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THE GEOLOGIC IMPLICATIONS OF THE EARTH-MOON RELATIONSHIP

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Mr. Barbicane, fictional president of the Baltimore Gun Club, included in his famous address in Chapter II of Jules Verne's, *From Earth to the Moon and a Trip Around It*, these words: "There is no one among you, my brave colleagues, who has not seen the Moon, or, at least, heard speak of it (Verne, 1865: 10)."

That was supposed to have been a century ago. Today, after nine Ranger shots, uncounted Russian Lunik ventures, and the very considerable publicity given to the manned lunar landing vehicle program known as Apollo, who has not heard of the moon? We now have new photographs, from which new maps of the lunar topography have been prepared. If good fortune graces the Surveyor series, we should soon have new information on the composition of the surface materials. The exploration of the moon has begun.

Of what significance is all this to the geologist, or to the earth scientist? To this question, I will direct this evening's remarks.

As a proper beginning, let us examine the relationship of the earth to the moon, or the moon to the earth. Let us speak, not of the earth and its natural satellite, but of two planets—the earth-moon system. The earth, with a diameter of 7,900 miles, is nearly four times larger than the moon. However, the moon is itself a substantial body, by earth standards. Because of the disparity in mass between the moon and the earth (the moon represents only 1/80 of the mass of the earth) the center of gravity of this two-planet system is within the sphere of the earth, almost 1,000 miles below the surface of our planet. As the moon revolves about the earth, and the earth moves in its orbit around the sun, this two-planet system swings around, like a giant dumbbell in space. Despite the distance that separates the earth and the moon, the two planets affect each other, perhaps to an extent that might escape the casual observer.

The principal effect of the moon's presence is to create a bulge in the oceans of the earth on the side facing the moon, and a counterpart bulge on the side opposite as well. As the earth turns on its axis, these bulges move westward around the earth; these are the true tidal waves. "The tides are the heartbeat of the ocean, a pulse that can be felt all over the world. This mysterious rhythm has gripped man's imagination since the beginnings of recorded history, spurring him to try to understand its causes and grasp its meaning" (Defant, 1958: 9). If the earth were entirely covered by water, these bulges could move unhampered around the earth. But our oceans are separated by continental landmasses, and these get in the way of the tidal waves. This produces many interesting and complex events.

While the moon is the principal tide-producing body, the sun also creates a

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tidal force. Only the vastly greater distance of the sun reduces its share of tidal force to a level below that of the moon.

The moon describes an ellipse as it revolves around the earth; thus, it is sometimes closer, sometimes farther from the earth. Correspondingly, the tides are greater when it is closer, and vice versa. When the moon is "new," earth, moon, and sun are in a straight line, and the combined tidal force of moon and sun produce the highest tides, called "spring" tides.

When tidal forces are magnified or intensified by the shape and topography of the continental border, the height of the tide can be significantly increased. The Bay of Fundy is perhaps the most famous, where the tidal range reaches a maximum of 70 ft. Mont St. Michael on the coast of Normandy often experiences 40-ft tides and, in Cook Inlet on the south-central coast of Alaska, 30-ft tides are commonplace.

Less spectacular differences between high and low tide are a familiar feature along thousands of miles of coast. The zone exposed by low tide has been termed "tidal flat." These areas are drained by "tidal channels" and, as the water moves seaward, "tidal currents" are produced. These currents are powerful agents of erosion, producing "tidal scour" on the bottom, and thus contribute to the sculpturing of the sea floor immediately offshore.

Of what significance, if any, are tidal phenomena to the subject of historical geology? The reconstruction of boundaries between ancient land areas and ancient seas is the domain of the paleogeographer. Using a variety of stratigraphic clues, he must determine where these boundaries were situated at some given point in time, for some particular area under study. The accurate location of shore lines can be helpful in the search for petroleum, to name only one economic motivation.

Paleogeographic considerations are also of interest to the paleontologist, as he attempts to correlate faunal groups with their environments.

Since tidal features are today not clearly understood, it is not surprising that tidal effects, as preserved in shoreline sediments, have rarely been recognized. Immediately the question arises, were tides as important or unimportant in the geologic past as they are today? To use a classic approach—ancient tides were either greater, the same, or less important than modern tides. This brings us to the history of tidal forces, a subject upon which little work has been done.

If we assume that tidal forces have not substantially changed during recorded geologic time, then we must also assume that the earth-moon relationship has not changed. There is general agreement among astronomers, however, that the latter is not the case. The moon appears to be gradually increasing the radius of its orbit around the earth.

Where the modern sea is shallow and, particularly, where the tides move great volumes of water over extensive areas, considerable friction occurs between the water and the bottom. This "tidal friction," based on the present-day geography, has been studied in detail by Jeffreys (1920) and Heiskanen (1921). Their calculations, much too detailed to be reviewed here, lead them to believe that tidal friction over the years has slightly reduced the rotational speed of the earth, thus increasing the length of day.

Baldwin (1913: 198) summarizes the significance of this reduction in rotational speed. "A loss in the angular rate of rotation of the earth is a loss in angular momentum; yet angular momentum cannot be destroyed, but only transferred. Since the moon is the most important body in producing tides, its action on the earth results in a reacting transfer of angular momentum of rotation into the moon's angular momentum of revolution. The moon is thus gradually receding from the earth, and the length of the month is slowly increasing."

If we examine the calculations of Jeffreys and Heiskanen, we find that they searched the oceanographic data then available for areas where significant amounts of tidal friction could occur. The Irish Sea, the English Channel, the Northwest Passage, the Bay of Fundy—all were included in their principal areas of energy dissipation. Both agreed the Bering Sea, however, to be the principal "sink" of tidal energy. According to Jeffreys, three-fourths of the total dissipation of tidal energy takes place here (Jeffreys, 1920: 215).

The work of Jeffreys and Heiskanen served to settle the problem of tidal friction and a slowing rate of earth rotation; at least, their conclusions were not challenged for 40 years. Then, in 1960, Walter Munk, of the Scripps Institution of Oceanography at La Jolla and Gordon J. F. MacDonald of NASA reopened the problem. They examined new data on oceanographic phenomena in the Bering Sea, but could not find sufficient evidence to support Jeffreys and Heiskanen's conclusions; they believed the values given in the earlier work to be too high. Some other way of dissipating energy would have to be found.

Although the problem of tidal friction is fascinating, we cannot hope to give it the attention it deserves here. The one fact that we must now examine for its geologic implications is the lengthening distance of the moon from the earth. Whatever the choice of method for dissipating energy, has the rate of dissipation of tidal energy been constant during the geologic past?

If we rely principally on tidal friction, or on the movement of water in shallow seas, then the paleogeographer can provide valuable data.

Beginning with the Cambrian, the ocean invasions of what is now the North American continent are well recorded in the stratigraphic record. Pre-Cambrian sea level distribution becomes progressively less understood, since only scattered remnants of evidence in the oldest rocks provide quite meager data. On repeated occasions in the Paleozic, however, the interior of what is now North America was covered by shallow seas. Ordovician seas covered more than 50 per cent of the continental area, Mississippian seas more than 45 per cent, Silurian and Devonian seas more than 40 per cent, and so on. The length of stay of these invasions was considerable.

If the paleogeographer could have at his disposal complete synoptic world maps showing the distribution of land and water areas in comparable degree of detail to the present knowledge of the globe, it might be possible to offer evidence that the seas in the geologic past were far more effective in slowing down the earth's rotation than are the present seas. Such maps are not yet available. In their absence, their interpretation is, for now, only a matter of conjecture.

Let us suppose, however, that such complete paleogeographic data were available, and that from such data we could show that tidal friction has been substantially *greater* in the past than it is today. Because of such increased friction, was the rate of the retreat of the moon increased? Is the rate of retreat, then, *not* a constant?

MacDonald believes that the dissipative powers of the seas are an insufficient "sink" of tidal energy, that a substantial fraction of this energy may be dissipated within the body of the earth. "Extrapolation back in time of the present rate of dissipation is warranted only if the rate of energy dissipation has remained constant. The dissipative character of the earth's mantle depends only on the prevailing conditions of the temperature and pressure. The time constant for the change in temperature and pressure within the earth is very long, and it may be safely assumed that the earth now has much the same dissipative properties that is possessed a few billion years ago. The time needed for the moon to recede from a distance of 10^5 kilometers to its present distance from the earth is 1.3×10^9 years, provided our estimate of energy dissipation is correct. This calculation does not take into account the nonlinear interactions as the moon moves closer to the earth. If the nonlinear terms are considered, the time needed for the moon to recede from a distance of 10^5 kilometers to its present distance would be a few hundred million years" (MacDonald, 1961: 1049).

If the moon, as we move back in geologic time, was then closer to the earth by a significant amount, what role did the tides play in early geologic history? If they were "higher" than modern tides, would they not have strongly influenced stratigraphic processes?

I put this question to a distinguished associate of mine, Dr. Clarence Bell, and he prepared for me a calculation of the change in the moon's tidal force based on the presently accepted rate of recession on one hand, and at an increased rate (3×) of recession in the other (Bell, personal communication). His findings are summarized in table 1.

TABLE 1
Comparative tidal forces in ancient times

Years ago	Geologic Period	F then/F now	
		With stated F	With increased F
100×10^6	Cretaceous	1.025	1.078
200×10^6	Permian	1.051	1.165
300×10^6	Devonian	1.078	1.261
400×10^6	Ordovician	1.106	1.368
500×10^6	Cambrian	1.135	1.488

F = tidal force.

These changes are not sufficiently significant to suggest any substantial increase in tidal forces in the Palezoic, but they were certainly not any *less* than those of modern times.

In the middle and upper latitudes, where paleogeographic clues indicate long, bay-like penetrations of ancient seas, we should find evidence of strong tidal action.

Field investigators are now becoming increasingly aware of tidal phenomena and are reporting them. For example, recent work of D. W. Lane has identified tidal phenomena in the Cretaceous Dakota Sandstone in northwestern Colorado. "The tidal features previously discussed are not randomly distributed but form a definite pattern. Those features which indicate relatively great current velocities occur in and near the main channels which, on true tidal flats, radiate landward from the tidal inlets between barrier islands. Included in this group of features are the channel scours (wash-outs), large scale cross-bedding, current ripples and sand waves, shale-pebble beds, coarse-grained sediments, and interbedded laminae of sand and mud. Away from the main channels and on the tidal flats proper these features become less common and are gradually replaced by ones indicative of quiet-water conditions. Important among these latter are burrowing structures and oscillation ripple marks. As the highest part of the flats is approached, ripples become rare, grain size diminishes, and burrows become extremely abundant (Lane, 1963: 236)."

Paleontologists seeking ecological data on shallow-water marine organisms should keep in mind the powerful circulating currents produced by tidal action. Indeed, the transition from marine life to amphibian to land-dwelling life must be inextricably interwoven with the history of the tides.

The farther we go back in geologic time, the less distinct and the less readable the record. "If we assume that the energy dissipated by ancient lunar tides varied in proportion to the tidal forces, then an extension of the calculations of table 1 shows that the moon's orbital radius was nearly 0 about 5¼ billion years ago, and that the tides then were enormous!" (Bell, personal communication). Now, we are entering that realm where mathematics and physics, the "great-uncles" of astronomy, take over from the geologist.

The "accepted" theories of moon origin have changed considerably in recent years, but now the majority of authorities seem to follow a sort of modified condensation hypothesis. The debris from a stellar explosion gathered in some manner, as yet unexplained, into gravitationally-bound bodies orbiting around our Sun. By repeated collisions, they accumulated into solid objects about the size of our Moon. Some of these became unstable and, due to tidal disruptive forces, came apart. A new generation of debris was formed, which in turn rained on the planets which survived. Perhaps this era of monumental impacts marked the naked moon as we see it today. This same era must have profoundly altered the composition of our own planet.

New discoveries of ancient and partially absorbed craters are being made here on earth. Recent "finds" in the Canadian shield (Beals, Innes, and Rottenberg, 1960) seem to indicate that the farther we go back in geologic time, the more common the impact phenomena become. The forces which are ever at work to change the face of the earth have largely obliterated our once moon-like topography.

Somewhere, sometime, in the early dawn of earth history, the earth may have "acquired" the moon, and the radius between the two planets, at first much smaller than today, produced enormous stresses in the primeval crust. To paraphrase Defant, the "earth's pulse" then began.

How can any geologist, any student of the history of our little planet, proceed without considering the moon, and our changing relationship to our "original" satellite?

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