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ON THE HISTORY OF THE OCEANS[1]

By

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I shall discuss two problems concerning the history of the ocean: (1) The volume of water on the earth's surface at different times in the past. (2) Former conditions in the water and in the overlying atmosphere compared with those existing today. Specifically, we may ask whether the waters were acid, or slightly alkaline as at present, and whether conditions were oxidizing or reducing, that is, whether or not free oxygen was present.

Much of the discussion is not original. It owes a good deal to the flashing insight of Harold Urey, who was among the first to apply the principles of chemistry to the problems of the early history of the earth and the solar system; to the skillful observations of Gerard Kuiper, who has described in quantitative detail the atmospheres of planets other than our own; and to the careful analysis of William Rubey, who has marshalled the facts of geology to throw light on the broad questions we are discussing.

The scarcity of the noble gases (neon, xenon and krypton) in the earth, compared with their cosmic abundance, shows that these gases were driven away from the earth at some time in its early history. Other gases of comparable molecular weights must therefore have escaped also if they were not held in some kind of chemical or physical combination (Brown, 1952). Thus, in this respect the atmosphere and the ocean must be secondary. The ocean waters did not condense from a primitive hot and heavy atmosphere but were squeezed out of the interior of the earth. But the rare gases probably escaped from the "protoplanet" before the earth achieved its present size and degree of compaction (Kuiper, 1952: 320–324). We may ask, then, did the squeezing out of the water and of the atmospheric gases take place mostly before the geological record began or have the atmosphere and the ocean slowly grown throughout geologic time?

During the past 50 years geologists have expressed diverse views on this question. Some advocate the doctrine of permanency, that

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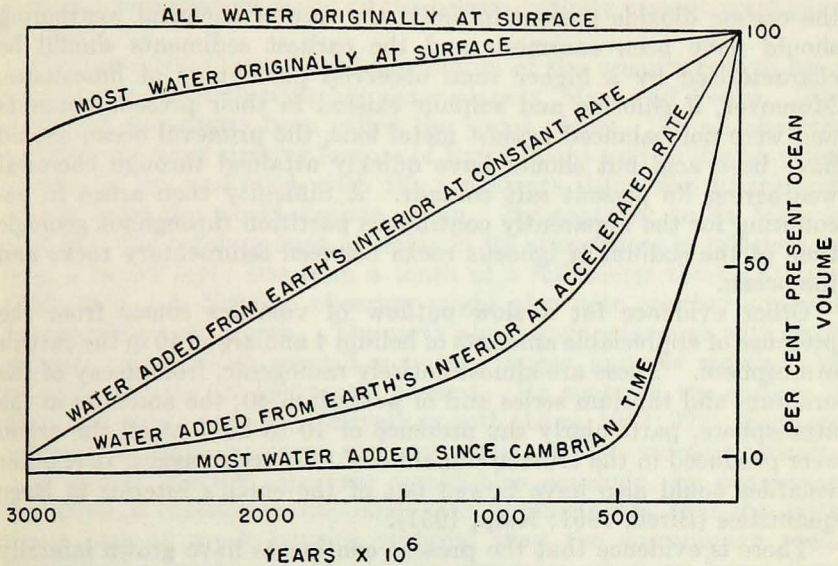
Figure 1. Possible volumes of the ocean during the geologic past, according to different hypotheses.

ever since the beginning of the geologic record the volume of ocean waters has been about the same as that which exists at present; others claim that in the earliest Archaeozoic the ocean volume was probably less than 10% of what it is today (Fig. 1).

Those (for example, see Rubey, 1951) who have argued for the slow growth of the ocean have shown that the quantity of water now flowing from volcanic springs is more than sufficient, if extrapolated back through geologic time, to account for all the water in the ocean. Furthermore, they have pointed out that in volcanic gases and in igneous rocks the ratios of the "volatiles" (water, carbon dioxide, chlorine, nitrogen, and sulphur) are similar to the ratios in the ocean, atmosphere and sedimentary rocks combined. The total amounts of these substances present on the earth's surface are roughly equivalent to the amounts contained in a layer of igneous rocks only 50 to 100 km thick, so that a relatively small loss of certain of the volatiles in igneous rocks would be sufficient to account for the amounts on the surface.

If the volatiles other than water were present to more than a minor extent at the beginning of geologic time, the earliest sedimentary rocks should be different in several respects from those laid down since. We do not believe this is the case. For example, with all

the carbon dioxide present initially, the rate of chemical weathering should have been enormous and the earliest sediments should be characterized by a higher than observed percentage of limestones. Moreover, if chlorine and sulphur existed in their present amounts and were not balanced against metal ions, the primeval ocean should have been acid but should have quickly attained through chemical weathering its present salt content. A difficulty then arises in accounting for the apparently continuous partition throughout geologic time of the sodium of igneous rocks between sedimentary rocks and the ocean.

Other evidence for a slow outflow of volatiles comes from the presence of appreciable amounts of helium 4 and argon 40 in the earth's atmosphere. These are almost entirely radiogenic, from decay of the uranium and thorium series and of potassium 40; the amounts in the atmosphere, particularly the presence of 10 to 20% of all the argon ever produced in the crust and mantle of the earth, suggest that other volatiles could also have flowed out of the earth's interior in large quantities (Birch, 1951; Kulp, 1951).

There is evidence that the present continents have grown laterally throughout geologic time (Wilson, 1954). For the most part, the oldest rocks are concentrated in the central shield areas, with younger rocks around their edges. If the growth of the continents has included the greater part of their present areas, the area occupied by the ocean has been considerably reduced and the sea floor must have become deeper relative to the continental level. Isostasy would require a thickening of the continental crust, and this profound redistribution of the earth's materials could very well have been accompanied by an outward flow of water, which would have deepened the ocean still further.

Geologists (for example, see Kuenen, 1950) who believe in the permanence of the oceans have pointed out that the water contained in the total volume of volcanic rocks produced during geologic time is far less than the volume of water in the oceans. The volatiles other than water may have slowly seeped from the interior of the earth through volcanic springs and in other ways while the water itself may have simply recirculated in the upper part of the crust (Conway, 1942). The chemical mechanism by which the water contained in igneous rocks could have been released is not clear. All the atmospheric argon may have appeared in the atmosphere in pregeologic time, because the rate of production was then much higher (Birch, 1951). However, this cannot be true of the helium 4 now present in the atmosphere, because it is known from the ratio of helium 3 to tritium (Libby, 1946) that helium escapes from the atmosphere

at such a rate that virtually all the helium initially present must have escaped.

Light may be thrown on this question of the ocean's growth by a comparison of Earth with her sister planets, Mars and Venus. The earth has sometimes been called the water planet. To an observer on Mars the most striking feature of Earth might well be the beautiful pattern of sea and land, with the continents rising like varicolored islands from the world-girdling ocean. By contrast, to us Mars is dust dry; the total amount of water in its atmosphere is sufficient to form a liquid layer less than a tenth of a millimeter thick (Kuiper, 1952: 389). A Martian observer might also note another contrast between Mars and Earth. The earth's land surface is rough with great elongate ridges which we call mountain ranges, and the red flares of volcanic activity are frequently present. By contrast, the surface of Mars appears to us to be relatively smooth (Urey, 1952: 222); there are probably no high mountains, and as we shall see, little volcanic activity.

A careful Martian observer would also conclude, by comparing the speed of rotation of the earth with its oblateness, that the earth has a core of much heavier material than the surrounding shell. Probably he would not be able to recognize what we know from seismic evidence that this core is liquid. We believe, from a similar comparison of speed of rotation and oblateness, that if Mars has a core it must be small (Brown, 1950: 641).

It is possible that these differences between Earth and Mars are related and, if so, they may help us to reconstruct the history of our own ocean. The scarcity of water on Mars has often been attributed to photochemical dissociation and the escape of hydrogen and oxygen. Because of the smaller size of Mars, its escape velocity is only about half of that from the earth, and probably some oxygen as well as hydrogen, produced by the photochemical dissociation of water, have been lost. As I shall attempt to show, however, Mars may never have had much water on its surface.

To examine this question further, let us take a more detailed look at the composition of the volatiles of Mars, Venus and Earth. Table I shows what is known about the amounts of water, carbon dioxide, oxygen, nitrogen plus argon, methane and sulphur dioxide on the surfaces of these terrestrial planets. The total mass of atmospheric gases per unit area on Mars is about 20% of that on the earth. Of this Kuiper (1952: 388) believes that perhaps 96% is nitrogen and nearly 4% argon. There is about twice as much carbon dioxide per unit area as that in the terrestrial atmosphere. Oxygen has not been detected, and, according to Dunham (1952: 299), the amount in the atmosphere is less than 0.35 g cm^{-2}. To this should be added

TABLE I. Surface Volatiles on Earth, Venus and Mars* in g cm^{-2}. Numbers Outside Parentheses Indicate Amount in Planet's Atmosphere. Numbers in Parentheses Indicate Estimated Total Amount in Atmosphere, Hydrosphere and Sediments

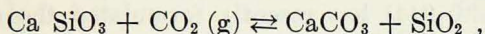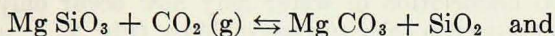| Substance	Earth	Venus	Mars
H_2O	6.25	<0.12	0.01
	(3.15×10^5)		(0.1)
CO_2	0.46	210	0.92
	(1.8×10^4)		
O_2	232		
	(1430)	<4.5	<0.35
			(50)
$N_2 + A$	770	?	190
	(850)		
CH_4	9.4×10^{-4}	<0.015	<0.008
$SO_2^+SO_4^=$	10^{-9}	?	$<3 \times 10^{-9}$
	(10^3)		

* Values for Earth principally from Hutchinson (1954); for Mars and Venus from Kuiper (1952), Dunham (1952), and author's estimate of amount of oxidized iron.

the amount used in oxidizing ferrous iron to ferric iron in the surface rocks. This amount can be estimated in the following way: Assume that 10% of the planet's surface was once covered with mountains of impact origin, like those on the moon, and that the average height of these mountains was 1000 m. During the lifetime of the planet these mountains could have been leveled by wind erosion, leaving a layer of eroded material. If the mountains were conical in shape and if the eroded material was originally similar to the average terrestrial igneous rock in our continental crust, the eroded layer must be about 25 m thick, its density must be 2.7, and 8 g O_2/kg would have been required to oxidize the contained iron, or 50 g cm^{-2} over the planet's surface.

Less than 0.01 g cm^{-2} of water is present in the Martian atmosphere. The polar snow caps probably contain an amount of water equivalent to about 0.1 g cm^{-2} when spread out over the planet's surface (Kuiper, 1952; 397).

Neither methane nor sulphur dioxide have been detected on Mars, even though the methods of analysis (ultraviolet and infrared spectroscopy) are quite sensitive. The absence of sulphur dioxide in a virtually water-free atmosphere suggests the absence of vulcanism (Kuiper, 1952: 367). We will discuss the significance of the absence of methane later.

On Venus, neither water nor oxygen have been found; according to Dunham (1952: 295), the amounts present are less than 2% of those in the earth's atmosphere. The principal gas is carbon dioxide, which is present in large amounts. This fact in itself indicates the absence of water. In the presence of water, the tendency to approach the "Urey Equilibrium,"

$$Mg \ SiO_3 + CO_2 \ (g) \leftrightharpoons Mg \ CO_3 + SiO_2 \quad \text{and}$$

$$Ca \ SiO_3 + CO_2 \ (g) \rightleftharpoons CaCO_3 + SiO_2 \ ,$$

would quickly result in the production of carbonates and in the depletion of the atmospheric carbon dioxide (Urey, 1952: 148–149). As on Mars, the absence of methane is noteworthy. The amount of nitrogen plus argon is not known, but it may be quite large. These gases cannot be detected spectroscopically and their presence on Mars is inferred from other observations.

If Mars originally had an appreciable quantity of water and nitrogen, but no oxygen, on its surface and in its atmosphere, then some solar ultraviolet radiation should have penetrated to the surface and some water would have been dissociated photochemically into hydrogen and oxygen. The hydrogen would escape rapidly from the planet, the oxygen much more slowly, at a rate determined by the temperature in the Martian exosphere. Some oxygen would also be withdrawn from the atmosphere by oxidation of iron in surface rocks. The oxygen remaining in the atmosphere would absorb the ultraviolet radiation before it reached the planet's surface. Further dissociation of water would then be confined to the outer region of the atmosphere. Just as on Earth, there should have been at least one and perhaps two atmospheric layers of very low temperature, between 150° and 200° K. Harteck and Jensen (1948: 591) and Kuiper (1952: 310–314) have pointed out that on Earth these low temperature layers and the overlying layers of increasing temperature act as a "cold trap" through which water can pass only very slowly. Kuiper has estimated that the rate of flow of water through the stratospheric cold trap on Earth is 1.4×10^{-14} g cm^{-2} sec^{-1} or 1.5 kg cm^{-2} in 3.5×10^9 years. He suggests that, because of the lower temperature in the corresponding atmospheric layer on Mars, the rate of outward flow of water is perhaps 100 times slower. In any case, the oxygen content of the Martian atmosphere should have increased rapidly to such an amount that a steady state equilibrium would exist between the rate of transfer of water to the upper atmosphere and the rate of escape of oxygen from the exosphere. This equilibrium may well exist at the present time. Dunham's (1952)

upper limit for oxygen in the Martian atmosphere, 0.35 g cm^{-2} (Table I), is about 50 times the amount of oxygen required in the earth's atmosphere to absorb solar radiation with wave lengths between 1800 and 2000 angstroms (Goldberg, 1954: 748). Radiation of these wave lengths is responsible for photochemical dissociation of water in the outer layers of Earth's atmosphere (Bates, 1954: 591–592). Thus, photochemical dissociation of water may now occur only some tens of kilometers above the solid surface of Mars (Fig. 2).

Spitzer (1952: 239–244) has recently formulated the relationship between escape velocities for atmospheric gases and temperature in the exospheres of Earth and Mars. His results are confirmed as to order of magnitude by Libby's (1946: 671) essentially experimental determination of the rate of escape of helium 3 from the earth's

TABLE II. Times Required for Nitrogen and Oxygen to Decrease by 1/e Through Escape from Martian Atmosphere, at Different Exosphere Temperatures

| Temperature in °K at base of Martian exosphere | Time of escape in years | | Oxygen |
| | Nitrogen | | |
	$N/N_2 = 0.01$	$N/N_2 = 0.001$	
1200	5.0×10^9	5.0×10^{10}	5.9×10^8
1300	1.7×10^9	1.7×10^{10}	1.5×10^8
1400	6.1×10^8	6.1×10^9	4.7×10^7
1500	2.5×10^8	2.5×10^9	1.7×10^7
1600	1.2×10^8	1.2×10^9	6.4×10^6
1700	5.9×10^7	5.9×10^8	2.9×10^6
1800	3.4×10^7	3.4×10^8	1.6×10^6

atmosphere, based on the ratio of helium 3 to tritium. Table II, computed from Spitzer's equations, shows the times required at different exosphere temperatures for nitrogen and oxygen in the Martian atmosphere to decrease by 1/e. The escape time for nitrogen depends on the degree of dissociation of molecular nitrogen into the atomic form at the base of the exosphere. The percentage dissociation has been estimated as being between 0.01 and 0.001 by both Bates (1954: 589) and Nicolet (1954: 687). If we assume that the total amount of nitrogen ever present in the atmosphere of Mars is equal to the nitrogen now in the earth's atmosphere, the Martian exosphere temperature lies between 1300° and 1700° K (Table III). The actual value depends: (1) on whether all the nitrogen was originally present 3.5 × 10^9 years ago or has come from the interior during the planet's lifetime; and (2) on the ratio of molecular to atomic nitrogen in the exosphere. The range of escape times for oxygen over this tempera-
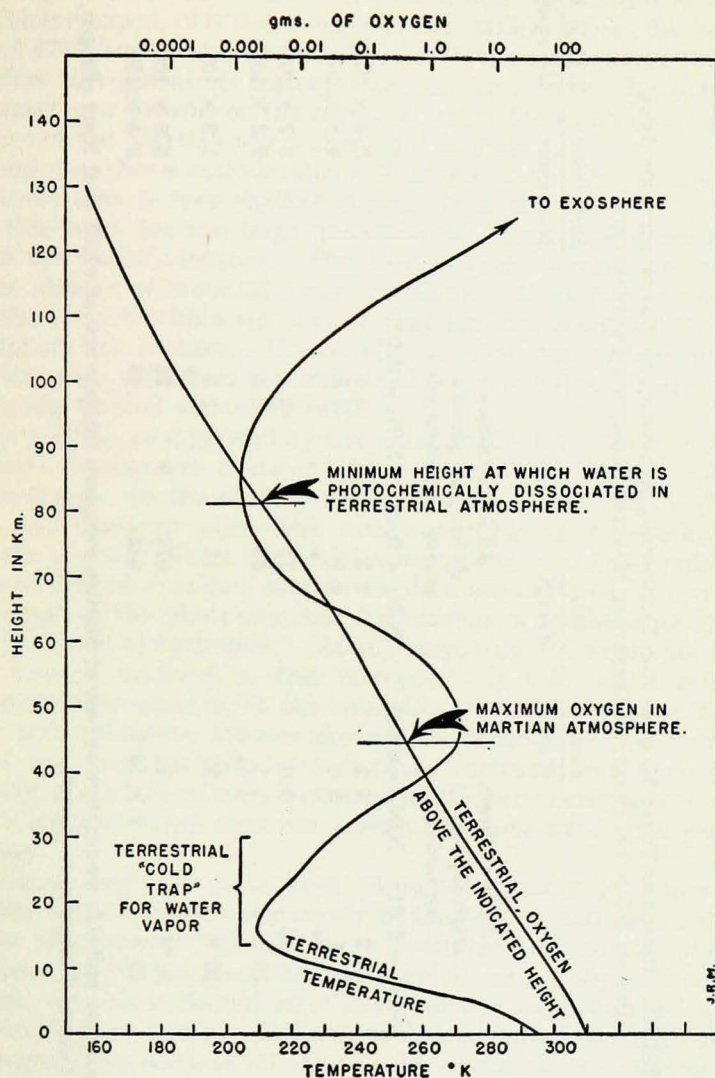
Figure 2.   Temperature and oxygen content of the terrestrial atmosphere, showing the minimum height for photochemical dissociation of water, the "cold trap" for upward transport of water and the height above which the oxygen of the terrestrial atmosphere is equal to the maximum oxygen content of the Martian atmosphere.

TABLE III. RATIOS OF TOTAL MARTIAN AND TERRESTRIAL NITROGEN AND WATER, PER UNIT AREA, DURING 3.5×10^9 YEARS, for DIFFERENT MARTIAN EXOSPHERE TEMPERATURES

Temperature at base of Martian exosphere, °K	$\dfrac{\text{Earth N}}{\text{Mars N}} = \dfrac{850}{\text{Mars N}}$				$\dfrac{\text{Earth water}}{\text{Mars water}} = \dfrac{3.15 \times 10^5}{\text{Mars water}}$
	All Mars nitrogen originally present on surface		All Mars nitrogen derived from planet's interior at constant rate		
	$N/N_2 = 0.01$	$N/N_2 = 0.001$	$N/N_2 = 0.01$	$N/N_2 = 0.001$	
1200	2.2	4.2	3.2	4.4	5.3×10^3
1300	1.5 *	3.6	1.9 *	4.0	4.8×10^3
1400	.13	2.6	.79	3.4	3.7×10^3
1500	10^{-5}	1.1 *	.32	2.4	2.3×10^3
1600	10^{-12}	.27	.15	1.5 *	1.2×10^3
1700	10^{-25}	.14	.076	.76	5.9×10^2
1800	10^{-44}	2×10^{-4}	.043	.43	3.4×10^2

* Indicates maximum probable temperature at base of Martian exosphere (temperature at which total Mars nitrogen, in g cm^{-2} $\approx$ total terrestrial nitrogen, in g cm^{-2}).

ture range is 1.5×10^8 to 2.9×10^6 years, and the amount of oxygen which has escaped, plus the amount used in oxidizing iron, lies between 60 and 470 g/cm^{-2}.   As shown in Table III, the total amount of water on Mars throughout its history was less than one six-hundredth of the water now present on the earth, provided the equilibrium oxygen content of the Martian atmosphere is 0.35 g cm^{-2}.

From the above considerations it seems likely that Mars never had more than a very shallow ocean.   It is not difficult to believe that this is so, because large quantities of water have never seeped out of the planet's interior.   This in turn may be related to the apparent absence of mountains and volcanoes.   Mars may never have had the turmoil within its interior that has characterized the earth throughout its lifetime.   Conversely, it does not appear illogical that the great volume of the terrestrial ocean is a direct result of the continuing turmoil within the earth.

It is possible, as suggested by Urey (1952: 149–157), that the earth's primitive atmosphere contained large amounts of water, ammonia and methane.   In the absence of free oxygen, a cold trap might not exist, and moreover ultraviolet radiation could have penetrated to near the ground.   Then the initial atmospheric methane would have become oxidized to carbon dioxide within a few hundred million years as a result of the photochemical dissociation of methane and water and the escape of hydrogen.   (At the same time the ammonia would have become oxidized to free nitrogen.)   If this initial methane corresponded in amount to the total CO_2 present in oceans, atmosphere and sediments, intense chemical weathering should have occurred and vast amounts of sediments, including carbonates particularly, should have been deposited in the very early stages of the earth's history.   This does not seem to be consistent with geologic evidence.

Methane may not have been present originally in appreciable quantity but may have come slowly to the surface, but we must then explain why present volcanic gases contain CO_2 and CO and not methane.   If the methane did not come in as rapidly as hydrogen escaped, conditions should soon have become oxidizing and a cold trap should have arisen.   The rate of flow of water through the cold trap required to produce all the CO_2 by oxidation of methane is 10 times greater than that computed by Kuiper.

It is possible that the methane appeared rapidly enough in the early stages of the earth's history so that conditions remained reducing for a long period and under those conditions no free oxygen and no cold trap existed.   During later geologic time the rate of outflow decreased to the point where free oxygen could appear.   This would imply

that nearly all carbon dioxide now present in the atmosphere, ocean, and sedimentary rocks was produced during early geologic time. Of course, we cannot invoke the hypothesis of photosynthetic production of oxygen and burial of reduced carbon in the form of organic matter in marine sediments to account for production of carbon dioxide and free oxygen from methane and water.

In attempting to resolve this question we may look again with profit to our sister planets Mars and Venus. Urey (1952: 148–150) has suggested that the high concentration of CO_2 and the absence of water in the atmosphere of Venus are due to the photochemical dissociation of methane and water and the resulting oxidation of carbon. But both water and methane are now virtually absent on Venus. Urey's hypothesis would explain this observation if: (1) the amounts of water and methane originally present were just sufficient to balance each other, a coincidence that appears quite unlikely when we remember that both water and methane are also scarce on Mars; or (2) there was an excess of methane, which decomposed to carbon and perhaps refractory carbon compounds. Urey (personal communication) has pointed out that the light yellow color of the Venus cloud layer would appear to rule out the presence of finely divided carbon, which should give a dark "smoky" color.

As several writers have emphasized, the existence of reducing conditions during early stages of the earth's history may have been an essential prerequisite for the origin of life on our planet. The complex organic molecules that are the building blocks of living creatures probably could not have evolved in an oxidizing environment. Thode and his coworkers (Szabo, *et al.*, 1950), from studies of sulphur isotope ratios in sulphides and sulphates of different geologic ages, have suggested that free oxygen did not exist in large amounts until perhaps 800 million years ago. If this were correct, then we might have a satisfactory explanation for the absence of animal fossils in pre-Cambrian rocks and an explanation also for the sudden appearance of fossil remains in many diverse, highly developed animal forms in the Cambrian.

With the growth of biochemical knowledge, the extreme chemical complexity of living things is becoming ever more apparent (see, for example, Wald, 1954). Nearly all this complexity is possessed by even the simplest organisms. It may be that by far the most difficult and time-consuming part of the evolutionary process was the development of the chemistry of the single cell, the building block of all living creatures. This development, including the processes of fermentation, then photosynthesis, and finally respiration could have been carried out entirely by plantlike organisms, which, unlike animals, require no external source of oxygen for their metabolic processes.

Given the essential chemistry for the organization of living cells, the evolution of animals represents little more than mutations required for the development of a complex morphology, and conceivably they might have happened within a few hundred million years. If we remember that precipitation of calcium carbonate, though easy for plants, which raise the pH by removing carbon dioxide, is a most difficult process for animals, whose principal metabolic products are acid, then it seems likely that the first animals had no hard parts. Considerable diversity of form might have arisen before animals learned how to manufacture shells or skeletons. But once this process was learned, its advantages would be so overwhelming that few animals could survive for long without hard parts.

Thus the sudden appearance of animal fossils in the Cambrian strongly suggests that appreciable amounts of free oxygen did not exist more than a few hundred million years before that time. How, then, can we reconcile the need for reducing conditions in relatively late geologic time with the difficulties previously discussed concerning methane? I believe the answer has been given by Rubey (1951). He has reminded us that volcanic gases contain both CO_2 and CO and has suggested that the organic carbon in the sedimentary rocks can be balanced against the oxygen in the atmosphere, in sulphates and in ferric oxide, provided that approximately a third of the total carbon came to the earth's surface as CO and two-thirds as CO_2. During the early stages of the earth's history, the existence of CO in the atmosphere and oceans would have assured reducing conditions, at least in some parts of the oceans and at times elsewhere. Free oxygen would appear in significant quantities only after the process of photosynthesis had been developed and after sufficient reduced carbon as organic matter had been buried in marine sedimentary rocks.

The reader may well have noted that comparisons of the three terrestrial planets given in preceding pages raise several unanswered questions. For example, why was there more nitrogen than water on Mars and less on the earth? Why is there virtually no water or carbon monoxide on Venus?

It is interesting in this connection to note that the scarcity of oxygen on Mars may be partly an oceanographic phenomenon in reverse. Mars has no oceans, and therefore there is no possibility for the formation of marine sediments with their contained organic remains. Thus, if primitive plants exist on Mars, as seems probable, the oxygen produced by their photosynthesis is used up again by respiration so that none accumulates.

According to Rubey (1951), the geologic evidence indicates that the concentration of CO_2 in the atmosphere and ocean has always been

approximately the same as that now existing. From this he concludes that the rate of outflow of volatiles from the earth's interior has been relatively constant. But in the presence of water, the Urey equilibrium would insure a relatively low concentration of atmospheric and oceanic carbon dioxide at all times regardless of the rate of outflow from the interior. At times of more rapid outflow the rates of chemical weathering and of deposition of limestones and other sediments would be increased; at times of slow outflow the rates of weathering and deposition would be slow, other things being equal.

There is some evidence that a considerable portion, perhaps as much as a fourth of all the water in the oceans, has appeared since the late Mesozoic, that is, in the last thirtieth or fortieth of geologic time. Throughout a large area within the "andesite line" in the Pacific Ocean, the presence of coral atolls and flat-topped sea mounts indicates subsidence of the sea floor relative to sea level. This subsidence may have been regional in character, and if so, the approximate constancy of sea level relative to the continental surfaces would require an increase in the total volume of sea water. There is good evidence that, if the subsidence did occur, it took place during the last 100 million years. The fossils found in the drill holes on Bikini and Eniwetok by Ladd and his coworkers (Emery, *et al.*, 1954) are at all depths those of shallow-water, mostly lagoon-dwelling, organisms. At 2500 feet on Bikini, these were early Miocene or late Oligocene in age; at 4500 feet on Eniwetok the fossils were Eocene. Remains of reef corals, echinoids and shallow-water mollusks, dredged from the flat-topped summits of the submerged mid-Pacific mountains between Hawaii and Wake Islands, have been identified by Hamilton (1953) as Middle Cretaceous in age. These summits now lie at depths of 5000 to 6000 feet.

Evidence for a marked increase in the rate of outflow of volatiles may be found also in the character and rate of deposition of deep sea sediments. At the present time, nearly half the deep sea floor is covered with sediments high in calcium carbonate, such as globigerina ooze. These are being deposited at rates of the order of 0.1 to 1 g $Ca/m^2/1000$ years (Kuenen, 1950). If this rate of deposition has prevailed since the late Mesozoic, that is, since the rise of the pelagic foraminifera, then about a fourth of all limestones now on the earth's surface has been laid down during the last 100 million years. Prior to that time, the deep sea sediments must have been low in calcium. Otherwise, it would be impossible to arrive at a geochemical balance, because both deep-sea and continental sediments would be higher in calcium than the igneous rocks from which they were derived. Because of this change, Kuenen (1950) has suggested that, with the

rise of pelagic foraminifera, the rate of deposition of calcium carbonate on the deep sea floor has been increased at the expense of the shallow water areas. He supposes that a gradual shift in the location of the sedimentary calcium on the earth is occurring; limestones on the continental platforms are being eroded, and calcium carbonate is accumulating on the deep sea floor, where it will be lost from the calcium cycle. But an alternative explanation is possible: that during late geologic time there has been a great increase in the rate of outflow of carbon dioxide from the earth's interior, with a corresponding increase in the rate of chemical erosion of rocks other than carbonates and in the rate of sediment deposition. The increase in carbon dioxide should have been accompanied also by a corresponding increase in water and other volatiles. The increased supply of calcium from erosion may have stimulated the development of the pelagic foraminifera.

That great events took place in the sea floor in the not distant geologic past is strongly suggested by the extreme thinness of deep sea sediments, as found in both the Atlantic and Pacific by seismic refraction methods. Over a large area in the Pacific, Raitt (Capricorn, 1953) has found that these sediments (at least in unconsolidated form) are only 100 or 200 m thick. A far greater thickness of deep sea sediments is called for by geochemical considerations. The earlier deep sea sediments may have been buried or consolidated in extensive lava flows or other volcanic extrusions that blanketed the sea floor, perhaps during the Mesozoic. Such vast-scale vulcanism should have been accompanied and succeeded by an outpouring of volatiles that may have persisted to the present time.

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