THE MARINE ENVIRONMENT

SEC. 20.1.1 - PHYSICAL OCEANOGRAPHY

SEC. 20.1.2 - MARINE CHEMISTRY

SEC. 20.1.3 - MARINE GEOLOGY

by

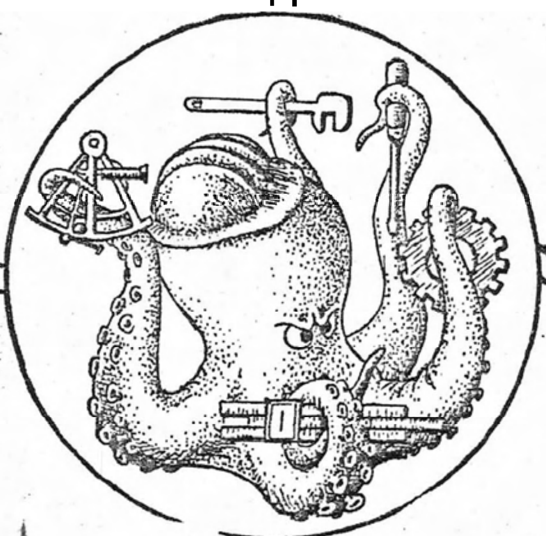
Pat Wilde

From

Society of Mining Engineers:

Mining Engineering Handbook Vol. II

A. B. Cummins and I. A. Givens: Editors



COMMITTEE ON OCEAN ENGINEERING

COLLEGE Of ENGINEERING

UNIVERSITY OF CALIFORNIA

BERKELEY

SME Mining Engineering Handbook

In Two Volumes

Volume 2

ARTHUR B. CUMMINS

Chairman, Editorial Board

IVAN A. GIVEN

Editor

Sponsored by

Seeley W. Mudd Memorial Fund of AIME
Society of Mining Engineers of AIME
U.S. Bureau of Mines, Dept. of the Interior

Society of Mining Engineers
of
The American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc.
New York, New York

20.1.1—PHYSICAL OCEANOGRAPHY

PAT WILDE

The fundamental parameters measured in physical occnnogrnphy are: (1) three-dimensional position, (2) tempernture nnd (3) salinity (more exactly, conductivity). Other important parameters, such ns pressure, density, water particle velocity, sound velocity and light transmittance are at least in part derived from the fundamental parameters.

Three-Dimensional Position

North-South—Parallels of latitude—degrees, minutes and seconds of arc, assuming the equator as 0° with the North Pole 90°N and the South Pole 90°S; 1° latitude is approximately equal 60 nautical mi; therefore 1 min latitude ≅ 1 nautical mi, ≅ 6,080 ft, and 1 marine lengue = 3 nautical mi.

TABLE 20-1—Area. Volume and Mean Depth of the Oceans (Menard and Smith[2])

Oceans and Adjacent Seas	Area, 10^6 Sq Km	Volume, 10^6 Cu Km	Mean Depth, m, Menard and Smith
Pacific	166.241	696.189	4,188
Asiatic Mediterranean	9.082	11.366	1,252
Bering Sen	2.261	3.373	1,492
Sea of Okhotsk	1.392	1.354	973
Yellow and East China sens	1.202	0.327	272
Sen of Japan	1.013	1.690	1,667
Gulf of California	0.153	0.111	724
Pacific and adjacent seas, total	181.344	714.410	3,940
Atlantic	86.557	323.369	3,736
American Mediterranean	4.357	9.427	2,164
Mediterranenn	2.510	3.771	1,502
Black Sea	0.508	0.605	1,191
Baltic Sea	0.382	0.038	101
Atlantic and adjacent seas, totnl	94.314	337.210	3.575
Indian	73.427	284.340	3,872
Red Sea	0.453	0.244	538
Persian Gulf	0.238	0.024	100
Indinn and adjacent seas, total	74.118	284.608	3,840
Artic	9.485	12.615	1,330
Arctic Mediterrnnean	2.772	1.087	392
Arctic and adjacent seas, total	12.257	13.702	1,117
Totals and mean depths	362.033	1349.929	3,729

East-West—Meridians of longitude--degrees, minutes, seconds of arc assuming Greenwich, England, as 0° or the prime meridian (French charts often use Paris as the prime meridinn); meridinna east of prime meridinns to 180" are east longitude; meridians west of prime meridian to 180° nrc west longitude.

Vertical—Depth in linear units—fathoms, feet, meters, (U.S. now only major country that uses fathoms for depth measure), datum sea surface. One fathom = 6 ft = 1.8288 m. Echo sounding depth recorders rending (1) in fathoms assume a speed of sound in seawater of 800 fathoms (1,463 m) per sec, (2) in meters, 1,500 (820 fathoms) per sec. Corrections for variations of the speed of sound in seawater are given in Matthews Tnbles' for the ocenn divided into 46 regions. The area, volume nnd depth of the world's oceans and seas nre listed in Table 20-1.

Temperature

°**Centigrade** (Celsius), °**Fahrenheit.** "Fahrenheit = $9/5°C + 32$. Temperature is mensurcd by (1) substances with a **linear coefficient** of thermal expansion (mercury thermometer), (2) temperature-sensitive resistor (resistance thermometer or thermistor), (3) a crystal whose oscillation frequency is temperature dependent

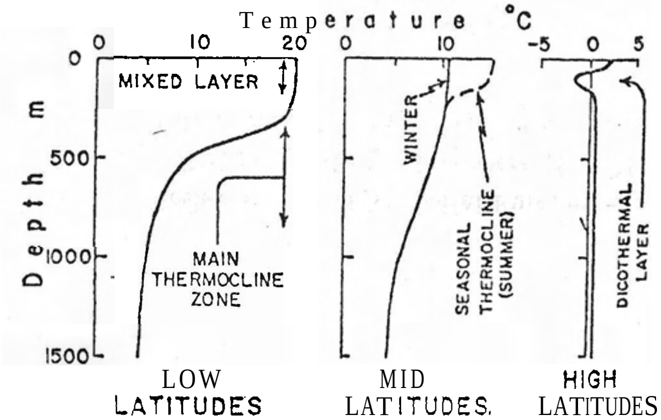


Fig. 20-1—Typical mean temperature profiles in the open ocean (Pickard[5]).

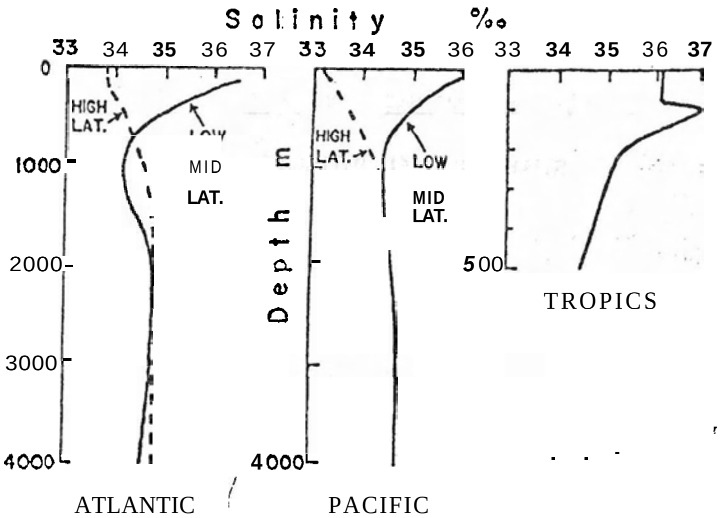


Fig. 20-2—Typical mean snlinity profiles in the open ocean (Pickard[5]).

(quartz thermometer) and (4) by infrared emissions (radiation thermometer or bolometer).

Tcmpcrnture profiles in the ocean (Fig. 20-1) typically show a threefold zonntion: (1) n surface isothermal mixed layer of higher tcmperntures, (2) a transition zone of decreasing tcmpernture called the thcrmoclinc, nnd (3) a deep relatively isothermal zone of lowest temperatures. In general, temperature profiles are stable; that is, wnrmcr wntcr overlies colder water. The average tcmpernture of seawater is about 4°C.

Salinity

0/00, parts per thousand, ppt. Classically done by nrgentometric titration of the **chlorinity (CL)** (total halogens). Total dissolved solids (ppt) = $0.073 + 1.811$ CL (ppt), although salinity (ppt) = $0.03 + 1.805$ CL (ppt). Approximnte salinity determinations can be mnde by titrating 10 cu cm of seawater with n solution of 27.25 g $AgNO_3$ per 1. The volume of $AgNO_3$ solution required in cubic centimeters approximates the salinity (ppt) (Harvey[6]).

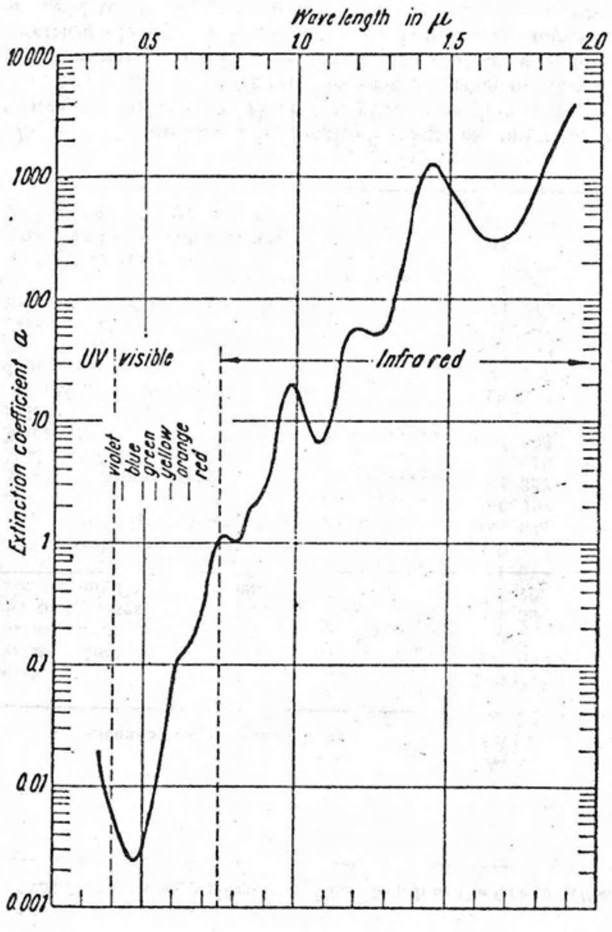


Fig. 20-3—Extinction coefficient (a) for light beam in pure water as a function of its wave length, 1-m thickness of layer (Dietrich[7]).

Most modern measurements are made **conductometrically with** an induction **salinometer** where salinity (ppt) = 1.80655 CL (Cox[8]). Salinity profiles in the oceans generally look like tempcrnture profiles. However, mnny exceptions are found. **The vertical** salinity distribution usually is unstable as higher snlinity water due to evaporntion nt the surface overlies lower salinity water at depth. The nverngc salinity of the oceans is about 35 ppt.

Pressure — Atmosphere = 1.01325×10^6 dynes per sq cm; bnr = 0.98692 atmospheres = 1×10^6 dynes per sq cm; dccibnr = 0.1 bars. As the depth in the ocenn in meters is approximately numerically equal to the pressure in decibars, most pressure values are derived from depth measurements. However, pressure sensors also are used to measure depth in in-situ real-time remote probes.

Density—ρ = g per cu cm; $\sigma_{S,T,P} = (\rho_{S,T,P}-1)1{,}000$. Density is a function of salinity, temperature and pressure. Tables of in-situ density are bnsed on deviations from the stnndsrd ocean where the salinity = 35 ppt, temperature = 0°C, and pressure = 1 atm (Kundsen[6]). The inverse of density, specific volume, α, often is used. The specific volume anomaly, thus, is $\delta = \alpha_{S,T,P} - \alpha_{35,0,1}$. The average density of the ocenns is about 1.025 g per cu cm, or σ = 25.

Optical Properties—*Index* of *Refraction*—A function of salinity and temperature, or $n_{D,25°} = 1.332497 + 0.000334$ CL (ppt).

Absorption—In seawater with little pnrticulate matter the coefficient of absorption is similar to pure water (Fig. 20-3) with the major nbsorption towards the

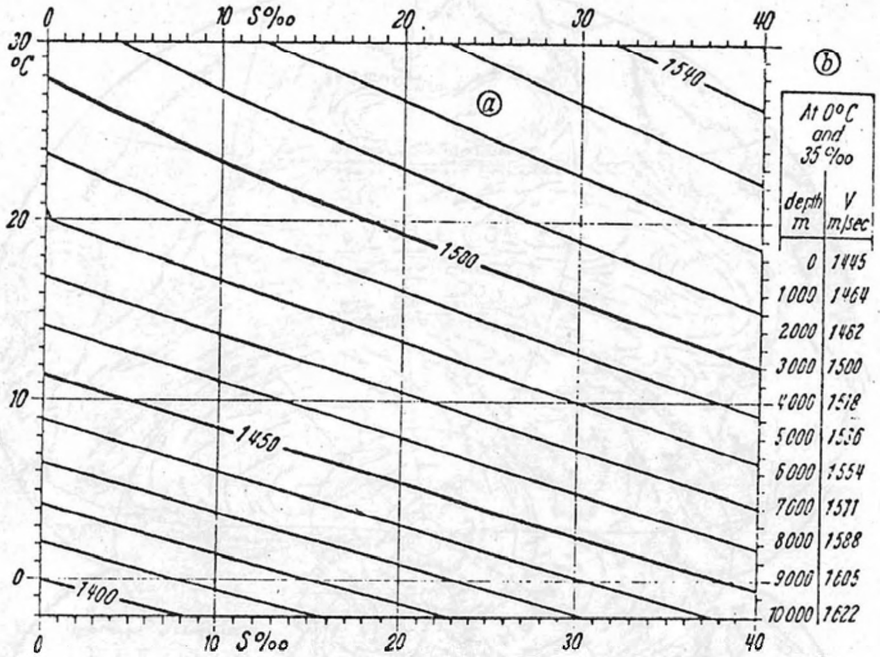


Fig. 20-4—a, velocity of sound V (in meters per sec.) in seawater as a function of temperature nnd salinity, neglecting pressure; b, at different depths at a temperature of 0°C and a salinity of 35% as a function of pressure (a and b after S. Kuwahara, 1938) (Dietrich[7]).

red end of the spectrum. This is why most objects in seawater illuminated with sunlight have a bluish cast.

Color—The color of seawater for clear skies with the optical center of incident light st 0.47μ is (1) blue for clear open-ocean water where extinction is due to absorptive properties alone (see Fig. 20-3); (2) blue-green to green with the addition of organic particles, for example, near a cord reef; (3) yellow in regions of high humic content near major rivers, (4) chocolate-brown off coastal regions delivering silts and clays so that the sea color is due partially to light reflection off individual particles, and (5) green, brown or red for high concentrations of plankton, as in red-tide blooms.

Acoustic Properties—The velocity of propagation of sound wnves in the ocean can be approximated by $V \sim \frac{\sqrt{1}}{\kappa}$, where κ = the adiabatic compressibility, a function of temperature and pressure (Fig. 20-4).

The combination of a stepwise increase in the temperature profile nnd the linear increase in pressure with depth produces sound velocity profiles as shown in Fig. 20-5, which generally have velocity maxima nenr 1,000 m.

Circulation

Surface—Fig. 20-6 shows the major surface currents of the world ocean. The basic circulation pattern is gyroidnl, clockwise in the northern hemisphere due to the right-handed Coriolis deflection and counterclockwise in the southern hemisphere where the Coriolis deflection is left-handed. The western boundary currents, such as the Gulf Stream and the Japan Current, are the swiftest, again due to the rotation of the earth. An exception is in the South Pacific, where the Peru Current on the east boundary is the strongest, presumably due to the pileup of water in the Drake Passage between Antarctica and South America in the West Wind Drift.

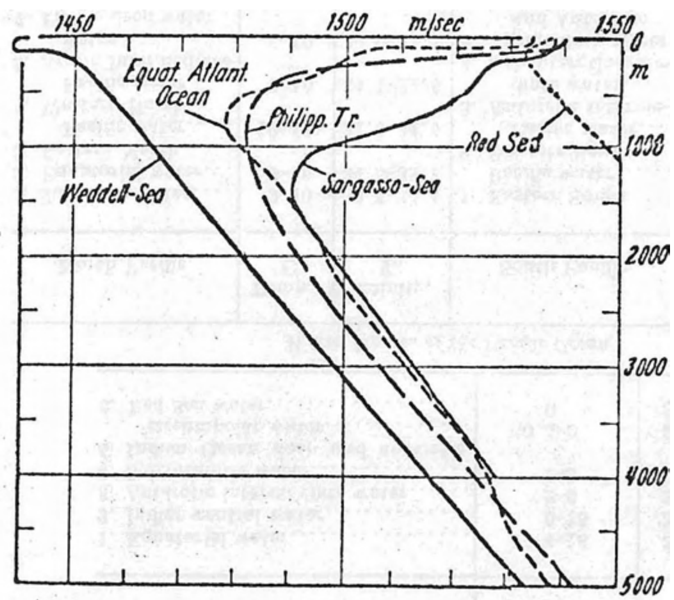


Fig. 20-5—Examples of horizontal velocity of sound in the world ocean (Dietrich[7]).

Deep—The deep circulation of the oceans is monitored by tracing water masses, which are relatively homogeneous packets of water which move essentially along density surfaces horizontally from their place of formation. Table 20-2 lists some of the major water masses. The geographic prefix usually refers to the site of formation. Most of the deep-water characteristics of the oceans are produced in the winter in high latitudes where cold temperatures and freezing ice tend to mnke the water cold and more saline, thus more dense. This denser water flows toward the equator under less dense surface water, driving the oceanic circulation, and imparts a polar character to the deep and bottom waters of the world ocean.

Kinetics—The driving force for the movement of seawater apparently is the effect of solar insulation on seawater on the rotating earth. Nenr shore, there is the additionnl tidal effect of the sun-moon system. According to Ekman,[10] there are three major hydraulic regimes in the ocenns: (1) a surface region where wind-driven frictional forces predominate, (2) nn intermediate zone where rotational forces predominnte and (3) a lower region nenr the bottom where frictional drag forces predominate. Nenr shore, the upper and lower zones merge. In the deep

Fig. 20-6—Tho surface **currents** of the **oceans.** The pattern of **gyres** (clockwise in the **Northern Hemisphere and** counterclockwise in the Southern) can be explained as a result of global wind pntterns—the **prevailing** westerlies blowing from west to east at **about 40°N and 40°S** and the trnde winds blowing **from east** to west just north and south of the Equator (from "Tho Circulation of the Oceans," **Walter Munk**[12]). Copyright 1955 by *Scientific* American, *Inc.* All rights reserved.

TABLE 20-2—Water Masses of tho Ocean (Defant[9])

North Atlantic	Temp., °C	Salinity.	South Atlantic	Temp., °C	Salinity,
1. North Polar water........	−1 to +2	34.0	1. Central water..	+5 to +16	34.3–35.6
2. Subarctic water,.	+3 to $5	34.7–34.9	2. Antarctic intermediate water	+3 to +5	34.1–34.6
3. Central water....	+4 to +17	35.1–36.2	3. Subantarctic water..	+3 to +9	33.8–34.5
4. Deep water..	+3 to $4	34.9–35.0	4. Antarctic circum-polar water.......	+0.5 to +2.5	34.7–34.8
5. Bottom water....	+1 to +3	34.8–34.9	6. Deep and bottomwater...	0 to +2	34.5–34.9
6. Mediterranean water..	+6 to +10	35.3–36.4	6. Antarctic bottom water.. .	− 0.4	34.66

Water Masses of the Indian Ocean

	Temp., °C	Salinity, ‰
1. Equatorial water..	4–16	34.8–35.2
2. Indian central water..	6–15	34.E–35.4
3. Antarctic intermediate water..	2–6	34.4–34.7
4. Subantarctic water..	2–8	34.1–34.6
6. Indian Ocean deep and antarctic circumpolar water..	0.5–2	34.7–34.75
6. Red Sea water..................	9	35.5

Water Masses of the Pacific Ocean

North Pacific	Temp., °C	Snlinity, ‰	South Pacific	Temp., °C	Salinity, ‰
1. Subarctic water.. ..	2–10	33.5–34.4	1. Eastern South Pacific water..	9–16	34.3–35.1
2. Equatorial water.. .	6–16	34.5–35.2	2. Western South Pacific water.. ..	7–16	34.5–35.5
3. Eastern North Pacific water.. ...	10–16	34.0–34.6	3. Antarctic intermediate water.	4–7	34.3–34.5
4. Western North Pacific wnter.	7–16	34.1–34.6	4. Subantarctic water	3–7	34.1–34.6
6. Arctic Intermediate water..........	6–10	34.0–34.1	5. Pacific deep water and Antarctic circumpolar water..	(−1)–3	34.6–34.7
6. Pacific deep wnter and Arctic circumpolar water..	(−1)–3	34.6–34.7			

ocean, however, the nonfriction **or geostrophic** (earth-turned) forces **determine the** water **movement.**

Frictionless Flow

Geostrophic Equation—

$$c = \frac{a}{f}\frac{\partial P}{\partial N}$$

where c = **geostrophic** velocity (oriented perpendicular to the direction of N—from high **pressure** to low pressure—and (a) to the right of N in the Northern Hemisphere (b) to the lelt of N in the Southern Hemisphere): a = specific volume = 1 per density; f = geostrophic parameter = $2\omega \sin\phi$; ω = rotation earth; ϕ = geographic latitude; $\frac{\partial P}{\partial N}$ = pressure **gradient.**

Gradient Equation—For sloping isobaric surfaces,

$$c = \frac{g \tan\theta \max}{f}$$

where $\tan\theta$ = slope of isobars.

Margules Equation—Where a lighter water mass **overrides** a dcnscr,

$$\tan\gamma = \frac{f}{g}\frac{(\rho c - \rho' c')}{(\rho' - \rho)}$$

where γ = slope of interface between two water masses, ρ = density of lighter water, c = geostrophic vclocity in lighter wnter, ρ' = density of **heavicr** wnter, c' = geostrophic vclocity in heavier water.

Helland-Hansen Equation—To determine **relative** velocities between two stations, knowing temperature and salinity **profiles** at **each** station:

$$c_1 - c_0 = \frac{1}{fAB}\int_{P_1}^{P_0}(\alpha_B - \alpha_A)\,dP$$

mhere c_1 = geostrophic velocity at'givon depth, c_0 = geostrophio velocity at reference depth, AB = distance **betwecn** stations, P_1 = pressure **at** given depth, P_0 = pressure **at reference depth,** α_B = specific volume Station B, α_A = specific volume Station A

See **Formin**[11] for details.

Friction Flow

Wind-Generated Currents—At the sea surfnce empirically **(Dietrich[7])**

$$V_0 = \frac{\lambda W}{(\sin\phi)^{1/2}}$$

mhere V_0 = surface **current velocity,** W = wind velocity, λ = constant = 0.0126 if W in cm per **sec,** ϕ = geographic Intitude.

Munk[12] believes that 700 cm per **sec** is **the** threshold velocity to initiate **wind-drift** currents.

The decay of wind-generated currents **with** depth is given by **Ekman**[10] as

$$V = V_0 e^{\frac{-\pi z}{D}}, \quad D = \pi\frac{\sqrt{A_z}}{\rho\omega \sin\phi}$$

where V = velocity **at** some depth z, V_0 = surface current velocity, A_z = **eddy** viscosity, ρ = density.

If $z = D$, Velocity V is directed 180° from the surface velocity, V_0, so, for **practical** purposes, wind frictional effects cease. The depth **where** $z = D$ is **called** the depth of **frictional** resistance. **Beneath** this zone **the** Row **should** be geostrophic.

Waves—As $L = cT$, **where** L = **wave** length, c = **phase** vclocity nnd T = wave period. Assuming linear theory, the rclntionships among mave vclocity, wave period, mave length and water depth are given by

$$c = \frac{gT}{2\pi}\tanh\frac{2\pi d}{L} = \left(\frac{gL}{2\pi}\tanh\frac{2\pi d}{L}\right)^{1/2}$$

where d = water depth.

For deep water, $d/L > 1/2$, practically,

$$c = \frac{gT}{2\pi} = \left(\frac{gL}{2\pi}\right)^{1/2}$$

For shallow water, $d/L < 1/25$, practicnlly, $c = (gd)^{1/2}$ **(Wiegel[11]).**

Tides—The interaction of **the** gravitational fields of **the** enrth, moon and sun **produce the** periodic **rise** and **fall** of **the** oceans called the tides. The **average interval** between **two** high or two low tides is 12:25 hr, or one-half a lunar **passage. Diurnal** and semidiurnnl deviations from the **lunar** time nre caused by the sun's **field.** Nenr new and full moon, **the** moon-sun fields reinforce each other to produce **maximum** high and low water, called spring tides. Near the first and third quarter

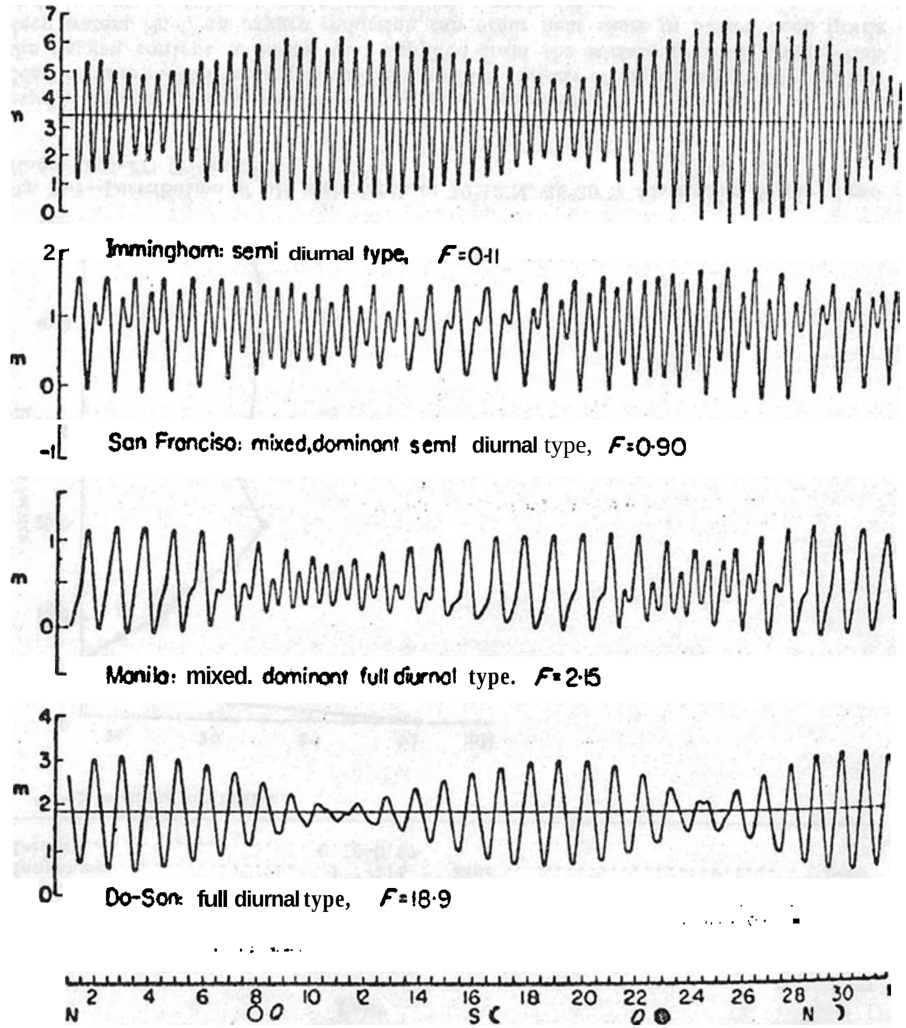


Fig. 20-7—Tide curves for March 1930 phases of the moon. N and **S** are the largest northern and southern declination of the moon; Q, passage of the **moon** through **the** Equntor **(Defant[9]).**

moon, the fields are in opposition, producing a minimum tidnl **range, called** nenp tides. Modifications of the **ideal tidal** cycles **are** caused by the configuration of **the** sea bottom nnd **the** constlinc, nnd thus are pnrticulnr to the locale. Fig. 20-7 **shows** some representntive tides.

Where geographical frictional effects on tlre tidal **cycle are large,** for **example, in** eomplcx estuaries, a pnrticulnr tide is not repented for 18.6 yr, **when the sun-moon**

return to a given porition. **Thus, 19 years** of record nre **necessary** to **completely** describe tidnl fluctuntions.

20.1.2 — MARINE CHEMISTRY

PAT WILDE

Composition

Major Ions-Seawater is not simply evapornted river water, as the ions in each are in different proportions. Unlike river water, which may have n variable dissolved ionic content, seawater has the property thnt the major dissolved ions are in relatively constant proportion to each other (Dittmar[14]). By determining the concentrntion of one ion the others may be computed. Tnble 203 gives the

TABLE 20-3—Ion-Chlorinity Relationships of the Major Ions In Sea-water (Cl, B. F: Sverdrup and others;[16] Na, K, Mg, Ca, Sr, Culkin and Cox;[17] Br, SO_4, Morris and Riley[18])

Ion Concentration, *G* per kg	
Cl^- = 0.9989 Cl(ppt)	Sr^{++} = 0.0004 CL
Na^+ = 0.5555 CL	Br^- = 0.003473 CL
K^+ = 0.0206 CL	B^- = 0.00023 CL
Mg^{++} = 0.06692 CL	F^- = 0.00007 CL
Ca^{++} = 0.02126 CL	$SO_4^{=}$ = 0.1400 CL

TABLE 20-4—A Recipe for Artificial Seawater (Lyman and Fleming[15])

	G		G
NaCl	23.477	$NaHCO_3$	0.192
$MgCl_2$	4.981	KBr	0.096
Na_2SO_4	3.917	H_3BO_3	0.026
$CaCl_2$	1.102	$SrCl_2$	0.024
KCl	0.664	NaF	0.003

H_2O to 1,000 g; allow for water of hydration to produce water of CL = 19 ppt.

senwnter relationships in terms of chlorinity, the most commonly determined parameter. The concentrntions of 60 elements in seawater is given in Sec. 20.1.4 (Tnble 20-17).

Tnble 20-4 shows a recipe for artificial seawater (Lyman and Fleming[u]).

Trace Ions—Trace metals do not show the constancy of proportion of the major ions (Tnble 20-5) but vary midcly in concentration.

Other Parameters

pH—pH, or $-\log[H^+]$, of seawater usually is mensured with glass electrodes. Surface values average about 8.1 with a minimum value of nbout 7.6, corresponding to the depth of the oxygen minimum (Fig. 20-8). Thus, the seawater is slightly alkaline throughout the entire verticnl column.

Alkalinity—Seawater is a good pH buffer. Therefore, it usually is titrnted with a strong ncid, HCl, to determine excess base. The various parameters measured nre:

1. Titration nlknlinity $\equiv [HCO_3^-] + 2[CO_3^=] + [H_2BO_3^-] + [OH^-] - [H^+]$
2. Carbonate nlkalinity $\equiv [HCO_3^-] + 2[CO_3^=]$
3. Specific alkalinity $\equiv \dfrac{\text{titrntion nlknlinity}}{\text{chlorinity}}$

Dissolved Gases—Table 20-6 gives tho saturation values of the major dissolved gases in seawater with varying temperature and salinity.

Oxygen—Oxygen is introduced into senwntcr by surface mixing with the nt-mosphere and by photosynthetic plants. Oxygen distribution in the oceans (Fig. 20-9) is monitored by biological nctivity nncl the presence of oxidizable organic matter. Thus, the oxygen content is not completely a function of solubility. The

TABLE 205—Concentration of Trace Metals In Seawater

	Concen-tration in Senwater, Ppb*		Concen-tration in Seawater, Ppb*
Chromium	0.13–0.25	Molybdenum	4–12
Cobalt	0.1–0.04	Nickel	0.75–2
Copper	0.7–27	Silver	0.145
Gold	0.016–0.4	Tungsten	0.12
Manganese	1.7–114	Zinc	1–20
Mercury	0.15–0.27		

* Ppb = parts per billion.

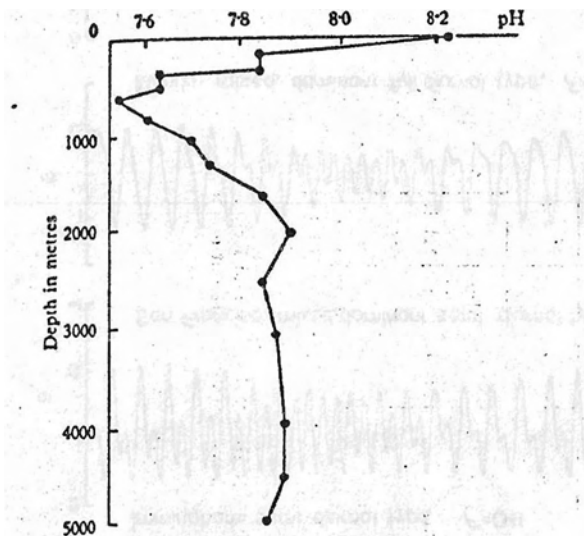


Fig. 20-0—Distribution of pH with depth at 10°12′N, 26°36′W (data from Meteor *Expedition, 1925–27*) (Pickard[4]).

oxygen profile usually shows a well-defined minimum at about 1,000 m where dead orgnnic matter raining down from surface regions of high productivity reduces the oxygen content to below thnt supplied from the surface or from oxygen-rich deep waters. Such an oxygen reduction can occur near shore in barred deep fjords and other areas of poor circulation with high organic debris.

Nitrogen—Apparently, nitrogen is affected little by biologicnl activity. Therefore, its concentrntion in senwnter is n direct function of solubility (Table 20-6).

Carbon *Dioxide*—Carbon dioxide is supplied to seawater by plants plus respiring animals, in nddition to the ntmosphere. The solubility of CO_2 varies gently, par-

TABLE 20-6—Coefficients of Saturation of Atmospheric Gases (C.) in Water (Concentrations of Oxygen,[a] Nitrogen[b] and Carbon Dioxide[c] as Ml per L and Mg-Atoms per L in Equilibrium With 760 Torr = 1 Atmosphere of Designated Gas) (Sverdrup and others[16])

Temperature	0°						12°						24°					
	O_2		N_2		CO_2		O_2		N_2		CO_2		O_2				CO_2	
Chlorinity, ‰	Ml/L	Mg-Atoms O/L	Ml/L	Mg-Atoms N/L	Ml/L	Mg-Atoms C/L	Ml/L	Mg-Atoms O/L	Ml/L	Mg-Atoms N/L	Ml/L	Mg-Atoms C/L	Ml/L	Mg-Atoms O/L	Ml/L	Atoms N/L	Ml/L	Mg-Atoms C/L
0............	49.24	4.40	23.00	2 06	1715	77.0	36.75	3.28	17.80	1.59	1118	50.2	29.38	2.62	14.63	1.31	782	35.1
16............	40.1	3.60	15.02	1.73	1489	66.8	30.6	2.75	11.56	1.33	980	44.0	24.8	2.22	9.36	1.08	695	31.2
20............	38.0	3.40	14.21	1.64	1438	64.5	29.1	2.61	10.99	1.26	947	42.5	23.6	2.12	8.96	1.03	677	30.4

[a] Fox (1909).
[b] Distilled water, Fox (1909); seawater, Rakestraw and Emmel (1938b).
[c] Buch et al (1932). after Bohr. Concentrations represent amounts of free CO_2 and H_2CO_3.

Mg-Atom N/L
1.31
1.08
1.03

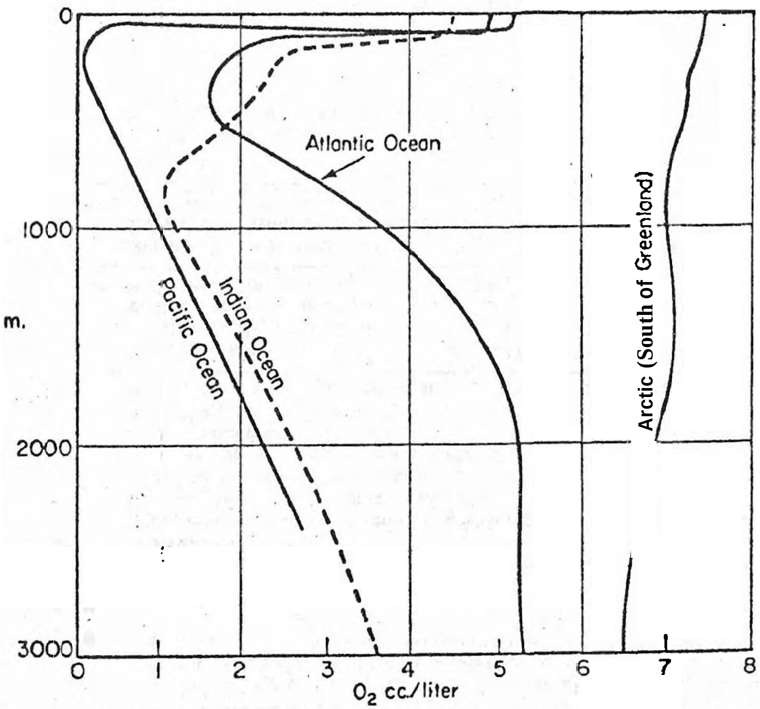


Fig. 20-9—Vertical distribution of oxygen in the Pacific, India nan d Atlantic oceans, well as in the area of formation of Atlantic Deep Water sout hof Greenland: positions, 12°N, 137°W, 80°E, 9°S, 5.5°W, 5.5°N, 45°W (after H. Watten brg, 1943) (Dietrich[7])

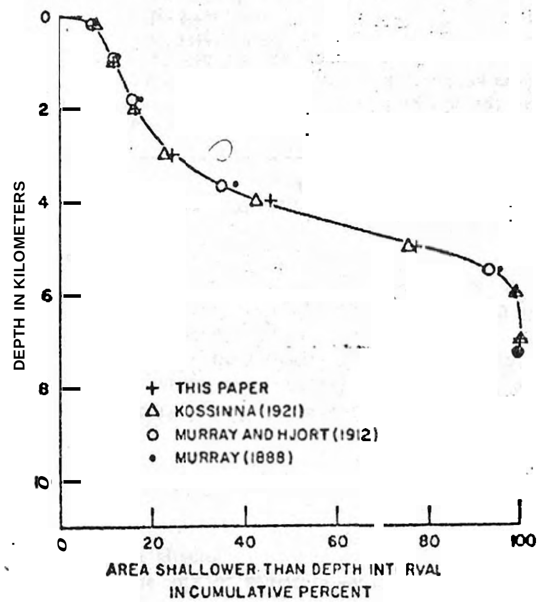


Fig. 20-10—Hypsometry of all ocean basins ac ordi g t various studies (Men rd a d Smith[16]).

	Depth, M	Relief	Seismicity	Sediment/Rock Type
Continental shelf	0–200	Flat	—	Continental sands, gravels, muds, bed-rock continental sediments
Continental slope	200–3,000	5° slope	—	—
Continental margin or rise	2,500–4,000	Smooth slope up to 1°	—	Continental-derived muds, small percentage of sands lenses
Abyssal plains	Deeper than 3,000	Flat, generally featureless	—	Deep-sea oozes and clays
Abyssal hills	Deeper than 3,000	Rolling topography; generally less than 100 fathoms relief; features lobate oriented	—	Deep-sea oozes and clays
Ridge-rise system	—	Ridge, rugged; rise, smooth	High shallow focus	Bedrock basaltic
Fracture zones	—	Rugged-elongate orientation of ridges and troughs	Generally aseismic	Bedrock basaltic
Trenches	Deeper than 6,000	—	High intermediate to deep focus	Bedrock basaltic; some areas ultra mafic
Sea-mount provinces	Various	Submarine volcanoes, generally individual conical; some with flatter tops called guyots	Aseismic except if active	Bedrock basaltic

ticularly inversely with temperature (Table **20-6). CO_2** dissociates rendily by tho following **reactions:**

$$H_2O + CO_2 \rightleftarrows H_2CO_3$$
$$H_2CO_3 \rightleftarrows H^+ + HCO_3^-$$
$$HCO_3^- \rightleftarrows H^+ + CO_3^-$$

At the pH of seawater—about 8—the bicarbonate ion, HCO_3^-, is the dominnte dissolved specie.

26.1.3—MARINEGEOLOGY

PAT WILDE

Physiography of the Sea Floor—Fig. 20-10 shows the frequency distribution of oceanic depth **with** respect to area. Thd **shape** of the curve outlines the gross physiographic provinces: (1) the continentnl **shelf,** from 0 to 200 m; (2) the continental **slope,** from 200 to 3,500 m; (3) the deep sen, from 3,500 to 6,000 m (**mcnn depth** of the occnn, nbout 4,000 m); (4) trenches, from 6,000 to about 10,000 m. A more complete description of the physiographic provinces is given in Table **20-7.**

TABLE **20-8—Classification of** Deep-Sea Sediments (Classification Modified From **Revelle**[19]) (Submarine Deposits by **Wilde)**

Pelagic Depoaita: Sediments that were at one time within **200** m of the ocean surface and arrived at the bottom by settling through the ocenn

A. Oozcs—skeletal remains of organisms greater than **30%:**
  1. Calcium-carbonate ooze:
    a. Globigerina
    b. Ptcropod
    c. Coccolith remains
    d. Mixed **with** clay, **hydroxides,** volcanic glass, detrital quartz and feldspar
  2. Siliceous ooze:
    a. **Radiolarian**
    b. Diatom remains
    c. Mixed with clny, hydroxides, volcanic glass, detrital quartz **and** feldspar

B. Red **clay—skeletal** remnins less than **30%** quartz, feldspar, mica, clny **minerals** mixed with meteoritic **spherules,** manganese nodules, shark's teeth and vertebrate hard parts

Terrigenous Deposits: Sediments derived from the lnnd and **carried** to the site of deposition by bottom currents

A. Organic muds—skeletal remains greater **than 30%,** clay in apprecinble amounts
  1. **Calcium** carbonate, mud and **sand:**
    a. Carbonate shells and clay
    b. Mixed with volcanic nnd detrital particles
  2. Siliceous mud and sand:
    a. Siliceous shells **and** clny
    b. 'Mixed with glauconite, detritnl **and** volcnnic particles.

B. Inorgnnic muds—skelctnl remains less **than 30%**
  1. Clay muds: detritnl pnrticles
  2. Silty or sandy muds: detritnl pnrticles
  3. Volcanic muds **and** sunds: volcnnic particles

Submarine deposits: Sediments that never were exposed to the atmosphere

A. Dctritul—erosion products from submarine erosion or from submarine volcnnic eruptions mixed with pelngic deposits

B. Chemical—authigenic formation on **the** sen floor:
  1. Authigenic clays
  2. Mangnnese nodules
  3. Phosphate nodules, mixed with pelngic **and terrigenous** deposits

Marlne Rock Types

Sediments

Classification—A classification of deep-sea sediments is given in Table 20-8. Shelf dcposits, because of their obvious affinities with the continents, usually are not given a unique mnrine classification. Table 20-9 gives the areal extent of the commonest marine sediments.

Mineralogy—The minernls in each sediment class nrc further identified by their origin (Table 20-10).

Sediment Distribution—Fig. 20-11 shows the major environmental factors of the oceans.

Terrigenous *Deposits*—Terrigenous deposits are found adjacent to land areas, pnrticularly where there are high volumes of sediments carried to the sea. Most terrigenous material is deposited on the shallow shelf. In many areas, such as off central California, the Eastern Seaboard of the United States and in the Bay

TABLE 20-%Area Covered by Marine Sedlments (Kuenen[20])

Type of Deposits	Aren. Millions Sq Km	% of Sea Floor
Shelf	3 0	8
Terrigenous	63	18
Pelagic	268	74
Globigerina ooze	126	35
Pteropod ooze	2	1
Diatom ooze	31	9
Radiolnrian ooze	7	2
Red clay	102	28

TABLE 20-10—Genetic Classification of Marine Minerals

1. Authigenic: minerals formed directly in the seawater
2. Pyroclastic: detritus from volcanic eruptions
3. Biotic: hnrd pnrts formed by an organism in its life process
4. Terrigenous: erosion products from the continents
5. Dingenetic: minerals altered from their state ns a response to mnrine environment
6. Extrsterrestrinl: material from outer space

of Bengal, large volumes of sediments nre carried to the deep sea via submarine cnnvons nnd deposited in large submnrine fnns nnd nprons.

Pelagic *Deposits*—Pelagic dcposits are almost exclusively deep-sea in areas of little terrigenous contribution. Organic deposits or oozes are found as a function of organic productivity in the surface water, the rate of solution of the orgnnic hard part, nnd the depth of water. Oozes mill form in regions where the rate of production exceeds the rate of solution in the water column. Carbonate oozes, which nre relatively soluble, are found in shallow to intcrmediaie depths.

Siliceous *Oozes*—Siliceous oozes, which nre relatively insoluble, occur where either (1) siliceous organisms have a higher productivity than carbonate organisms, or. (2) silica hnrd pnrts are prescrvcd at the expense, of carbonate hard parts due to diffcrentinl solutions in the water column.

Inorganic Clays—Inorganic pelagic dcposits, such ns red clays, are found in regions of (1) low organic productivity or (2) deep water where surfnce-produced orgnnic matter has dissolved before sinking to the bottom.

Chemical Deposits—Chemical dcposits are limited to arens (1) of very low rates of pelagic or terrigenous deposition or (2) where chemical precipitation is

enhanced by localized supersaturntion or changes in the oxidntion-reduction potential near the sediment-seawater intcrfoce.

Ferromanganese *Oxide* Deposits—Fcrromangnncsc oxides are found in two distinct forms: (1) nodules and (2) crusts. Nodules occur as bottom surfncc features in

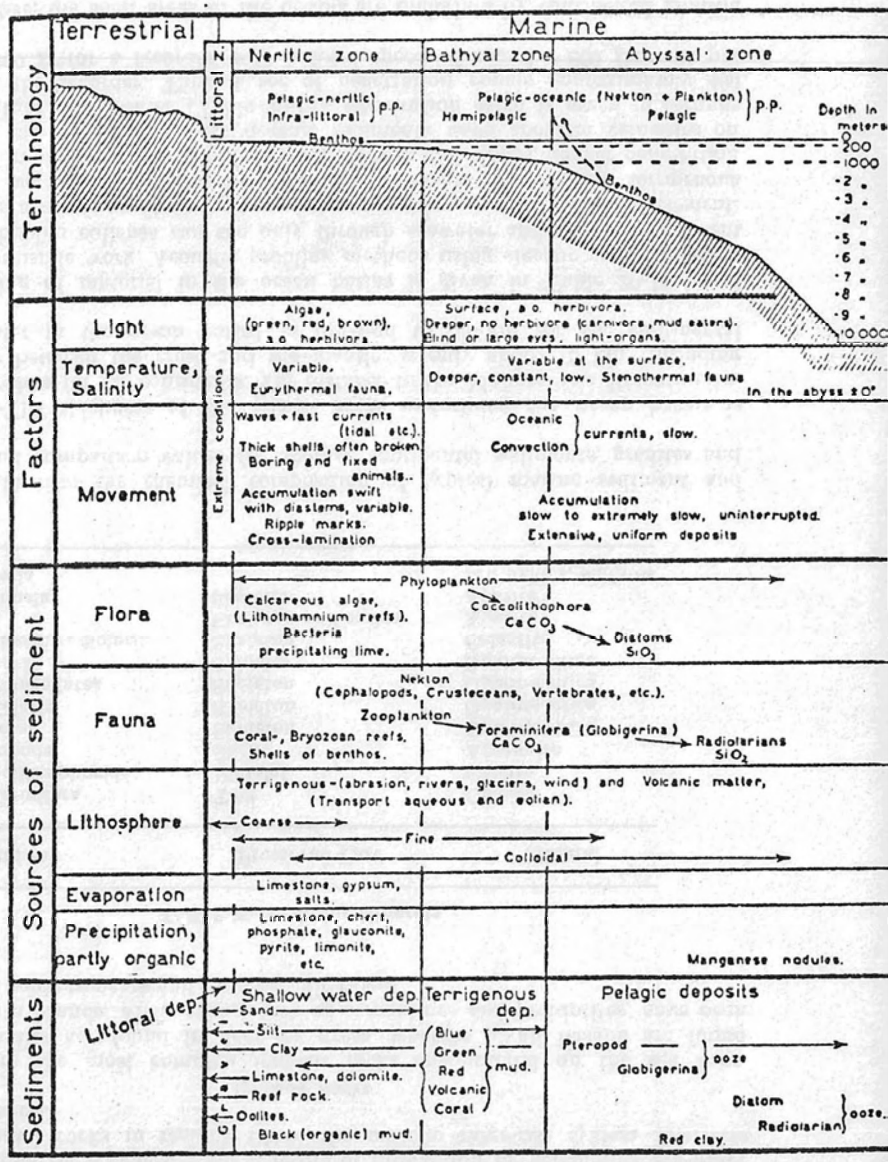


Fig. 20-11—The marine environment (Kuenen[20]).

deep water often associnted with red clay. One means for their fornation and growth may be the migration of iron and mangnncsc ions in solution from the reducing layer within the sediments to the surface oxidized lnyer where the metallic ions precipitate much like desert varnish. Crusts up to several centimeters thick

TABLE 20-11—Principal Minerals of the Deep Sea

Authigenic	Pyroclastic	Biotic*	Terrigenous	Diagenetic	Extra-Terrestrial
Phillipsite-hormotone	Pyroxene	Aragonite	Kaolinite	Phillipsite-hormotone	Nickel-iron spherules
1 Md mica	Plagioclase	Calcite	Biotite	Montmorillonoid	Olivine-pyroxene-chondrules
Opaline silica	Labradorite-oligoclase	Opaline silica	Chlorite	Nontronite	
Francolite	Orthoclase	Celestite	High Ab feldspars	1 M mica	
Celesto-barite	Microcline		Quartz	Orthoclase	
Gypsum	Sanidine			Dolomite	
Anhydrite	Volcanic glass			Maghemite	
Sphalerite				Mixed layer clays	
Goethite				Palagonite	
Fe oxides					
Magnetic Fe oxides					
δ MnO_2					
Manganites					

form ... outcrops on the tops and flanks of sea mounts where iron and mnnganese has apparently been released by underwater weathering of iron- nnd manganese-rich bnsnlts.

Phosphorite Deposits—Phosphorite deposits occur as (1) nodules nnd crust by replacement of calcite by apatite in offshore carbonate banks in the presence of phosphorous-rich upwelling water or (2) phosphatic muds—again in regions of upwelling of deep phosphorous rich water.

Metalliferous Muds—Iron oxide, Fe_2O_3, geothite with sphnlerite, ZnS with other trnce metals associated with the hot salty brines occur in certain closed basins in the Red Sea. The origin of such deposits still is uncertain. The high metallic content suggests these deposits are a result of interaction of percolating sen-water with continental rocks in regions where the oceanic ridge-rise system intersects continental crust.

Igneous Rocks

Basalts are the most common igneous rocks encountered on the sen floor. Tholeiitic basnlts are found in deep-sen nreas, whereas alkali basalts are found nssociated with islands. Mnfic rocks, such ns scrpcntines and peridotites, have been dredged from some trenches and from oceanic ridges.

TABLE 20-12—Biotic Minerals

Organism	Preserved Part	Mineral
Foraminifera	Test	Calcite
Coccolithophorids	Platelet	Calcite
Pteropods	Shell	Aragonite
Diatoms	Skeleton	Opaline silica
Radiolaria	Skeleton	Opaline silicn
Silicoflagellates	Skeleton	Opaline silica
Sponges	Spicules	Opaline silica
Acatharid radiolaria	Skeleton	Celectite
Fish	Skeleton and scales	Apatite
Mammals	Skeleton	Apatite
Bncteria	—	Mn oxides, sulfates

Table 20-13 lists the chemical composition of typical marine sediment and rock types and comparison values for average continentnl sediments, granites and basalts.

Structure—The thickness of the crustal rocks underlying the ocean basins is much thinner than for the continents. The distance to the Mohorovicic discontinuitv. the boundary between the crust and the mantle, is only about 10 km (including 5 km of wnter in the ocean bnsin) as opposed to 35 km for the continentnl areas).

The layering of material in the ocean bnsins is given in Table 20-14 bnsed on explosion seismic work. Acoustic profiling methods using electric arcs, exploding wires or nir bubble collapse can see only through seawnter nnd the first sediment layer. Thus, in ncoustic profiling the top of the second layer is the neoustic basement. Reflectors in the first layer cnn be volcanic ash layers or turbidite terrigenous sandy lnyers. In shnllow water on continentnl shelves nnd slopes, deeper penetrntion than 0.5 km cnn be obtnined. As oceanic sediments hnve acoustic velocities on the order of that of senwnter (Table 20-14), penetrntion often is given in seconds as shown on the recorder. Thus, 1 sec of pcnctration equnls npproximntely 400 fathoms = 2,400 ft for a recorder with a fixed speed of sound = 800 fathoms per sec.

To generalize, the shelf nrens of the oceans nre underlain by continental granitic basement rocks while the deep ocean is underlnin by true oceanic basaltic rocks.

TABLE 20-13—Chemical Composition of Typical Marine Sediment and Rock Types

	I Avg. Sed.	II Red Clay	III Calc. Ooze	IV Silic. Ooze	V Avg. Mn Nodule	VI Avg. Granite	VII Avg. Basalt	VIII Oceanic Tholeiities	IX Oceanic Alkali Basalt	X Oceanic Peridotites	XI Red Sea Geothite	XII Red Sea Sulfide
SiO_2	57.95	53.93	24.23	67.36	19.2	71.6	49.1	49.94	48.16	43.87	8.7	24.7
Al_2O_3	13.39	17.46	6.60	11.33	3.8	14.5	15.7	17.25	18.31	3.14	1.1	1.5
Fe_2O_3	3.47	8.53	2.43	3.40	24.3	1.5	5.4	2.01	4.24	5.33	64.2	24.3
FeO	2.08	0.45	0.64	1.42		1.1	6.4	6.90	5.89	2.58	2.7	13.4
MgO	2.65	4.35	1.07	1.72		0.9	6.2	7.28	4.87	40.45		
CaO	5.89	1.34	0.20	0.89		2.0	9.0	11.86	8.79	4.30	3.4	2.5
Na_2O	1.13	1.27	0.75	1.64		3.0	3.1	2.76	4.05	0.23		
K_2O	2.66	3.65	1.40	2.15		4.1	1.5	0.16	1.69	<0.02		
H_2O	3.23	6.30	3.31	6.33	13.0	0.8	1.6					
CO_2	5.38											
$CaCO_3$		0.39	56.73	1.52	4.1							
$MgCO_3$		0.44	1.78	1.21	2.7							
TiO_2	0.57	0.96	0.25	0.59				1.61	2.91	0.01	ZnO 0.7	12.2
MnO		0.78	0.31	0.19	31.7			0.17	0.16	0.07	Mn_3O_4 1.1	1.1
P_2O_5	0.13	0.09	0.10	0.10				0.16	0.93		CuO 0.3	4.5

I. Pettijohn,[21] p. 106.
II. El Wakeel and Riley.[22]
III. El Wakeel and Riley.[22]
IV. El Wakeel and Riley.[22]
V. Mero,[23] p. 179.
VI. Pirsson and Knopf,[24] p. 169.
VII. Pirsson and Knopf,[24] p. 209.
VIII. Engle and others,[25] p. 723.
IX. Engle and others,[25] p. 723.
X. Engle and Fisher.[26] p. 1138.
XI. Bishoff,[27] p. 384.
XII. Bishoff,[27] p. 384.

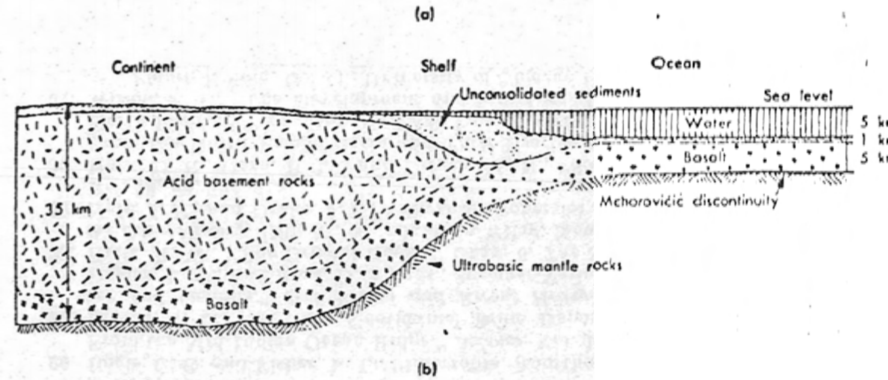


Fig. 20-12—Generalized section across a stable continental margin (reprinted from *The Earth as a Planet*, 1954, Kuiper, G. P., ed., by permission of the University of Chicago Press) (Wilson[22]).

TABLE 20-14—Average Layering of Oceanic Crust (Modified from Raitt[28])

Layer	Thickness, Km	Velocity, Km per Sec	Material
Ocean	4	1.5	Seawater
1	0.45	1.5–2	Sediment
2	1.11 ± 0.75	5.07 ± 0.63	Lithified sediment or transitional or weathered basalt
3	4.86 ± 1.42	6.69 ± 0.26	Basalt
4		8.13 ± 0.24	Upper mantle ultra mafics

TABLE 20-15—Compressional Wave Velocities for Oceanic Materials (Nafe and Drake,[29] p. 800–801; Horn and others,[30] p. 10)

Sediment or Rock	Compressional Wave Velocity, Km per Sec	Density, G per Cu Cm
Red clay	1.51	1.52
Silty mud	1.49	1.89
Carbonate ooze	1.62	1.59
Terrigenous mud	1.52	2.22
Volcanic ash	1.63	
Basalt	6.70	3.30

Except near the continents, where continental erosional detritus is plentiful, the sediment cover over the basement rocks may be less than a kilometer thick, or may be essentially nonexistent.

Current theories of sea floor spreading and plate tectonics (Wilson[31,32]) are providing interesting but still controversial explanations of many geological anomalies observed in the oceans and attempt to account for many of the geomorphologic

TABLE 20-16—Classification of Marine Mineral Resources

Marine Mineral Deposits				
	Unconsolidated			
Dissolved	Continental Shelf, 0–200 M	Continental Slope, 200–3,500 M	Deep Sea, 3,500–6,000 M	Consolidated
Seawater: Fresh water Metals and salts of: Magnesium Sodium Calcium Bromine Potassium Sulphur Strontium Boron Uranium Other elements *Metalliferous Brines:* Concentrations of: Zinc Copper Lead Silver	*Nonmetallics:* Sand and gravel Lime sands and shells Silica sand Semiprecious stones Industrial sands Phosphorite Aragonite Glauconite *Heavy Minerals:* Magnetite Ilmenite Rutile Monazite Chromite Zircon Cassiterite *Rare & Precious Minerals:* Diamonds Platinum Gold Native copper	*Authigenics:* Phosphorite Ferromanganese oxides and assoc. minerals Metalliferous mud with: Zinc Copper Lead Silver	*Authigenics:* Ferromanganese nodules and assoc. Cobalt Nickel Copper *Sediments:* Red clays Calcareous ooze Siliceous ooze	*Disseminated, massive, vein, tabular, or stratified deposits of:* Coal Ironstone Limestone Sulfur Tin Gold Metallic sulfides Metallic salts Hydrocarbons

features of the sea floor. The geologically nctive oceanic ridges and plnte boundaries appear to play a significant pnrt in tho formation of some potentially economic marine mineral deposits.

REFERENCES:

1. Matthews, D. J., "Tables of the Velocity of Sound in Pure Water and Sea Water for Use in Echo-Sounding and Sound Ranging," Pub. 282. 1939, Admirnlty Hydrographic Office.
2. Menard, H. W., and Smith, S. M., "Hypsometry of Ocean Basin Provinces," *Journal of Geophysical Research*, Vol. 71, 1966, pp. 4305–4325.
3. Harvey, H. W., *The Chemistry and Fertility of Sea Waters*, Cambridge University Press, 1966.
4. Cox, R. A., *International Oceanographic Tables*, Unesco, New York, 1966.
5. Pickard, G. L., *Descriptive Physical Oceanography*, Pergamon Press, New York. 1963.
6. Knudsen, M., *Hydrographic Tables*, G. E. C. Gad, Copenhagen, Denmark, 1901.
7. Dietrich, G., *General Oceanography*, John Wiley, New York, 1963.
8. Munk, W., "A Critical Wind Speed for Air-Sea Boundary Processes," *Journal of Marine Research*, Vol. 6, 1947, pp. 203-218.
9. Defant, A., *Physical Oceanography*, Pergamon Press, New York. 1961.
10. Ekmnn, V. W., "On the Influence of the Earth's Rotation on Ocean Currents," *K. Svenska Vetenskapad*, Vol. 2, No. 11, 1905.
11. Formin, L. M., *The Dynamic Method in Oceanography*, Elsevier, Amsterdam, *1964*.
12. Munk, W., "The Circulation of the Oceans," *Scientific American*, Vol. 193, No. 3, 1955, pp. 96–104.
13. Weigel, R. L., *Oceanographical Engineering*, Prentice-Hall, Englewood Cliffs, N.J., 1964.
14. Dittmar, W., "Report of Researches Into the Composition of Ocean Wnter Collected by H.M.S. Challenger During the Years 1873–1876," *Physics and Chemistry*, 1884, pp. 1–251.
16. Lyman, J., and Fleming, R. H., "Composition of Sea Water," *Journal of Marine Research*, Vol. 3, *1040*, pp. 134-146.
16. Sverdrup, H. V., Johnson, M. W., nnd Fleming, 11. H., *The Oceans*, Prentice-Hall, Englewood Cliffs, N.J., 1942.
17. Culkin, F. C., nnd Cox, R. A., "Sodium, Potassium, Magnesium, Calcium and Strontium in Sen Water," *Deep-Sea Research*, Vol. 13, 1966, pp. 789-804.
18. Morris. A. W., and Riley, J. P., "The Bromide-Chlorinity and Sulphate/Chlorinity Ratio in Sen Water," *Deep-Sea Research*, Vol. 13, 1966, pp. 699–705.
19. Revelle, R., "Marine Bottom Samples Collected in the Pacific Ocean by the *Carnegie* on Its Seventh Cruise," Pub. 556, 1944, Cnrnegie Institute, Washington, D.C.
20. Kuenen, H., *Marine Geology*, John Wiley, New York. Chapman & Hall, London, 1950.
21. Pettijohn, F. J., *Sedimentary Rocks*, Harpers, New York, 1957.
22. El Wakeel, S. K., and Riley. J. P., "Chemical and Mineralogical Studies of Deep-Sea Sediments," *Geochim. Cosmochim. Acta, Vol.* 25, 1961, pp. 110-146.
23. Mero, J. L., *The Mineral Resources of the Sea*, Elsevier, New York, 1965.
24. Pirsson, L. V., and Knopf, A., *Rocks and Minerals*, John Wiley, New York, 1947.
25. Engle, A. E., Engle, C. G., and Havens, R. G., "Chemical Characteristics of Ocennic Basalts and the Upper Mantle," Bulletin Geologicnl Society of America, Vol. 76, 1965, pp. 719-734.
26. Engle, C. G. nnd Fisher, R. L., "Lherzolite, Anorthosite, Gabbro and Basalt Dredged From tho Mid-Indian Ocean Ridge," *Science*, Vol. 160. 1969, pp. 1136-1141.
27. Bishoff, J. L., "Red Sea Geothermal Brine Deposits: Their Mineralogy, Chemistry and Genesis," *Not Brines and Recent Heavy-Metal Deposits in the Red Sea*, Digens, E. T., and Ross, D. A., eds., Springer-Verlag, New York, 1969, pp. 368-406.
28. Rnitt, R. W., "The Crustal Rocks," Chap. 6, *The Seas*. Vol. 3 of *The Earth Beneath the Sea— History*, Hill, *M. N.*, ed., John Wiley, New York, 1963, pp. 85–102.
29. Nafe, J. E., and Drake, J. L., "Physical Properties of Marine Sediments," Chnp. 29. Ref. 28, pp. 794-815.
30. Horn, D. R., Horn, B. M., and Delach, M. N., "Sonic Properties of Deep-Sea Cores From the North Pncific Basin nnd Their Bearing on the Acoustic Provinces of the North Pacific," Tech. Rpt. 10, 1968, Lamont Geological Observatory.
31. Wilson, J. T., "The Development and Structure of the Crust," Chnp. 4, *The Earth as a Planet*, Kuiper, G., ed., University of Chicago Press. Chicago, 1954, pp. 138-214.

BIBLIOGRAPHY:

"Oceanography Information Sources," Committee on Oceanography, Div. of Earth Sciences, National Academy of Sciences, National Research Council, Washington, D.C. **1966.**

Fairbridge, R. W., ***The Encyclopedia of Oceanography.*** Reinhold, New York, **1966.**

Hedgpeth, J. W., ed., "Trentise on hlnrine Ecology and Paleontology," Memoir **67,** Vol. 1, **1957,** The Geological Society of America, p. **1290.**

Hill, M. N., ed., ***The Sea,*** John Wiley, New York, **1963.**

"Guide to Submission of Data," Tech. Bull. No. **1,** 1st ed., July, **1969,** National Oceanographic Center, Washington, D.C.

Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., ***The Oceans, Their Physics, Chemist and General Biology,*** Prentice-Hall, Englewood Cliffs, N.J., **1942.**

"Catalogue of Accessioned Publications," Sup. No. **2, 1970,** World Data Center--A, Oceanography, Washington, D.C.

20.1.2—Marine Chemistry — see also Refs. **3,** 7, **14–18**

MacKenzie, F. T., and Garrels, R. M., "Chemical Mass Balance Between Rivers and Oceans, ***American Journal of Science,*** Vol. **264, 1966,** pp. **507–525.**

McIlhenney, W. F., and Zeitoun, M. A., "A Chemical Engineer's Guide to Sea Water," ***Chemicd Engineering,*** Nov. **1909,** p. **81.**

Stewart. F. H., "Marine Evaporites," ***Data of Geochemistry,*** Fleischer, M., ed., Chap. Y, Prof. Paper 440-Y, **1963,** U.S. Geological Suivey.

20.1.3—Marine Geology — see also Refs. 19–32

Alexander. T., "The Secret of Sprending Ocean Floors." ***Fortune,*** **1969,** pp. **112–150.**

Beall, A. O., Jr., "Deep-Sea Drilling Project Throws New Light on Gulf Sedimentation," Offshore Exploration, ***The Oil and Gas Journal,*** pp. **94–108.**

Cotter. C. H., ***The Physical Geography of the Oceans,*** **1965.**

Emery, K. O., "Atlantic Continentnl Shelf Slope of the United States — Geological Background." Prof. Paper, **1966,** U.S. Geological Survey, p. **519-A.**

Emery, K. O., ***The Sea Off Soulhern California,*** John Wiley, New York, **1909.**

Greene, H. G., "Morphology, Sedimentntion and Seismic Characteristics of an Arctic Beach, Nome, Alaska, With Economic Significance," Open File Rpt., **1970,** U.S. Geological Survey.

Guilcher, A.. ***Coastal and Submarine Morphology,*** John Wiley, New York, **1958.**

Hill, M. L., "Geological Revolution of the 60s," ***Geotimes,*** Sept. **1968,** pp. **10–12.**

McIlhenny, W. F., and Ballard, D. A., "The Sea as a Source of Dissolved Minerals," Symp. on Economic Importance of Chemicals From the Sea, American Chemical Society, **1963.**

Menard, H. W., ***Marine Geology*** of ***the Pacific,*** McGraw-Hill, New York, **1064.**

Orownn, E., "The Origin of Ocenn Ridges," ***Scientific American,*** Oct. **1969,** pp. **103–119.**

Pratt, R. M., "Atlantic and Contincntnl Shelf nnd Slopo of the U.S.—Physiography and Sediments of the Deep Sen Basin," Paper **529-A, 1968,** U.S. Geological Survey.

Shepnrd. F. P., ***Submarine Geology,*** 2d cd., Hnrper & Row, New York, **1983.**

Terry, R. D., "Bibliogrnphy of Marine Geology and Ocennogmphy, California Coast," Spec. Rpt. 44, **1955.** Californin Dept. of Natural Resources, Div. of Mines.

Uchupi, E., "Atlantic Continental Shelf and Slope of the U.S.—Physiography," Prof. Paper 529-C, **1968,** U.S. Geologicnl Survey.

Wilde, P., "Minernl Resourccs," Chap. **13,** ***California and Uae of the Ocean,*** Keim, R., ed., Institute of hlarine Resources. **1965.** Ref. **65-21.** pp. **13-6–13-27.**