projection developed by J. P. Goode. Comparison with a globe will show that the major outlines of the oceans are not distorted and that the margins of the oceans are clearly represented. This projection has the additional advantage of being "equal-area"; that is, that areas scaled from the map are proportional to their true areas on the surface of the earth. To show the relationships between the various parts of the oceans in high latitudes, polar projections are used, and for smaller areas Mercator and other types of projections have been employed.

Distribution of Water and Land

The continental land masses extend in a north-south direction, with the greatest percentage of land in the Northern Hemisphere (table 3), and there is a more or less antipodal arrangement of land- and water-covered areas. The North Polar Sea surrounding the North Pole is opposite to the continent of Antarctica, which is centered on the South Pole, and the continental land masses represented by Europe, Asia, and part of Africa are antipodal to the great oceanic area of the South Pacific. The ocean waters are continuous around Antarctica and extend northward in three large "gulfs" between the continents, on the basis of which three oceans are recognized. The Atlantic Ocean extends from Antarctica northward and includes the North Polar Sea. It is separated from the Pacific Ocean by the line forming the shortest distance from Cape Horn (70°W) to the South Shetland Islands, and the boundary between the Atlantic and the Indian Oceans is placed at the meridian of the Cape of Good Hope (20°E). The boundary between the Pacific and the Indian Oceans follows the line from the Malay Peninsula through Sumatra, Java, Timor, Australia (Cape Londonderry), and Tasmania, and follows the meridian of 147°E to Antarctica. In the north the limit between the Atlantic and the Pacific Oceans is placed in Bering Strait, which is only 58 km wide and has a maximum depth of 55 m. Unless otherwise stated, the oceans as defined above are considered to include the semi-enclosed adjacent seas that connect with them.

Generally speaking, only three oceans are recognized, but it is sometimes desirable to make a further division. The waters surrounding

Antarctica and extending northward about as far as the southern tips of the continents are sometimes designated as the Great Southern Ocean, Austral Ocean, or Antarctic Ocean. In the discussion of the distribution of properties in the sea (chapter XV) it is convenient to define an "Antarctic Ocean" that is limited on the north by a purely oceanographic boundary; namely, the Subtropical Convergence (p. 606).

The nomenclature applied to subdivisions of the oceans is very confused. Generic names designating certain types of features, such as sea, gulf, and bay, are used somewhat indiscriminately and hence have little physiographic significance. For example, the term *sea* is used in connection with inland salt lakes, such as the Caspian Sea, with relatively isolated bodies of the ocean, such as the Mediterranean Sea, with less isolated areas, such as the Caribbean Sea, and even for some areas with no land boundaries, such as the Sargasso Sea in the western North Atlantic.

Several systems for naming parts of the oceans are employed in oceanographic work. In certain instances the boundaries are selected arbitrarily by drawing straight or curved lines on the map where there are no land features which constitute natural boundaries. Such a system is followed by the International Hydrographic Bureau (1937). Wüst (1936) has suggested that the submarine ridges that are present at depths of about 4000 m be used to delimit the various parts of the oceans, and that the names now applied to the basins with depths greater than 4000 m be used to designate the areas above them. The general location of such boundaries may be seen in chart I. Oceanography is concerned not only with the form of the oceans as shown on a surface chart, but also with the distribution of properties and living organisms and the nature of the currents. Therefore, a system of nomenclature which indicates the relationships that exist in the sea would be very useful. Wüst's system, based on the ocean bottom topography, meets this purpose for the deep water but not for the upper layers. To formulate "natural regions" of the oceans, other workers, notably Schott (1926, 1935), have attempted to bring together not only geographic and topographic relationships, but also the distribution of properties and organisms, the climatic conditions, and currents. In the discussion of the distribution of organisms, fig. 220 (p. 804) shows how the oceans are subdivided upon the basis of the faunal distribution alone, and in the discussion of the water masses of the oceans, fig. 209 (p. 740) shows a subdivision based upon the characteristic temperature and salinity relations of the various regions. A comparison of such charts shows that, although there are certain boundaries which fall in approximately the same localities, there are many regions in which it is not possible to reconcile limits established in different ways.

In table 3 are given the areas of land and water between parallels of latitude five degrees apart. For the whole earth, the ocean waters cover

70.8 per cent of the surface, but the amount of land in the Northern Hemisphere is more than twice that in the Southern Hemisphere, and the water covers only 60.7 per cent of the former and 80.9 per cent of the latter. Between 45°N and 70°N the land exceeds the water surface, whereas between 35°S and 65°S the land forms only a small part of the surface.

TABLE 3
DISTRIBUTION OF WATER AND LAND BETWEEN PARALLELS
(Kossinna, 1921)

Latitude (°)	Northern Hemisphere				Southern Hemisphere			
	Water (10 ⁶ km ²)	Land (10 ⁶ km ²)	Water (%)	Land (%)	Water (10 ⁶ km ²)	Land (10 ⁶ km ²)	Water (%)	Land (%)
90-85.....	0.979	.....	100.0	.....	.....	0.978	.....	100.0
85-80.....	2.545	0.384	85.2	12.8	.....	2.929	.....	100.0
80-75.....	3.742	1.112	77.1	22.9	0.522	4.332	10.7	89.3
75-70.....	4.414	2.326	65.5	34.5	2.604	4.136	38.6	61.4
70-65.....	2.456	6.116	28.7	71.3	6.816	1.756	79.5	20.5
65-60.....	3.123	7.210	31.2	69.8	10.301	0.032	99.7	0.3
60-55.....	5.399	6.613	45.0	55.0	12.006	0.006	99.9	0.1
55-50.....	5.529	8.066	40.7	59.3	13.388	0.207	98.5	1.5
50-45.....	6.612	8.458	43.8	56.2	14.693	0.377	97.5	2.5
45-40.....	8.411	8.016	51.2	48.8	15.833	0.594	96.4	3.6
40-35.....	10.029	7.627	56.8	43.2	16.483	1.173	93.4	6.6
35-30.....	10.806	7.943	57.7	42.3	15.782	2.967	84.2	15.8
30-25.....	11.747	7.952	59.6	40.4	15.438	4.261	78.4	21.6
25-20.....	13.354	7.145	65.2	34.8	15.450	5.049	75.4	24.6
20-15.....	14.981	6.164	70.8	29.2	16.147	4.998	76.4	23.6
15-10.....	16.553	5.080	76.5	23.5	17.211	4.422	79.6	20.4
10-5.....	16.628	5.332	75.7	24.3	16.898	5.062	76.9	23.1
5-0.....	17.387	4.737	78.6	21.4	16.792	5.332	75.9	24.1
90-0°.....	154.695	100.281	60.7	39.3	206.364	48.611	80.9	19.1

All oceans and seas..... 361.059 × 10⁶ km², 70.8%

All land..... 148.892 × 10⁶ km², 29.2%

In table 4 are given the areas, volumes, and mean depths of the oceans and of certain mediterranean and marginal seas that together constitute the adjacent seas. The data are from Kossinna (1921), and in most instances the designated areas are readily recognized, but for details concerning the boundaries the original reference should be consulted. The Arctic Mediterranean includes the North Polar Sea, the waters of the Canadian Archipelago, Baffin Bay, and the Norwegian Sea, and is therefore separated from the open Atlantic by the line joining Labrador and Greenland in Davis Strait and running through Greenland, Iceland, Faeroe Islands, Scotland, and England, and across the English

Channel to the Continent. The Asiatic Mediterranean includes the waters eastward of the boundary between the Indian and Pacific Oceans (p. 11), and is separated from the open Pacific by the line extending from the coast of China through Formosa, Philippine Islands, Moluccas, and New Guinea to Cape York, Australia.

Additional data on the areas of the adjacent seas of the Atlantic Ocean are given by Stocks (1938). Littlehales (1932) gives slightly different values for the areas of the oceans.

Relief of the Sea Floor

From the oceanographic point of view the chief interest in the topography of the sea floor is that it forms the lower and lateral boundaries of water. The presence of land barriers or submarine ridges that impede a free flow of water introduces special characteristics in the pattern of circulation and in the distribution of properties and organisms. Furthermore, as will be shown in chapter XX, the nature of the sediments in any area is closely related to the surrounding topography. On the other hand, the geomorphologist or physiographer is concerned primarily with the distribution and dimensions of certain types of topographic features that occur on the submerged portion of the earth's crust. As 71 per cent of the earth's surface is water-covered, knowledge of the major features of the earth's relief will be fragmentary if based only upon those structures that can be seen on land. During the geological history of the earth which covers a span of some thousands of million years, areas now exposed above sea level have at one or more periods been covered by the sea, and parts of the now submerged surface have been above sea level. Many problems in historical geology are therefore dependent upon knowledge concerning the configuration of the sea floor surrounding the continents and the form of the deep-ocean bottom.

Although valuable work in the open ocean has been carried on by scientific organizations, by far the greater proportion of our knowledge of submarine topography is based on soundings taken by or for national agencies in the preparation or improvement of navigational charts. In the United States the U. S. Coast and Geodetic Survey prepares charts for the waters bounding the United States and its possessions, and the Hydrographic Office of the U. S. Navy carries out similar work on the high seas and in foreign waters. The earlier hydrographic work was limited largely to the mapping of coast lines and to soundings in depths less than about 100 fathoms, where hazards to the safe operation of vessels might occur, but deep-sea soundings received a great impetus when surveys were made prior to the laying of the transoceanic cables in the latter part of the nineteenth century. Up to and including the time of the voyage of the *Challenger*, 1873-1876, all soundings were made with hemp ropes, which made the process a long and tedious undertaking,

since in depths of several thousand meters it required several hours to make a single depth measurement. A great improvement in sounding equipment was made when wire ropes and, for sounding at great depths, single-strand wire were introduced, thereby reducing the size of the gear

TABLE 4
AREA, VOLUME, AND MEAN DEPTH OF OCEANS AND SEAS
(Kossinna, 1921)

Body	Area (10 ⁶ km ²)	Volume (10 ⁶ km ³)	Mean depth (m)
Atlantic Ocean	82.441	323.613	3926
Pacific Ocean	165.246	707.555	4282
Indian Ocean	73.443	291.030	3963
All oceans (excluding adjacent seas).....	321.130	1322.198	4117
Arctic Mediterranean.....	14.090	16.980	1205
American Mediterranean.....	4.319	9.573	2216
Mediterranean Sea and Black Sea.....	2.966	4.238	1429
Asiatic Mediterranean.....	8.143	9.873	1212
Large mediterranean seas.....	29.518	40.664	1378
Baltic Sea.....	0.422	0.023	55
Hudson Bay.....	1.232	0.158	128
Red Sea.....	0.438	0.215	491
Persian Gulf.....	0.239	0.006	25
Small mediterranean seas.....	2.331	0.402	172
All mediterranean seas.....	31.849	41.066	1289
North Sea.....	0.575	0.054	94
English Channel.....	0.075	0.004	54
Irish Sea.....	0.103	0.006	60
Gulf of St. Lawrence.....	0.238	0.030	127
Andaman Sea.....	0.798	0.694	870
Bering Sea.....	2.268	3.259	1437
Okhotsk Sea.....	1.528	1.279	838
Japan Sea.....	1.008	1.361	1350
East China Sea.....	1.249	0.235	188
Gulf of California.....	0.162	0.132	813
Bass Strait.....	0.075	0.005	70
Marginal seas.....	8.079	7.059	874
All adjacent seas.....	39.928	48.125	1205
Atlantic Ocean	106.463	354.679	3332
Pacific Ocean	179.679	723.699	4028
Indian Ocean	74.917	291.945	3897
All oceans (including adjacent seas).....	361.059	1370.323	3795

necessary for deep-sea sounding and the time for lowering and reeling in. An earlier improvement was achieved by the introduction of methods of dropping the sounding weight after it had reached the bottom, thus reducing the load to be reeled in. The first such device was developed in the middle of the last century by J. M. Brooke of the U. S. Navy.

Equipment now used for wire sounding is described in chapter X, which deals with oceanographic apparatus and methods.

Because of their practical importance and the ease with which they could be obtained, the number of soundings in depths less than a few hundred meters accumulated rapidly during the nineteenth century, but in 1895 there existed only 7000 soundings from depths greater than about 2000 m, and of these only about 550 were from depths greater than 5500 m (Bencker, 1930). These data were used by Murray in preparing the bathymetric charts accompanying the reports of the *Challenger* Expedition.

During the next twenty-five years the number of deep-sea soundings increased slowly, but the introduction of sonic-sounding equipment after 1920 has completely changed the picture. Devices for measuring the depth by timing the interval for a sound impulse to travel to the sea bottom and back again (only a few seconds even in deep water) are used in surveying work and are now standard equipment on many coastwise and oceanic vessels. The development of automatic echo-sounding devices (chapter X) not only made depth measurements simple but, by making accurate bathymetric charts available, introduced another aid in navigation, since passage over irregularities of the sea floor may be used to check positions. This development has necessitated extending accurate surveys into deeper water and, hence, farther from shore. Along the coasts of the United States the bottom is now being charted in detail to depths of about 4000 m. With sonic methods, if the appropriate apparatus is available, it is no more trouble to sound in great depths than it is in shoal waters, and, since many naval vessels and transoceanic commercial vessels make systematic records of their observations, the soundings in the deep sea are now accumulating more rapidly than they can be plotted.

The most common method of representing submarine topography is to enter upon a chart showing the coast lines the numerical values of the soundings at the localities in which they were obtained. Charts issued by the national hydrographic services of the English-speaking countries give depths in fathoms or, if harbor charts, in feet (1 fathom = 6 ft = 1.8288 m). Those issued by other countries generally use meters, although still other units are employed by certain European countries.

Because it is generally impossible to enter all soundings, and as numerical values alone do not give any graphic representation of the topography, contours of equal depths (isobaths) are drawn in those regions in which the number of soundings or the purpose of the chart makes it desirable. On navigational charts, contours are generally restricted to shallow areas where soundings are also shown, but, for certain regions that have been carefully examined, charts are now issued with contours entered to depths as great as 2000 fathoms (for example, U. S.

Coast and Geodetic Survey Chart no. 5101A for the southern California coast, issued in 1939). In bathymetric charts prepared for oceanographic work, contours alone may be shown, but only in exceptional cases, such as in physiographic studies, are the isobaths shown for equal intervals of depth.

The accuracy with which submarine topography can be portrayed depends upon the number of soundings available and upon the accuracy with which the positions of the soundings were determined. Topographic maps of land surfaces are based on essentially similar data; namely, elevations of accurately located points, but the surveyor has one great advantage over the hydrographer. The surveyor is able to *see* the area under examination and thereby distribute his observation points in such a manner that the more essential features of the topography are accurately portrayed. The hydrographer, on the other hand, must construct the topography of the sea floor from a number of more or less random soundings. Sonic sounding methods and the introduction of more accurate means of locating positions at sea (see Veatch and Smith, 1939) have made it feasible to obtain adequate data for constructing moderately accurate charts or models of parts of the sea floor. This is particularly true of the coastal waters of the United States. Veatch and Smith have prepared contour maps of the eastern seaboard based on the investigations of the U. S. Coast and Geodetic Survey, and Shepard and Emery (1941) have made use of similar data from the Pacific Coast, where over 1,300,000 soundings were available.

In some instances it is preferable to represent the bottom configuration by vertical profiles or by relief models, but, because of the difference in magnitude of the vertical and horizontal dimensions of the oceans, it is generally necessary to exaggerate the vertical scale. The average depth of the ocean is about 3800 m, and the vertical relief of the ocean floor is therefore of the order of a few kilometers, whereas the horizontal distances may be of the order of thousands of kilometers. Hence such distorted representations give a false impression of the steepness of submarine slopes. If profiles are drawn to natural scale, the ocean waters form a shallow band with barely perceptible undulations of the bottom. Examples of undistorted profiles are given by Johnstone (1928).

In fig. 1 are shown two representations of a profile of the sea bottom in the South Atlantic based on the observations of the *Meteor* (Stocks and Wüst, 1935). The upper section (*A*) is constructed from thirteen wire soundings, and is comparable in detail to most of the profiles that could be prepared before the introduction of sonic methods. The lower section (*B*) is based upon over 1300 sonic soundings that were taken by the *Meteor* along the same route, shown in the map at the bottom part of the figure (*C*), where the depth contours are from chart I. The increasing complexity of the known topography of the sea bottom resulting

from the greater number of observations is readily seen from a comparison of *A* and *B*.

The water surface coincides, for all practical purposes, with the surface of the geoid, and the sea bottom, if "flat," would be parallel to the sea surface. Irregularities of the sea floor therefore represent departures

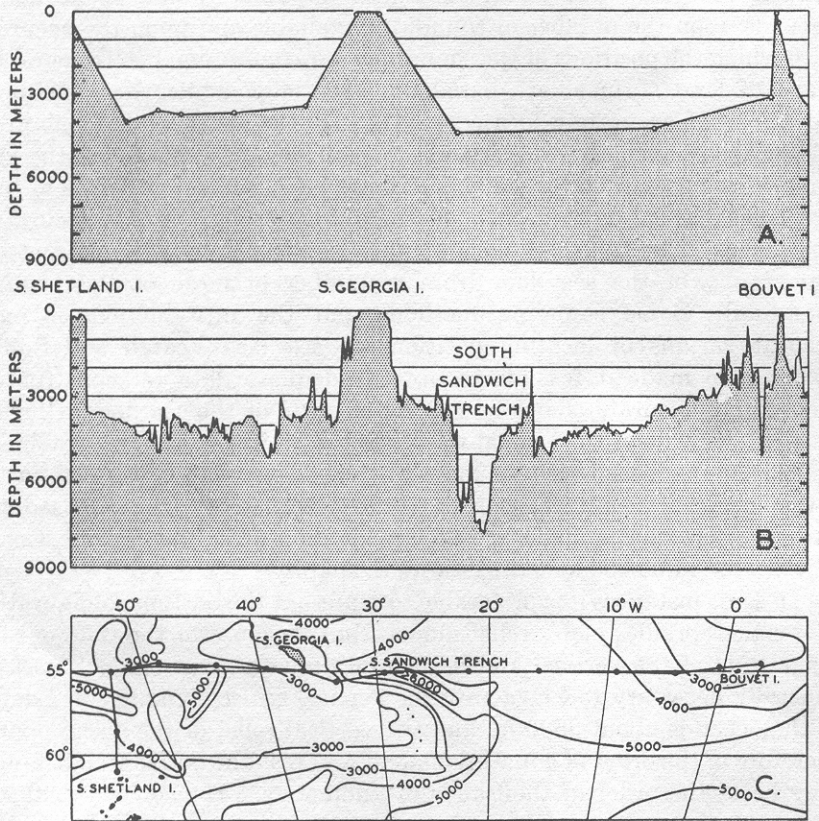


Fig. 1. Bottom topography in the South Atlantic Ocean. (A) Profile of the bottom between the South Shetland Islands and Bouvet Island based on 13 wire soundings. (B) Profile over the same course constructed from over 1300 sonic soundings (*Meteor*). (C) Bottom configuration as shown in Chart I and the track of the *Meteor*. Vertical exaggeration in (A) and (B) about 200:1. (In part, after Stocks and Wüst, 1935.)

from this surface, which is convex outward. Only in small features with steep slopes are depressions actually concave outward.

The greatest depths so far discovered are in the Pacific Ocean, where, in the Philippines Trench and the Japan Trench, soundings greater than 10,000 m have been obtained. In the Philippines Trench the German vessel *Emden* obtained a sonic sounding of 10,540 m, which, however, is considered to be about 200 m too great. The Dutch vessel *Willebrord*

Snellius, working in the same area and using wire sounding equipment, found depths greater than 10,000 m. A sounding of 10,550 m in the Japan Trench was made by the U.S.S. *Ramapo*, using sonic equipment. The deepest sonic sounding in the Atlantic Ocean, 8750 m, was obtained in the Puerto Rico Trough by the U.S.S. *Milwaukee*. Bencker (1930) has listed the numerous deeps as well as the shoals found in oceanic areas.

Representations of submarine topography are usually referred to sea level, and particular interest has always been attached to those regions

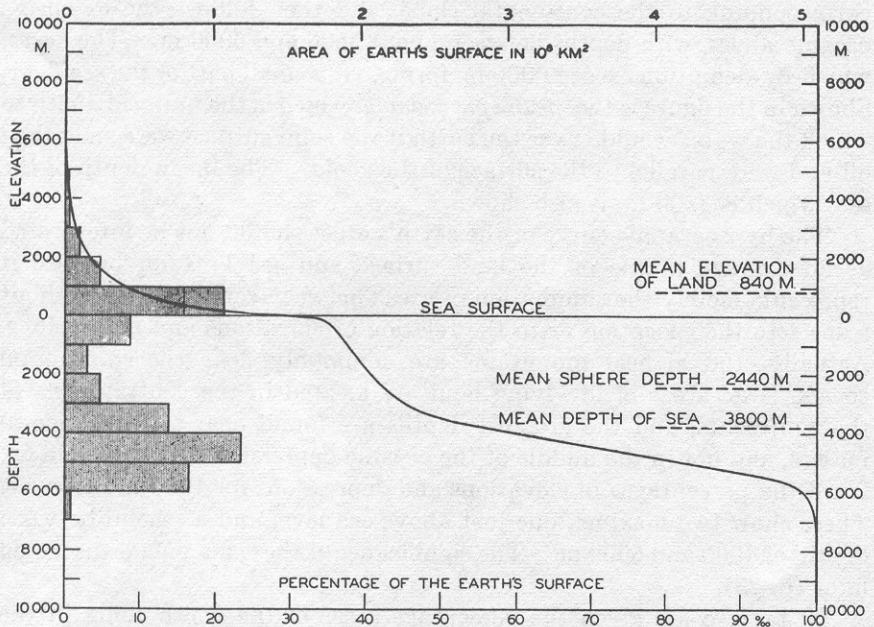


Fig. 2. Hypsographic curve showing the area of the earth's solid surface above any given level of elevation or depth. At the left in the figure is the frequency distribution of elevations and depths for 1000-meter intervals.

in which great depths are found. The greater detail with which the sea floor can now be mapped has emphasized the importance of *relative relief*; that is, the form and magnitude of elevations or depressions with respect to their general surroundings. In later pages it will be shown that there are two primary levels of reference on the earth's crust, one slightly above sea level, corresponding to the land masses, and a second at depths between 4000 and 5000 m, corresponding to the great oceanic basins. In comparing topographic features on land with those on the sea floor it is essential to consider them with reference to these levels.

One method of presenting the character of the relief of the earth's crust is by means of a hypsographic curve showing the area of the earth's solid surface above any given contour of elevation or depth. The hypsographic curve in fig. 2 is from Kossinna (1921). Although added data

concerning bottom configuration may slightly modify this curve, the general features will not be changed. The high mountains form a relatively small part of the land surface, and hence the mean elevation of the subaerial crust is only 840 m. The large areas of low-lying land have their counterpart in the relatively large areas in shallow water between the surface and approximately 200 m (table 5). These coastal areas of shallow depth correspond to the continental shelves. Below the continental shelf there is a relatively small area of depths between 200 m and 3000 m, corresponding to the continental slope, and then follows the extensive oceanic abyss, with depths between about 3500 and 6000 m. The *deeps*, which by definition exceed 6000 m, form a very small part of the sea floor. Shown in the figure is the *mean sphere depth*, which is the uniform depth to which the water would cover the earth if the solid surface were smoothed off and were parallel to the surface of the geoid. The mean depth of the sea, which is 3800 m, is also shown.

The hypsographic curve of the earth's crust should not be interpreted as an average profile of the land surface and sea bottom, because it represents merely the summation of areas between certain levels without respect to their location or to the relation of elevations and depressions. Actually, the highest mountains are commonly near the continental coasts, large areas of low-lying land are located in the central parts of the continents, and the greatest depths are found near the continental masses, and not in the middle of the oceanic depressions. Entered in fig. 2 are the percentages of elevations and depressions for 1000-m intervals. These show two maxima, one just above sea level and a second between depths of 4000 and 5000 m. The significance of these maxima is discussed later (p. 23).

In table 5 are given the percentage areas of the depth zones in the three oceans, and for all oceans with and without adjacent seas. It will be noted that the shelf (0-200 m) represents a prominent feature in the Atlantic Ocean, which is also the shallowest of the oceans. By combining data in tables 4 and 5 the absolute areas of the depth zones may be computed. The hypsographic curve in fig. 2 is based on the values for all oceans, including adjacent seas.

During the geological history of the earth, great changes have occurred in the relief of the land and sea bottom. The exact nature and extent of these vertical movements is beyond the scope of the present discussion, but it should be noted that changes in relative sea level of the order of 100 m, which are readily accounted for by the withdrawal and addition of water during glacial and interglacial periods, would expose and inundate relatively large areas.

The continental shelf is generally considered to extend to depths of 100 fathoms, or 200 m, but Shepard (1939) found that the limit should be somewhat less than this; namely, between 60 and 80 fathoms (110 and

146 m). Profiles of the shelf show the presence of many minor terraces that may represent the effects of waves and currents when the sea level stood at a lower level, probably during the glacial periods. Veatch and Smith (1939), from their detailed study of the continental shelf off the Atlantic coast of the United States, found many small ridges approximately parallel to the coast line. The continental shelf varies greatly in width and slope. In some cases, as off mountainous coasts, the shelf may be virtually absent, whereas, off glaciated coasts and off the mouths of large rivers and areas with broad lowlands, the shelf may be very wide.

TABLE 5
PERCENTAGE AREA OF DEPTH ZONES IN THE OCEANS
(Kossinna, 1921)

Depth interval (m)	Including adjacent seas				Excluding adjacent seas			
	Atlantic	Pacific	Indian	All oceans	Atlantic	Pacific	Indian	All oceans
0-200....	13.3	5.7	4.2	7.6	5.6	1.7	3.2	3.1
200-1000....	7.1	3.1	3.1	4.3	4.0	2.2	2.7	2.8
1000-2000....	5.3	3.9	3.4	4.2	3.6	3.4	3.1	3.4
2000-3000....	8.8	5.2	7.4	6.8	7.6	5.0	7.4	6.2
3000-4000....	18.5	18.5	24.0	19.6	19.4	19.1	24.4	20.4
4000-5000....	25.8	35.2	38.1	33.0	32.4	37.7	38.9	36.6
5000-6000....	20.6	26.6	19.4	23.3	26.6	28.8	19.9	26.2
6000-7000....	0.6	1.6	0.4	1.1	0.8	1.8	0.4	1.2
>7000....	....	0.2	....	0.1	....	0.3	....	0.1

For the world as a whole, the shelf width is approximately 30 miles, with a range from zero to over 800 miles. This extremely wide shelf is found in the North Polar Sea along the coast of Siberia.

From the above values it may be seen that the average slope of the shelf is of the order of 2 fathoms per mile, or 0.2 per cent. This corresponds to a slope angle of about 7'. Although there is a general seaward slope of the shelf, it is by no means an even-graded profile. As mentioned above, there may be terraces, ridges, hills, and depressions, and in many areas there are steep-walled canyons cutting across it. Shelf irregularities are most conspicuous off glaciated coasts, and were caused by the ice during a glacial period when this zone was exposed to glacial erosion (Shepard, 1931).

On land the slope is often more significant than the absolute range in elevation. According to Littlehales (1932) the smallest slope that the human eye can detect is 17'. Therefore, except for the minor irregularities, the continental shelf would in general appear flat.

From an examination of 500 profiles, Shepard (1941) found that the inclination of the continental slope varied with the character of the coast. Continental slopes off mountainous coasts have, on the average, a slope of about 6 per cent ($3^{\circ}30'$), whereas off coasts with wide, well-drained coastal plains the slopes are about 3.5 per cent ($2^{\circ}0'$).

The submerged slopes of volcanic islands are similar to the exposed slopes of volcanic mountains, and may be as great as 50° (Kuenen, 1935). In large submarine canyons the walls are as rugged and precipitous as those of the Grand Canyon of Arizona (fig. 8, p. 40). Fault scarps above and below sea level show comparable slopes.

The average slopes of the deep-sea floor are small. Krümmel (Littlehales, 1932) found that in the North Atlantic the mean slopes varied between about $20'$ and $40'$, but these are averages, or were obtained by dividing the difference in elevation by the distance between two points. Where the distances are great or when the number of soundings is small, the slopes obtained in this way do not give a true representation of the relief. The increased data now available have revealed irregularities comparable in ruggedness to the larger topographic features on land.

Major Features of Topography

The discussion of the bottom topography of the oceans will be restricted to a brief consideration of the large-scale topographic features that are represented on small charts with large contour intervals. In regions where many soundings have been obtained, it has been found that the sea bottom may be virtually as irregular as the land surface, but such details can be shown only on large-scale charts with small contour intervals, and are not included in this volume.

Submarine geology is concerned with the topography of the sea floor, the composition and physical character of the sedimentary and igneous materials that are found on the ocean bottom, and the processes involved in the development of topographic relief. The field is a relatively new one which has received great impetus from the development of sonic sounding methods that made it possible to obtain accurate maps of the sea floor, and from the development of geophysical methods (measurement and interpretation of gravity anomalies, of the earth's magnetic field, and of the path and velocity of earthquake and artificial seismic waves) that yielded estimates of the character and thickness of the materials forming the crust of the earth. However, there is yet no agreement concerning the processes involved in the geological history of the ocean basins, and the various hypotheses will not be discussed here. General reviews of the problems will be found in Johnstone (1928), Bucher (1933), Kuenen (1935), and Gutenberg (1939). A symposium on the geophysical exploration of the sea bottom (Field *et al.*, 1938) covers many of the developments.

The distribution of elevations and depressions on the earth's crust (fig. 2) shows that there are large portions with elevations between sea level and 1000 m, and with depths between 4000 m and 5000 m. According to Bucher (1933) the larger, lower ones are related to the character of the earth's crust, while the upper ones are the result of subaerial erosion and sedimentation. The question then arises as to the extent to which the topography of the ocean bottom with reference to a depth of about 4500 m corresponds to that of the land with reference to sea level or a slightly higher level. According to Bucher, the large-scale features are essentially similar, and elevations and depressions of comparable dimensions are found both on land and on the ocean bottom. Although the major features are comparable, the details are quite different, because erosion, which plays such an all-important role in the creation of sharp relief and in the ultimate destruction of elevations on land, is virtually absent in the sea. In the sea the most effective agents of erosion are the surface waves, and these tend to produce flat-topped features that are restricted to shallow depths, since the velocity of the water particles in such waves decreases rapidly with increasing depth (p. 528). Other processes which may contribute to erosion of the sea floor are discussed in chapter XX and in the section dealing with the origin of submarine canyons (p. 41). Deposition is the characteristic process that modifies the topography of the sea bottom. Sedimentary debris accumulates in depressions, while there is little or no accumulation on topographic highs, which are devoid of fine-grained sediment and are subject to erosion if near the surface or in localities of exceptionally strong currents.

Bucher (1933) has stated that there are essentially two types of large-scale topographic features on the land and on the ocean bottom: (1) those of approximately equidimensional lateral extent, to which he applies the names *swells* and *basins*, and (2) those of elongate form, generally with steeper sides, to which he applies the names *welts* and *furrows*. On the ocean bottom the elongate welts and furrows appear to be the more common, and there is a considerable range in the size of such structures. There is a tendency for the large welts on the sea bottom to be parallel to the continental coasts, so that the oceans are divided into elongate troughs. Transverse ridges in turn subdivide these major depressions into a series of basins that are separated from one another to a greater or lesser degree. This ridge and basin topography is clearly shown by the bottom of the Atlantic Ocean and the Indian Ocean and in the western part of the Pacific Ocean, but does not appear to be so conspicuous a feature in the main part of the Pacific.

Within the smaller welts and furrows, the steepest slopes, the highest elevations, and the greatest depths are found. The welts and furrows are commonly close together, with arced outlines, and are characteristically found near the continents. The deep furrows are generally on the convex

side of the arc-like welts, but in some instances great depths are found on the concave side of the ridges (chart I). Parts of the welts may extend above sea level, forming an island or chain of islands. Such features are found in the northern and western parts of the Pacific Ocean, in the East Indian Archipelago, in the West Indies, and in the region between South America and Antarctica. Along the west coast of South America the welt corresponds to the mountain chain of the Andes, and is therefore part of the continent. That these structures are of relatively recent origin and are in regions of crustal instability is shown by the presence of extinct or active subaerial or submarine volcanoes on the welts and by the fact that they are in regions of the most pronounced gravity anomalies and are the sites of great seismic activity (Field *et al.*, 1938).

Terminology of Submarine Topography

The terms applied to features of submarine topography will be classified according to the origin of the features rather than according to their size, although the latter procedure is the common one (for example, Niblack, 1928, Littlehales, 1932). The features of submarine relief may be grouped in two main categories, depending upon whether they have gained their characteristic form through diastrophic activity (crustal movements) or through erosion or deposition. The primary large-scale process involved in the development of relief must be diastrophic, but in many cases the characteristic feature is produced by erosion or deposition. No distinction will be made here between features that have been formed below the sea surface and those that may possibly owe their origin to subaerial erosion or deposition. As pointed out before, deposition in the sea tends to fill in the depressions and thus to level out the minor irregularities of the bottom, and, with the exception of those cases in which organisms play an important role (for example, in the formation of coral reefs), little or no deposition takes place on topographic highs.

There has been much discussion as to the processes that have led to the formation of the continental and insular shelves. Some authors maintain that they are wave-built (depositional); others consider that they are wave-cut (erosional), or that they are a combination of both processes (Johnson, 1919; Shepard, 1939). Geophysical studies on the two sides of the North Atlantic (Bucher, 1940) indicate that the shelves are composed of great prism-shaped accumulations of sedimentary rock that at the outer edge of the shelf bordering the eastern United States are 4000 m thick. To what extent these features resulted from the slow accumulation and sinking of the crust and to what extent violent diastrophic movements have been involved has not yet been decided. The characteristic form of the shelf and of isolated flat-topped banks and shoals, and other features of the shallow bottom indicate that wave erosion and transportation by currents have played an important part

in their development. Particular importance is attached to the relative lowering and rise of sea level that took place through the accumulation of continental ice during each glacial period and the subsequent melting. According to Daly (1934) the maximum lowering of sea level was of the order of 100 m, but recently Shepard (Shepard and Emery, 1941), in order to account for the origin of the submarine canyons, has advanced arguments in favor of a lowering of the order of 1000 m. Even a lowering of 100 m would expose large areas of the shelf and would explain the presence of the submerged terraces and other irregularities which could have been produced by wave action when the water stood at a lower level.

The terms used to designate certain types of topographic features, their French and German equivalents, and their definitions, which are given below, correspond to those suggested by the International Hydrographic Bureau (Niblack, 1928). Unfortunately, there is still considerable confusion in the use of certain terms, particularly those which apply to the larger features of the topography. Sometimes several different descriptive terms have been applied to the same structure, and in other instances the same term is applied to features of vastly different size and probably of different origin. A committee of the International Association of Physical Oceanography (Vaughan *et al*, 1940) attempted to clarify many of the problems relating to the terminology, but much confusion still prevails. In order to designate any individual feature, the descriptive term is prefixed by a specific name. The specific names attached to large-scale features are generally geographical, but those assigned to such features as banks, shoals, seamounts, canyons, and sometimes deeps are often those of vessels or individuals associated with their discovery or mapping.

FEATURES RESULTING FROM CRUSTAL DEFORMATION

1. ELEVATIONS. The large-scale elevations of the ocean bottom are termed *ridges*, *rises*, or *swells*.

Ridge (F, *Dorsale*; G, *Rücken*). A long and narrow elevation with sides steeper than those of a rise.

Rise (F, *Seuil*; G, *Schwelle*). A long and broad elevation which rises gently from the ocean bottom.

Isolated mountain-like structures rising from the ocean bottom are known as *seamounts*. Where the ridges are *curved*, and particularly if parts of them rise above sea level, they are sometimes termed *arcs*. The broad top of a rise is termed a *plateau*. The expression *sill* is applied to a submerged elevation separating two basins. The *sill depth* is the greatest depth at which there is free, horizontal communication between the basins.

2. DEPRESSIONS. The terms *trough*, *trench*, and *basin* are those most commonly applied to the large-scale depressions on the ocean bottom.

Trough (F, *Dépression*; G, *Mulde*). A long, broad depression with gently sloping sides.

Trench (F, *Fossé*; G, *Graben*). A long and narrow depression with relatively steep sides.

Basin (F, *Bassin*; G, *Becken*). A large depression of more or less circular or oval form.

The terms defined above are used rather loosely and are applied to features of a wide range in size.

For those parts of a depression which exceed 6000 m in depth, the term *deep* (F, *Fosse*; G, *Tief*) is used. As originally suggested by Murray, the term designated areas where the depths exceeded 3000 fathoms (5486 m), but it is now generally restricted to those depressions of greater depth (Vaughan *et al*, 1940). The term *depth* (F, *Profondeur*; G, *Tiefe*), prefixed by the name of the vessel concerned, may be used to designate the greatest sounding obtained in any given deep.

FEATURES RESULTING FROM EROSION, DEPOSITION, AND BIOLOGICAL ACTIVITY

As pointed out above, the features in this category have been produced by erosion of, or deposition upon, structures which may be primarily of diastrophic origin. The most prominent types of features in this group are the shelf and the slope.

Shelf. The zone extending from the line of permanent immersion to the depth, usually about 120 m, where there is a marked or rather steep descent toward the great depths. *Continental Shelf* (F, *Plateau continental*; G, *Kontinental-Schelff*) is applied to the feature bordering the continents, while *Insular Shelf* (F, *Socle*; G, *Insel-schelff*) is used for the feature surrounding islands.

Slope. The declivity from the outer edge of the shelf into deeper water. *Continental Slope* (F, *Talus continental*; G, *Kontinental-Abfall*) and *Insular Slope* (F, *Talus insulaire*; G, *Inselabfall*) are applied to the slopes bordering continents or islands.

The following terms are applied to the upper parts of elevations which show the effects of erosion or deposition.

Bank (F, *Banc*; G, *Bank*). A more or less flat-topped elevation over which the depth of water is relatively small, but which is sufficient for surface navigation.

Shoal (F, *Haut-fond*; G, *Untiefe* or *Sandgrund*). A detached elevation with such depths that it is a danger to surface navigation and which is not composed of rock or coral.

Reef (F, *Récif*; G, *Riff*). A rocky or coral elevation (generally elongate) which is dangerous to surface navigation. It may extend above the surface.

A variety of names has been applied to the steep-walled fissures that penetrate the slope and cut across the shelf. The most commonly used terms are *canyon* and *valley*, but *gully*, *gorge*, and *mock-valley* are also applied to these features.

In addition to the terms given above, many expressions are employed in descriptions of submarine topography with the same meanings that they have when used for land topography.

Bottom Configuration of the Oceans

The major features of the topography of the ocean bottom are of such large dimensions that they are readily shown on a chart with contour intervals 1000 m apart. Such a representation is given in chart I, where the contours are entered for 1000-m intervals between 3000 m and 7000 m. The areas with depths less than 3000 m represent a rather small part of the sea floor, and the complex nature of the contours for depths less than this would confuse rather than add to the value of a chart of this kind. The topography is based upon the most recent charts available, and primarily upon the bathymetric chart prepared by the International Hydrographic Bureau in 1939 (Vaughan *et al*, 1940). Other sources that may be consulted for details concerning the configuration of the ocean floor are listed on page 29. It will be noted that the complexity of the topography varies in different regions. This difference must be attributed, in part, at least, to the variable amount of data available, because in those regions where the soundings are widely spaced the contours will be smooth and rounded, whereas in those areas where there are numerous soundings the contours are more complex and irregular. The Atlantic Ocean, the central part of the North Pacific Ocean, the Northern Indian Ocean, and the area surrounding Antarctica are fairly well sounded, but in many other regions, such as the North Polar Sea and the Southern Indian and South Pacific Oceans, the observations are very sparse. The increase in the complexity of the known topographic features that follows the accumulation of more depth measurements can be seen by comparing recent bathymetric charts with those published in the early years of the present century. The status of bathymetric knowledge in 1937 is shown by a series of charts in Vaughan *et al* (1937).

As stated above, the topography of the ocean bottom is characterized by depressions and elongated ridges. Some of these features are of very

great dimensions, as may readily be seen from chart I. Longitudinal ridges divide the three oceans into elongated troughs. This feature is most conspicuous in the Atlantic Ocean, where the Atlantic Ridge, extending from Iceland to Bouvet Island in about 55°S , separates the western and the eastern troughs. Depths exceeding 5000 m exist on both sides of the ridge, which is continuous at depths less than 3000 m over the greater part of its length and in several places extends above sea level. There is one small but significant break in the ridge, in the Romanche Furrow just north of the Equator, where the saddle depth is located between 4500 and 4800 m. The Walfisch Ridge, which extends northeast from the Atlantic Ridge in the vicinity of Tristan da Cunha (37°S) to the coast of Africa in latitude 20°S , is continuous at 3500 m and almost so at 3000 m. The Rio Grande Ridge extends westward from the Atlantic Ridge (30° – 35°S) and is almost continuous at 4000 m. The presence of these two transverse ridges has a pronounced effect on the deep-water circulation in the Western and Eastern Atlantic and, hence, on the distribution of properties (chap. XV).

A longitudinal ridge, the Indian Ridge, is present in the Indian Ocean and extends from India to Antarctica, but differs from the one in the Atlantic Ocean in that it is wider and does not extend so near the surface. In the Pacific Ocean the longitudinal elevations are not so conspicuous; however, the West Pacific Ridge, which is actually composed of several shorter ridges, can be traced from Japan to Antarctica, and is continuous at depths less than 4000 m except for breaks at 11°N , 10°S , and 53°S . A second elevation extends from Central America to the south and west, reaching Antarctica in the longitude of New Zealand. This East Pacific Ridge is continuous at depths less than 4000 m and separates the central depression from the deep basins bordering Central and South America and the Pacific Antarctic Basin. The effect of these major elevations on the distribution of bottom-water temperatures is shown in fig. 211, p. 749.

Within the major depressions or troughs which are bordered by the continents and the longitudinal ridges are transverse ridges that separate to a greater or lesser degree a number of basins. Wüst (Vaughan *et al*, 1940) has suggested that the 4000-m contour be used as the boundary in designating basins, but this is a purely arbitrary delimitation that places undue emphasis upon the absolute depth rather than upon the relative relief, which in many instances is of greater significance. For example, the Mediterranean Sea Basin is virtually excluded from such a classification, although it is a deep, isolated basin, much of it extending more than 3000 m below the sill in the Strait of Gibraltar. In the tabulation accompanying chart I are listed the names for the major parts of the oceanic depressions which Wüst has termed basins; namely, those parts which have depths exceeding 4000 m. Certain individual basins are clearly

defined by the presence of ridges that are continuous at 4000 m, but names have also been applied to various parts of troughs, in which case the boundaries are located at the shallowest or narrowest part of the depression. In some areas the nomenclature is incomplete, and a single name is applied to a number of more or less isolated depressions, such as the Madagascar Basins. In the Central Pacific, where the knowledge of the topography has increased rapidly in recent years and where the basin and ridge type of topography does not appear to be present, no names have been applied. The names used to designate the major features of the topography are discussed at length by Vaughan *et al* (1940), and the names indicated on chart I generally conform to the recommendations made in their report.

In the tabulation of the basins given on chart I are listed some of the more prominent deeps; namely, those features where the depths exceed 6000 m. Some deeps are located more or less centrally in the large basins; for example, Wharton Deep, Byrd Deep, and the numerous deeps in the central part of the North Pacific, but these rarely exceed 7000 m in depth. On the other hand, numerous deeps of elongate character are located near and parallel to continental coasts, island arcs, or submarine ridges which correspond to the furrows discussed on p. 23. These marginal deeps, to which the term *trench* or sometimes *trough* is applied, are the features within which the greatest depths are found, in nearly all cases exceeding 8000 m. Only one such trench is found in the Indian Ocean; namely, the Sunda Trench. In the Atlantic are to be found the Romanche Trench, the South Sandwich Trench, and the Puerto Rico and Cayman Troughs. The greatest number are in the western part of the Pacific Ocean, although there is a chain of such features paralleling the mountainous coast of parts of Central and South America. As stated before, the regions in which these deep trenches occur are sites of volcanic and seismic activity. The complex topography of the East Indian Archipelago, which has been described by Kuenen (1935), is shown schematically in fig. 208, p. 736.

For a detailed description of the features of the sea bottom the reader should consult Littlehales (1932). Vaughan (1938) has described the topography of the Southern Hemisphere. There is much information of value in the large report by Vaughan and others (1940), which also contains the small-scale bathymetric chart prepared by the International Hydrographic Bureau on a Mercator projection, a special chart of the North Pacific prepared by the U. S. Hydrographic Office, and an excellent, detailed chart of the Caribbean Sea region prepared by the same agency. The standard charts on the bathymetry of the oceans are those in the series known as the *Carte Générale Bathymétrique des Océans*, published by the International Hydrographic Bureau at Monaco. These charts comprise twenty-four sheets which are revised from time to time

and are issued periodically as the new charts are completed. The third edition is now being issued. On these charts the depths are entered in meters. General bathymetric charts of the oceans are included in the publications of Schott (1926, 1935). Detailed charts of restricted regions and general charts of the oceans are issued by the various national agen-

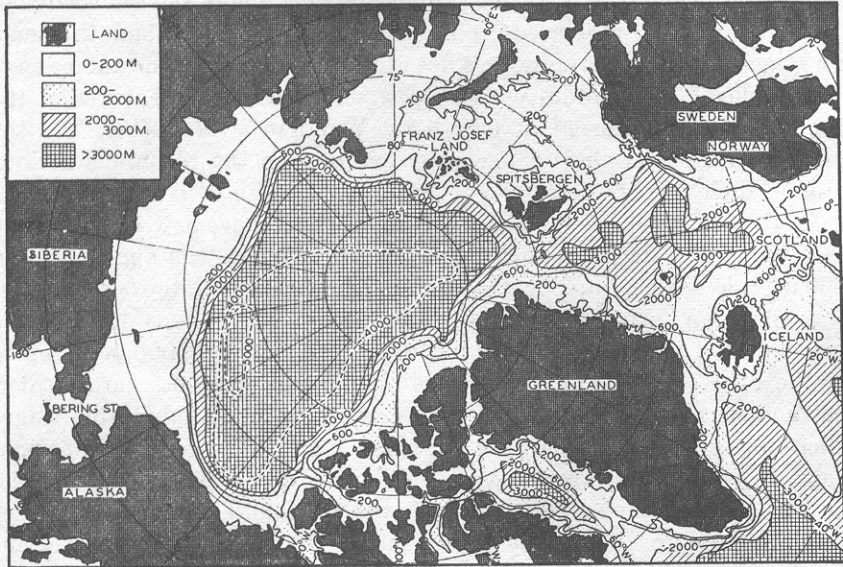


Fig. 3. Polar projection of the Arctic regions showing the generalized topography of the sea bottom. (Cherevichny's soundings of 1941 not included.)

cies responsible for the publication of navigational charts. The reports of the *Meteor* Expedition (*Deutsche Atlantische Expedition "Meteor" 1925-1927, Wissenschaftliche Ergebnisse*) will contain charts of the Atlantic Ocean, to be issued in thirteen sheets. The *Snellius* Expedition has produced excellent bathymetric charts of the East Indian region (van Riel, 1934). The Geological Society of America has sponsored the preparation and publication of detailed topographic charts of the eastern and western coasts of the United States based upon the soundings made by the U. S. Coast and Geodetic Survey (Veatch and Smith, 1939; Shepard and Emery, 1941).

Bottom Configuration of the Arctic and Antarctic Regions

Fig. 3 has been prepared to show the submarine topography of the North Polar regions, which cannot be properly visualized from the interrupted projection used in chart I. The figure is based on a chart by Stocks (1938) and incorporates all of the available data. Because of the larger scale it is possible to show the contours for the shallower depths that form such a large part of this area. The conspicuous topographic

features are the deep, partially isolated basins and the very wide shelf from which rise the large islands of the Canadian Archipelago, Greenland, and most of the islands to the north of Europe and Asia.

Very little is known of the topography of the North Polar Basin, and the form of the contours is largely hypothetical. Soundings greater than 3000 m are fairly numerous to the north of Europe, and there are some to the north of Alaska. A line of soundings also extends from the Pole and parallels the east coast of Greenland. These soundings were obtained by the Russian expedition which landed on the ice from planes and, in 1937-1938, drifted with the pack ice until picked up off the east coast of Greenland. Within 100 km of the Pole, this party obtained a sounding of 4300 m. The 5000-m contour is inserted on the basis of a single sounding of 5440 m obtained in 1927 by Sir Hubert Wilkins, who flew out by plane from Alaska, landed on the ice, and measured the depth with a portable sonic sounding instrument. The correctness of this sounding appears doubtful, however. In April, 1941, the Russian aviator Cherevichny, who landed on the ice in three different localities to the north of Wrangel Island and spent from three and a half to six days in each place, obtained much smaller depths (unpublished data communicated through the American Russian Institute, San Francisco, California). Cherevichny's soundings are as follows:

<i>Latitude, north</i>	<i>Longitude</i>	<i>Depth, m</i>
81°02'	180°00'E	2647
78 30	176 40 E	1856
80 00	170 00 W	3430

These soundings were not available when the bathymetric chart of the Arctic region (fig. 3) was prepared.

The more or less elliptical North Polar Basin is connected with the Norwegian Basin by a fairly deep channel between Greenland and Spitsbergen, in which the sill depth is about 1500 m (table 6). The Norwegian Basin, in which there are two depressions with depths exceeding 3000 m, is separated from the open Atlantic by a ridge extending from Greenland to Scotland, from which Iceland and the Faeroe Islands rise above sea level. The sill depths in Denmark Strait, between Greenland and Iceland, and over the Wyville Thomson Ridge, between the Faeroes and Scotland, are about 500 m. Rising from the floor of the Norwegian Basin is an isolated elevation that extends above the surface as Jan Mayen Island.

Another depression of considerable magnitude that does not appear on chart I is in Baffin Basin between Baffin Island and Greenland, where the depths exceed 2000 m. This basin is separated from the open Atlantic by a ridge in Davis Strait between Baffin Island and Greenland, where the sill depth is about 700 m.

Interesting topographic features which are well developed in the Arctic regions are the "troughs" that cut across the shelf. These U-shaped furrows were apparently cut by glaciers at a period when the sea surface stood at a lower level. One such trough extends around the southern tip of Norway, and others may be traced by the irregularities of the 200-m contour to the north of Russia and between the islands of the Canadian Archipelago. Nansen (1928), in a discussion of the topography of the North Polar Basin, has described these features.

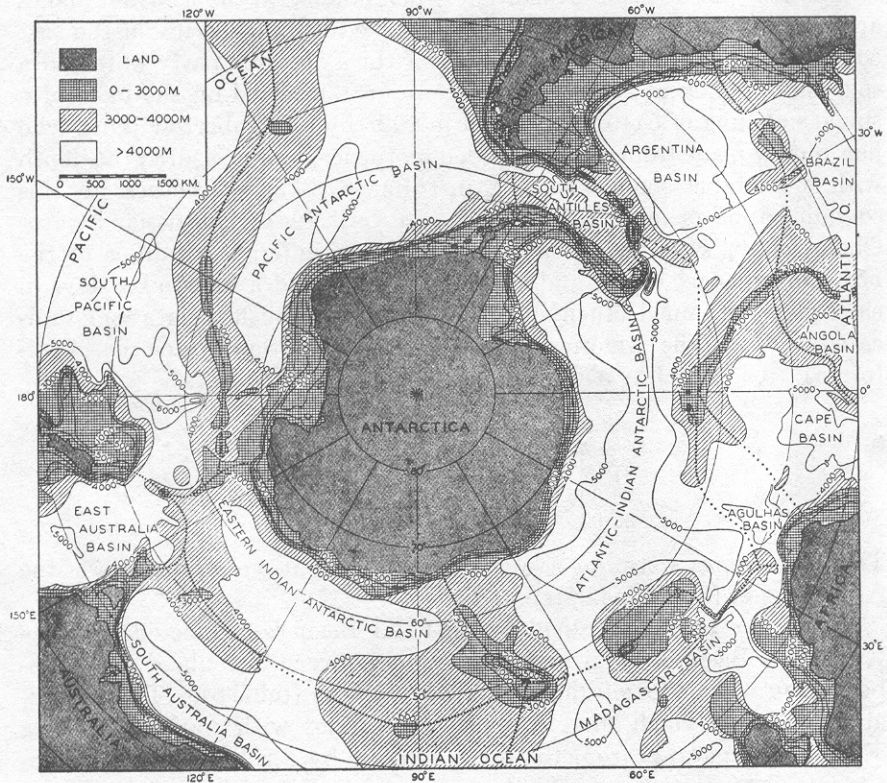


Fig. 4. Polar projection showing the generalized sea-bottom topography of the Antarctic regions. Depths less than 4000 m shaded. Heavy dotted lines show the location of the elevations which separate the various basins. Contours at depths of 3000 m and more correspond to those in chart I.

Fig. 4 is a polar projection of the Antarctic regions which shows the relationships between the major features of the submarine topography that cannot be visualized from chart I. The topography is based on the same data used for the preparation of chart I, supplemented from other sources. All major depressions are also shown in the world map, but it has been possible to enter in this figure the contours above 3000 m. There are many striking differences between the topography of the North

and the South Polar regions. The semi-isolated basins that are so prominent in the North Polar region are lacking in the South. The shelf, with depths less than 200 m, is extensive only off the east coast of the southern part of South America, where the Falkland Islands rise from the shelf.

The deep basins extend close to the continent of Antarctica, and the slopes are relatively steep. Joining South America to Antarctica is the South Antilles Arc, upon which are located South Georgia, South Sandwich, South Orkney, and South Shetland Islands. The ridge is continuous at 4000 m, and at 3000 m there are only relatively narrow openings. The Atlantic Ridge does not extend as far south as Antarctica, but is terminated in the vicinity of Bouvet Island. The ridge to the south of Africa and Madagascar is known as the Crozet Ridge, after the island of that name that rises from it. Forming a part of the Indian Ridge is the conspicuous elevation surrounding Kerguelen Island known as the Kerguelen Ridge. The ridge extending from Australia to Antarctica supports Macquarie Island and is known as the Macquarie Ridge. The importance of these ridges in determining the distribution of properties and the character of the circulation around Antarctica is discussed in chapter XV, p. 610 *et seq.* The greatest depths found in the region shown in fig. 4 are in the Byrd Deep to the south of New Zealand and in the South Sandwich Trench on the convex side of the South Antilles Arc.

Bottom Configuration of Adjacent Seas

It is beyond the scope of this volume to present charts or descriptions of the many marginal and adjacent seas. In table 4 are listed the area, volume, and mean depth of some of these features. The adjacent seas of the Arctic regions are shown in fig. 3, and in figs. 5 and 6 are shown the generalized topographies of the European and American Mediterraneans. Details of the topography of other marginal areas are presented elsewhere. The degree of isolation—namely, the extent to which free exchange of water with the adjacent ocean is impeded by the presence of land or submarine barriers—plays an important role in determining the characteristic distribution of properties in such regions (see chapters IV and XV).

The European Mediterranean, which comprises the Mediterranean Sea, the Black Sea, and the waters connecting them (namely, the Dardanelles, the Sea of Marmora, and the Bosphorus) forms an intercontinental sea bordered by Europe, Asia, and Africa. The Mediterranean Sea occupies a deep, elongated, irregular depression with an east-west trend, and the Black Sea occupies a small and topographically simpler depression offset to the north. The Black Sea Basin, with depths exceeding 2200 m, is virtually isolated from the Mediterranean Sea proper, the connection

being restricted to a narrow and shallow channel in the Bosphorus where the sill depth is only 40 m, and a similar channel in the Dardanelles where the sill depth is 70 m. In the Sea of Marmora, depths exceed 1000 m. The Mediterranean Basin, where depths reach 4600 m, is in restricted communication with the open Atlantic through the Strait of Gibraltar, which is only 20 km wide and where the sill depth is about 320 m. The peculiar oceanographic conditions that prevail in the Black Sea and Mediterranean Sea (p. 642 *et seq.*) can be attributed to the isolation of the deeper waters.

The generalized topography of the European Mediterranean is shown in fig. 5, which is based on a chart prepared by Stocks (1938). The Black Sea Basin (V) is of more or less elliptical form except in the north, where there are irregular shallow seas of which the largest is the Sea of

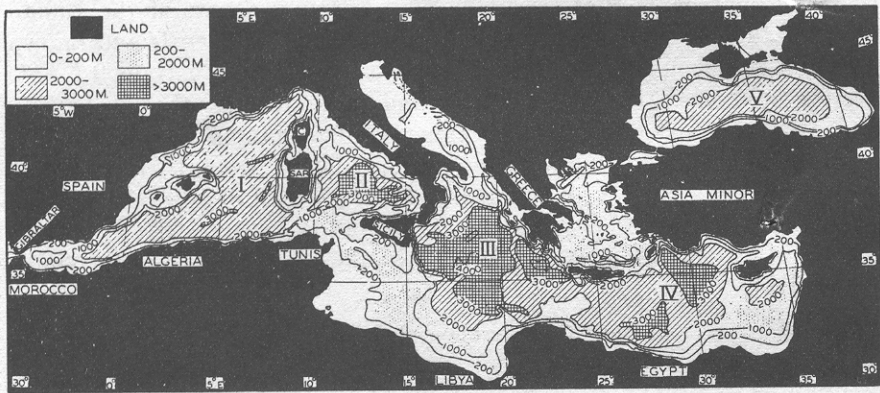


Fig. 5. Generalized bottom topography of the European Mediterranean. The larger basins are (I) Algers-Provençal, (II) Tyrrhenian, (III) Ionian, (IV) Levantine, and (V) Black Sea Basin.

Azov, east of the Crimean Peninsula. The connection with the Mediterranean Sea is through the Bosphorus, the Sea of Marmora, and the Dardanelles into the Aegean Sea, where the irregular topography is reflected in the large number of islands. The Mediterranean Sea Basin is subdivided by a series of transverse ridges with a north-south trend, parts of which extend above sea level. The primary division into the western and eastern depressions is effected by a ridge extending from Europe to Africa—namely, Italy, Sicily, and the submerged part of the elevation between these land areas and Africa. The sill depth in the strait between Sicily and Tunis is about 400 m. The Western Mediterranean, in turn, is subdivided into the Algers-Provençal Basin (I) and the Tyrrhenian Basin (II) by the ridge extending from northwestern Italy to Tunis, from which Corsica and Sardinia rise above the sea surface. The Eastern Mediterranean is subdivided into two major depressions: the Ionian Basin (III), in which maximum depths of 4600 m are found,

and the Levantine Basin (IV) by the ridge extending from Greece to Africa. There are other isolated depressions of smaller dimensions, such as the Alboran Basin between Spain and Morocco and those between Italy and Albania in the Adriatic Sea, to the north of Crete and to the south of Cyprus.

The American Mediterranean encompasses the partially isolated basins of the wide gulf bordered by North, Central, and South America which are separated from the open Atlantic by ridges, parts of which rise above sea level. The generalized topography of the region is shown in fig. 6, which is based on a chart by Stocks (1938). The chief difference

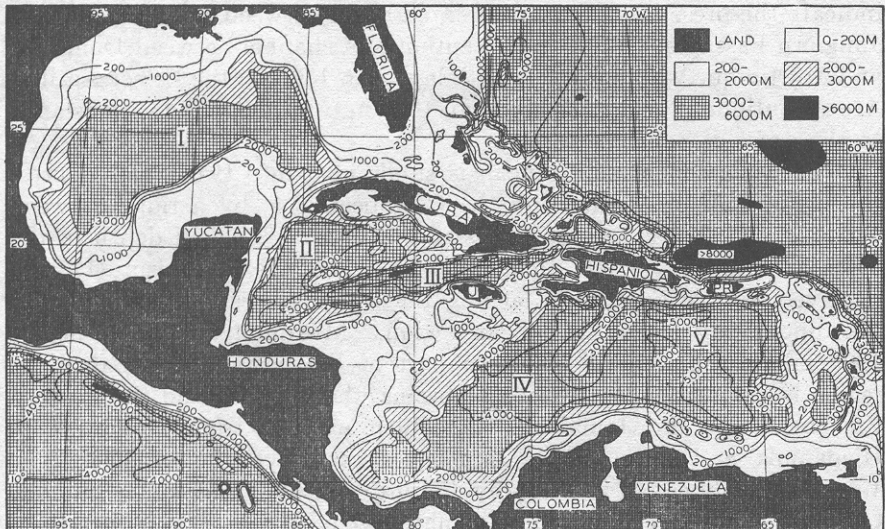


Fig. 6. Generalized bottom topography of the American Mediterranean. The larger basins are (I) Mexico Basin; (II) Cayman Basin and (III) Cayman Trough, in the Western Caribbean; (IV) Colombia Basin and (V) Venezuela Basin, in the Eastern Caribbean. The greatest known depth in the Atlantic Ocean, 8750 m, is located in the Puerto Rico Trough to the north of Puerto Rico.

between the European Mediterranean and the American Mediterranean is that the latter has numerous shallow and several deep connections with the open Atlantic. The topography of the American Mediterranean is extremely rugged, with deep trenches adjacent to steep-sided ridges, many of which rise above sea level. This is particularly true in the central and southern parts of the region, which are areas of pronounced gravity anomaly, volcanism, and strong seismic disturbances (Field *et al*, 1938). Bordering the low-lying coast of the Gulf of Mexico, off part of Honduras and Nicaragua, and surrounding the Bahama Islands are extensive shelves. The slopes leading down to deep water are in general rather steep, particularly between Cuba and Jamaica and along the

outer margin of the Bahama Islands. On the northern and outer side of the Lesser Antilles Arc is the Puerto Rico Trough, the deepest depression in the floor of the Atlantic Ocean, where the U.S.S. *Milwaukee* obtained a maximum sounding of 8750 m. Although there are many openings between the islands on the Lesser Antilles Arc, the openings with relatively great sill depths are few in number. In the Straits of Florida the sill depth is about 800 m, and in Windward Passage, between Cuba and Hispaniola, it is about 1600 m. A third deep channel with a sill at about 1600 m is located in Anegada and Jungfern Passages between the Virgin Islands and the Windward Islands and between the Virgin Islands and St. Croix Island. The oceanographic conditions (p. 640) indicate the presence of a small isolated basin between the Anegada and Jungfern Passages. With the exception of a channel between Dominica and Martinique with a saddle depth less than 1500 m, the Lesser Antilles Arc is continuous at depths less than 1000 m from the Windward Islands to the coast of South America.

The American Mediterranean is subdivided into two major depressions, the Gulf of Mexico and the Caribbean Sea, by a ridge between Yucatan and Cuba, and by the island of Cuba. The sill depth in the Yucatan Channel is less than 1600 m. The Mexico Basin (I) is a relatively simple depression lacking the irregularities that characterize the topography of the Caribbean region. Maximum depths of nearly 4000 m are found in the western part of the basin. The Caribbean region is separated into two major basins, the Western and the Eastern Caribbean, by the Jamaica Rise, which extends from Honduras to Hispaniola and from which Jamaica rises above the surface. The Western Caribbean is in turn divided into Yucatan Basin (II) and the Cayman Trough (III) by the Cayman Ridge, which extends westward from the southern extremity of Cuba. The Cayman Trough is the deepest depression in the American Mediterranean, and within the Bartlett Deep to the south of Cuba the U.S.S. *S-21* obtained a maximum sounding of 7200 m. The Windward Passage between Cuba and Hispaniola appears to be a continuation of the depression forming the Cayman Trough. The greatest saddle depth between the Western and Eastern Caribbean is located in the passage between Jamaica and Hispaniola, where it is about 1200 m. The Eastern Caribbean is partially divided into two basins by the Beata Ridge, which extends south and west from Hispaniola toward South America. The western portion of the depression is known as the Colombia Basin (IV) and the eastern as the Venezuela Basin (V). The Aves Swell separates a small basin with depths greater than 3000 m in the eastern part of the Venezuela Basin, which is called the Grenada Trough.

The terminology to be applied to the features of the American Mediterranean is discussed by Vaughan in the report by Vaughan

TABLE 6
ISOLATED BASINS IN ADJACENT SEAS

Basin	Max. depth (m)	Adjacent deep depression	Surface feature	Location of sill	Sill depth (m)	Max. depth - sill depth (m)
<i>Arctic Mediterranean Region</i>						
North Polar Basin.....	4300	North Pacific	Bering Strait	Siberia-Alaska	55	
Norwegian Basin.....	3700	Norwegian Basin	Denmark Strait	Greenland-Spitsbergen	1500	2800
Baffin Basin.....	2200	North Atlantic	Davis Strait	Faeroe Is.-Scotland	500	3200
		North Atlantic		Baffin Is.-Greenland	700	1500
<i>European Mediterranean Region</i>						
Western Mediterranean Basin.....	3700	North Atlantic	Strait of Gibraltar	Gibraltar-Morocco	320	3400
Eastern Mediterranean Basin.....	4600	Western Mediterranean		Sicily-Tunis	400	4200
Black Sea Basin.....	2200	Eastern Mediterranean	Bosporus		40	2200
			Dardanelles		70	
<i>American Mediterranean Region</i>						
Eastern Caribbean Basin.....	5500	North Atlantic	Anegada and Jungfern Passages	Virgin Is.-Lesser Antilles	1600	3900
Western Caribbean Basin.....	7200	North Atlantic	Windward Passage	Cuba-Hispaniola	1600	5600
		Eastern Caribbean	Jamaica Channel	Jamaica-Hispaniola	1200	
		Western Caribbean	Yucatan Channel	Yucatan-Cuba	1600	2300
Mexico Basin.....	3900	North Atlantic	Strait of Florida	Florida-Bahama Is.	800	
<i>Other Regions</i>						
Japan Sea Basin.....	3700	Philippines Basin	Tsushima Strait	Korea-Japan	150	3550
Red Sea Basin.....	2800	Indian Ocean	Strait of Bab-el-Mandeb	Somaliand-Arabia	100	2700
Baltic Sea Basin.....	300	North Atlantic	Danish Sounds	Danish Is.-Germany	20	280

et al (1940), which also includes an excellent bathymetric chart of the Caribbean region prepared by the U. S. Hydrographic Office. The currents and distribution of properties in this area are described in chapter XV, p. 637.

Isolated basins are of great interest from an oceanographic point of view, and in table 6 are brought together some of the data relating to the larger basins in adjacent seas. This tabulation does not include the basins in the East Indian Archipelago, which are discussed elsewhere (table 87, p. 738). The maximum depth within each basin and the greatest sill depth at which there is horizontal communication with the adjacent basins are listed as well as the difference between the greatest depth in the basin and the sill depth. The latter value corresponds to the depth of the "lake" that would be formed if the water level were lowered to the greatest sill depth. It will be seen that most of the basins listed are without horizontal communication through vertical distances of 3000 to 4000 m, and that in the Yucatan Basin the greatest depth is 5600 m below the sill. In great contrast to these deep basins is the Baltic Sea (average depth, 55 m), where depths greater than 300 m are restricted to small, isolated depressions and where the sill depth is only 20 m.

In fig. 7 is shown the topography of the area off the coast of Southern California. This coastal area is one of considerable interest in that it is physiographically similar to the adjacent land area and apparently represents a down-warped portion of the continent. The continental shelf is relatively narrow, and offshore is a series of basins and ridges upon which several islands are located. In the southern part the real continental slope leading down to the oceanic abyss is approximately 150 miles from the coast. This is not shown in the map. Several small canyons are also depicted in the figure.

Submarine Canyons

For many years it has been known that there were furrows cutting across the shelf in certain regions, but only since it became possible to obtain large numbers of accurately located soundings of the shelf and slope were such features found to be numerous and widespread. Various terms, canyons, valleys, mock-valleys, and gullies by different authors, they have stimulated a great deal of interest among geologists, and a large literature has been built up dealing with the character and mode of formation of these canyons. The data concerning the topography of the canyons have largely been obtained by national agencies engaged in the careful mapping of nearshore areas. Such data have been used by Veatch and Smith (1939) and by Shepard and Emery (1941) to prepare general and detailed topographic charts of the canyons off the east and west coasts of the United States. Stetson (1936) has carried out independent observations on the east coast, and Shepard

The head of a canyon may sometimes be traced into shallow water within a few hundred meters of the land, and in other cases it is restricted to the upper part of the slope in depths of 100 to 200 m and at distances of fifty or more km from the coast. Certain canyons can be traced outward for great distances and into depths of several thousand meters, but Shepard is doubtful whether the deeper parts of the canyons, which are wider and have much gentler wall slopes, are of the same origin as the inner parts. The canyons are characteristic of continental coasts, but

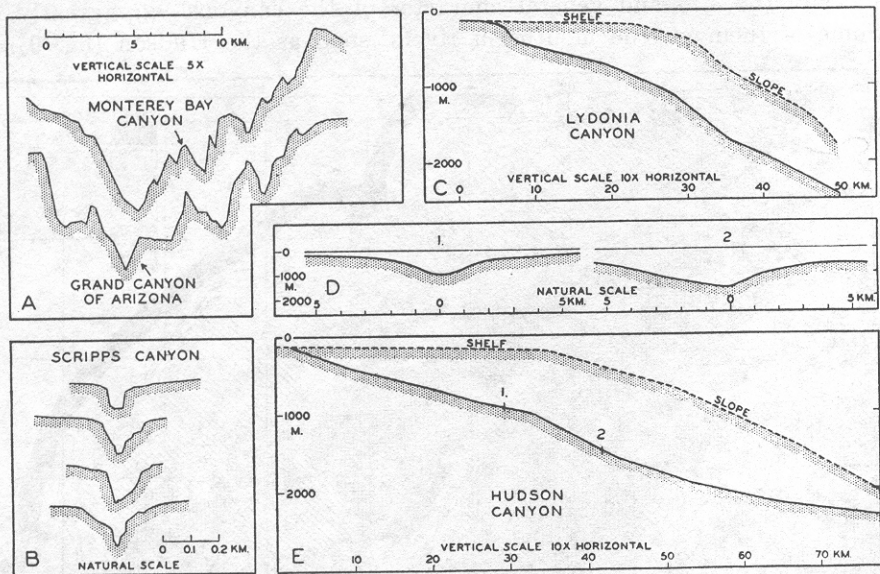


Fig. 8. Profiles of submarine canyons. (A) Transverse profile of the submarine canyon in Monterey Bay compared to a profile of the Grand Canyon of the Colorado River in Arizona (cf. fig. 10). (B) Transverse profiles of a small, steep-walled canyon off the southern California coast. (C) Longitudinal profiles of the Lydonia Canyon and the adjacent shelf and slope. (D) and (E) Transverse and longitudinal profiles of the Hudson Canyon, showing the relation to the adjacent shelf and slope. The locations of the transverse sections (D) are shown on the longitudinal profile. Note the vertical exaggeration in certain of the diagrams and the differences in horizontal scales (A and B after Shepard, 1938; C, D, and E after Veatch and Smith, 1939).

there is some evidence to show that similar features occur around oceanic islands.

The steep walls of the canyons are generally free of unconsolidated sediment, and in those canyons where special investigations have been made the walls appear to be generally of sedimentary rock; in a few cases (for example, Monterey Canyon off the California coast, fig. 10) the canyons are cut into granite that is overlain by sedimentary rock. The sediments in the bottom of the canyons are generally coarser than those on the adjacent shelves, and in some of them cobbles and gravel have been found.

The following agencies have been advanced as possible causes for the formation of the canyons:

1. Diastrophism.
2. Erosion by submarine currents. Daly (1936) advanced the theory that "density currents" produced by suspension of much fine-

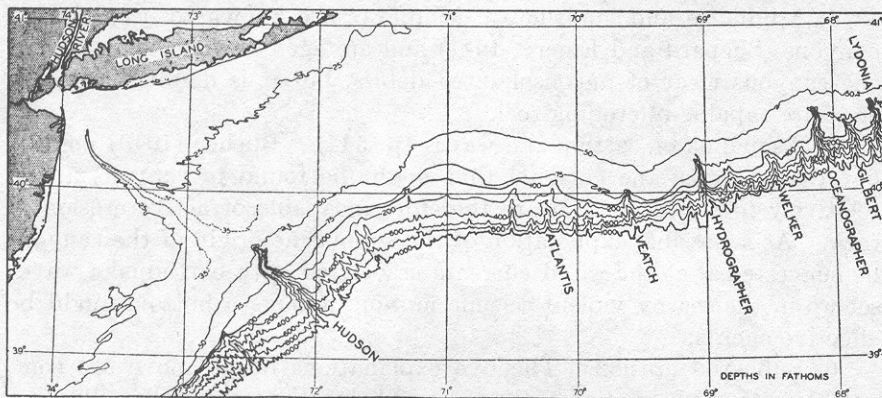


Fig. 9. Topography of the shelf and slope off part of the eastern coast of the United States showing different types of submarine canyons. The Hudson Canyon can be traced far across the shelf; others, such as the Lydonia, Oceanographer, and Hydrographer Canyons, cut into the outer margin of the shelf, while others are restricted to the slope itself. Depth contours in fathoms. (Simplified from chart in Veatch and Smith, 1939.)

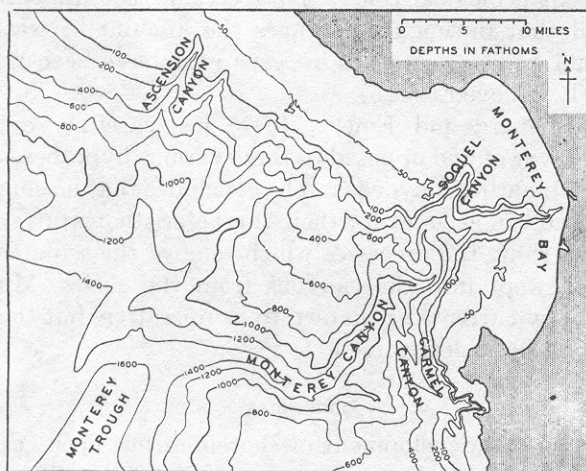


Fig. 10. Monterey Canyon off the coast of California.

grained sediment may have flowed down the slope and cut the canyons, particularly during intervals of lowered sea level during the glacial periods. Density currents occur in reservoirs, but there is no evidence of their existence in the sea, where the density stratification of the water impedes vertical flow.

3. Spring sapping. Johnson (1939), in a thorough review of the literature concerning the character and origin of submarine canyons, develops the hypothesis that solution and erosion resulting from the outflow of underground water might contribute to the formation of the canyons.

4. Mudflows and landslides. Mudflows are known to occur in the canyons (Shepard and Emery, 1941) and are agents which tend to keep the canyons clear of unconsolidated debris, but it is doubtful whether they are capable of eroding rock.

5. Tsunamis or earthquake waves (p. 544). Bucher (1940) pointed out that most of the currents that might be found in canyons are of relatively low velocity and are therefore incapable of active erosion of rock. As a possible explanation of the submarine origin of the canyons he suggested that the rapid currents associated with earthquake waves set up in the sea by violent seismic motion of the sea bottom might be effective agents.

6. Subaerial erosion. The five explanations listed above are compatible with the formation of the canyons below the sea surface. Because of their many resemblances to river-cut canyons on land, many investigators, notably Shepard, believe that the canyons must have had a subaerial origin. However, there is no accepted geological theory that would account for the world-wide exposure of the shelf and slope within relatively recent geological time. To overcome this difficulty, Shepard has suggested that during the ice ages the amount of water removed from the ocean and deposited as ice caps may have been much greater than ordinarily believed (p. 25).

Shepard (Shepard and Emery, 1941) has carefully evaluated the arguments in favor of and opposed to these various hypotheses concerning the origin of submarine canyons, and he concludes that no single hypothesis yet advanced can account for their characteristic features. Problems also exist concerning the processes which remove the sedimentary debris that must be swept into the canyons from the shelf. Mudflows and transportation by currents are known to be operative, but their effectiveness has not yet been determined.

Shorelines

The study of the development of shorelines has been carried out by geologists and physiographers who have classified the different types of coasts largely upon the basis of the extent to which erosion and deposition have affected the coastal configuration. Johnson (1919, 1925) has described the characteristic features of the coast and shallow-water zone, and these and other sources should be consulted in order to appreciate the complex nature of the transition zone between land and sea, where the effects of erosion and deposition, both subaerial and marine, must be

taken into account. In the chapter on marine sedimentation (chapter XX) the properties of beach and shallow-water sediments are discussed with reference to the source of sedimentary debris, the transporting agencies, and the roles of waves and currents in erosion and deposition. Although many observational data have been obtained on the features of the coastline, the evaluation of the relative importance of the different factors involved has been handicapped by the lack of adequate knowledge of the characteristics of waves, tidal currents, and other motions in the sea as transporting and eroding agents.

The classification of shorelines has been treated by Johnson (1919) and Shepard (1937). Shepard's primary classification is based upon a consideration of the following factors:

1. Primary or youthful coasts with configurations due mainly, to nonmarine agencies.
 - a. Those shaped by terrestrial erosion agencies and drowned by deglaciation or down-warping.
 - b. Those shaped by terrestrial depositional agencies such as rivers, glaciers, and wind.
 - c. Those shaped by volcanic explosions or lava flows.
 - d. Those shaped by diastrophic activity.
2. Secondary or mature coasts with configurations primarily the result of marine agencies.
 - a. Those shaped by marine erosion.
 - b. Those shaped by marine deposition.

The beach is defined as the zone extending from the upper and landward limit of effective wave action to low-tide level. Consequently, the beach represents the real transition zone between land and sea, since it is covered and exposed intermittently by the waves and tides. The characteristics of beaches depend so much upon the nature of the source material composing their sediments and the effects of the erosion, transportation, and deposition by waves and currents that they can be more profitably discussed in the chapter on marine sedimentation. The upper part of the beach is covered only during periods of high waves, particularly when storms coincide with high spring tides. The slope of the beach is largely determined by the texture of the sediments (p. 1018), but the extent of the beach will depend upon the range in tide. The terminology applied to the various parts of the beach and the adjacent regions is shown in fig. 11, taken from a report by the Beach Erosion Board (U. S. Beach Erosion Board, 1933).

Beaches composed of unconsolidated material are characteristically regions of instability. Every wave disturbs more or less of the smaller sedimentary particles, and the character of the waves will determine whether or not there is a net removal or accretion of sediment in any

locality during a given time interval. Currents that effect a net transport of material kept in suspension by the waves also play an important part in shaping the beach. Fluctuations in the direction and height of the waves or in the direction of the currents alongshore usually result in changes in the profile of the beach. Such changes are commonly seasonal, and corresponding changes occur in the amount of sand in any locality and in the profile of the beach (Shepard and LaFond, 1940). The instability of the beach over relatively short time intervals has many implications in connection with the beach as an environment for sedentary organisms (chapter VIII).

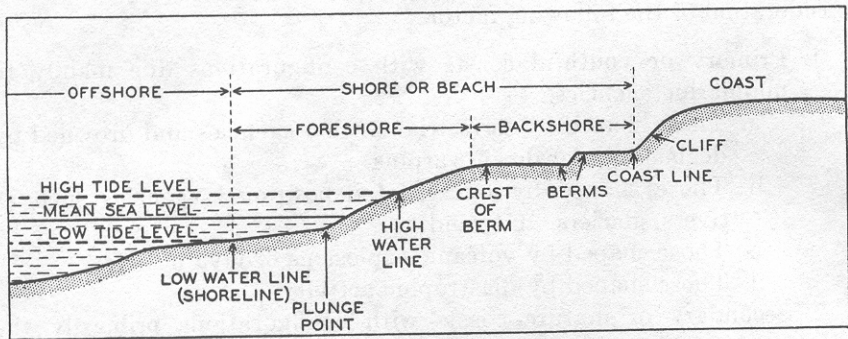


Fig. 11. Terminology applied to various parts of the beach profile. *Berms* are small impermanent terraces which are formed by deposition during calm weather and by erosion during storms. The *plunge point* is the variable zone where the waves break, hence its location depends on the height of the waves and the stage of the tide.

Although subject to short-period disturbances, the beach in general represents an equilibrium condition, despite the slow erosion of the coast or the permanent deposition that may be taking place. If the normal interplay of waves and currents is impeded in any way, as by the building of piers, breakwaters, or jetties, the character of the beach may be entirely changed. In some instances, highly undesirable erosion of the coast may result, and in others equally undesirable deposition may result. These changes will proceed until a new equilibrium is established that may render the value of the structure worthless for the purpose for which it was originally intended. The construction of breakwaters, jetties, sea walls or groins, and similar structures on an open coast should be undertaken only after a careful investigation of the character and source of the sedimentary material, the prevailing currents, the strength and direction of the waves, and other factors that determine the equilibrium form of the beach. The Beach Erosion Board of the U. S. Army, Corps of Engineers, as well as various private organizations, are engaged in studies of this type.

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