THE EARTH, THE MOON AND TIDAL SEDIMENTS :
AN ANALYTICAL REVIEW

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by

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Summary

An attempt is made to relate contemporary tidal sedimentation to that of the past. The causes of the tides are considered at an elementary level, and it is shown that their magnitude depends on a number of factors which may have varied over geological time. The validity of theories in which these variations are implicit are considered, while the scale of the implied fluctuations is investigated semi-quantitatively. One theory is found which dominates all others in its effects on tidal magnitude variation. This is the theory associated with tidal-friction. The implication is that, on descending the stratigraphical column, preserved tidal deposits should show increasing tidal ranges. Recent tidal sediments are examined and apparently offer adequate criteria for identification of fossil deposits of similar origin. Palaeozoic quartzites and tilloids are both suggested as evidence for higher tides and this places a possible question mark against Hutton's Principle of Uniformitarianism. The quantitative studies carried out by geologists on Phanerozoic rocks seem to show that, although tides were higher then, they were not sufficiently high to satisfy the astronomers. The astronomers require tides that are kilometres high and, unless the deposits left by these tides are unrecognised by geologists for what they are, such tides have not occurred. It is possible that the moon is of recent origin, but no theory fits the facts and this conflict between astronomy and geology remains to the end. The only solution offered is that the radioactive decay constants vary with time, which solves the underlying time-scale difficulty, that prevents the geological and astronomical theories from being compatible. But the cure seems to be worse than the disease.

Introduction

This paper is an attempt to compare tidal sedimentation today with that of the geological past. These investigations have two main aims. Firstly, after giving a brief general review of tidal sediments, to examine tidal ranges in Palaeozoic and older rocks in order to see what evidence is available for or against Hutton's Principle of Uniformitarianism, which postulates that the present is the key to the past. Secondly, to throw some light on the history of the earth-moon system, which has an important bearing on the whole of earth history. In order to achieve these aims, a preliminary insight into tidal theory is necessary. An analysis of present day tidal deposits will follow, combined with a search for criteria that can be used to identify tidal deposits in the sedimentary record.

A number of current astronomical and cosmological theories predict, either explicitly or implicitly, that tidal magnitudes have previously been higher. These theories are contrasted with the sparse results available from the rock record of tidal ranges in various geological

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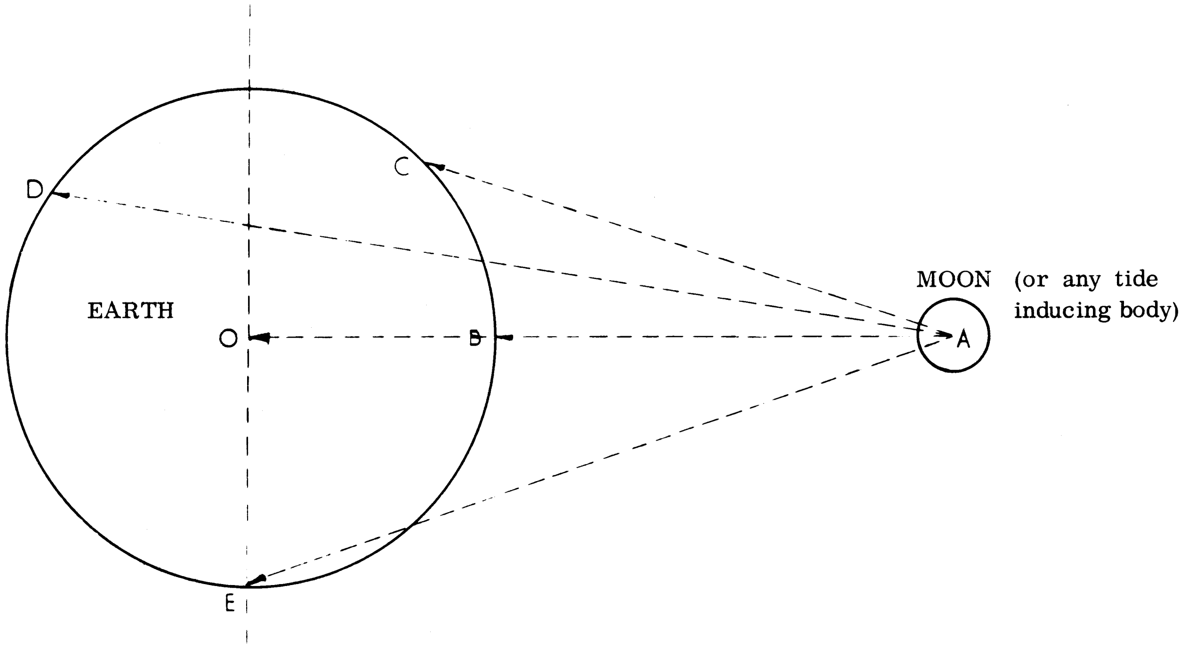
epochs. This paper does not set out to solve the problems associated with tidal action in geological history but rather to pose clearly the dilemmas and to suggest a tentative route towards their resolution.

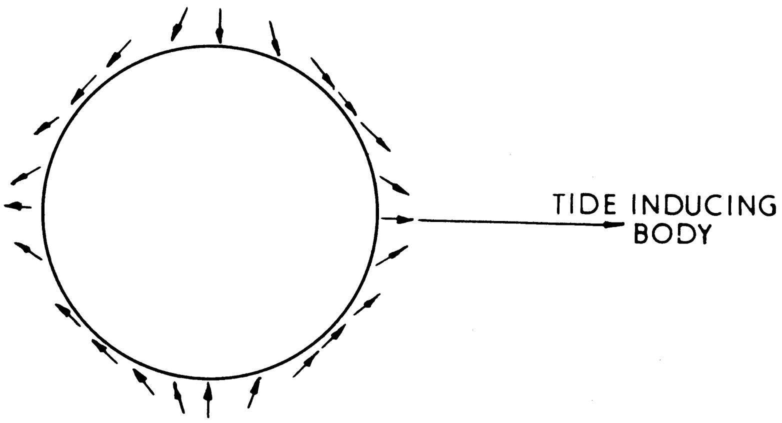
The causes of tides

Tides are caused by the varying gravitational attraction of the sun and the moon upon the individual particles of the earth. The directions along which the gravitational forces act are not uniform, as the earth is a sphere and the particles on it are therefore at varying angles to the tide inducing body. These angles are of similar magnitude but the small variations are significant. The magnitude of the forces also varies, to a similarly small but important extent, as some particles are further away from the tide inducing body than others and the magnitude of the gravitational force is dependent on the separation of the bodies. These two effects can be seen in text-fig. 1 : for example, the angle BAC is greater than angle BAD, while the distance AB is less than distance AC. The average force on the particles is that along the line ABO at a distance AO.

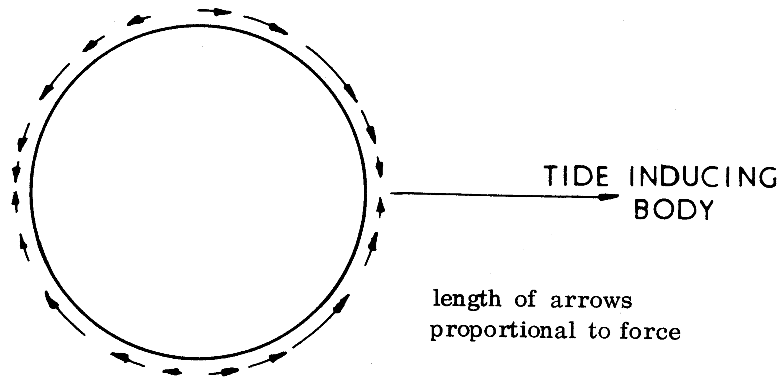


Text-fig. 1. The variation in gravitational force due to distance and position on the earth's surface.

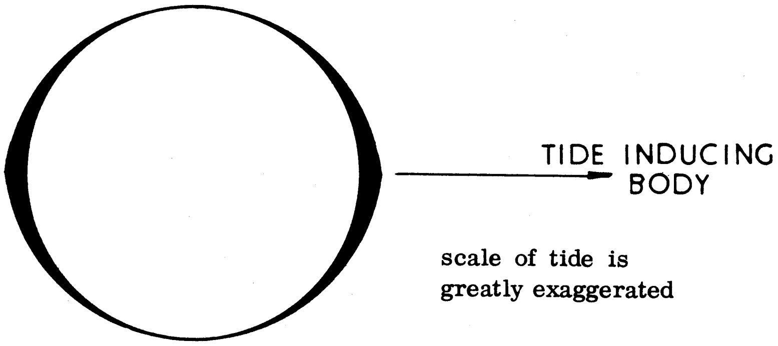
Therefore if the average force on each particle due to gravitational attraction is subtracted vectorially from the actual force on each particle, a system of residual forces remains which vary systematically in strength and direction over the earth's surface (see text - fig. 2). These residual forces can be resolved into horizontal and vertical components with respect to the surface of the earth. The vertical component can be neglected as it simply adds to, or subtracts from the weight of particles by an insignificant amount. The resulting horizontal forces are shown in text-fig. 3, and these are the effective tide generating forces, producing what is known as the 'equilibrium' tide (see text-fig. 4). This tide is to a large extent conceptual, bearing only a limited correspondence to the hard facts of observation with regard both to timing and to magnitude.



Text-fig. 2. The residual tide inducing forces remaining after subtracting the average force from the actual force.



Text-fig. 3. The horizontal tide generating forces.



Text-fig. 4. The 'equilibrium tide', resulting from the horizontal tide generating forces.

While the explanation above is for only one tide inducing body, the earth has two such bodies acting upon it - the sun and the moon. The moon exerts a stronger tidal influence on the earth than the sun, inducing tides that are 2.17 times as strong.

One point which must be clarified is that these tidal forces act on the whole body of the earth and while the aqueous layer of the earth responds noticeably to these, the solid earth is also affected to a lesser degree. These tides within the solid earth hold no further interest in this paper.

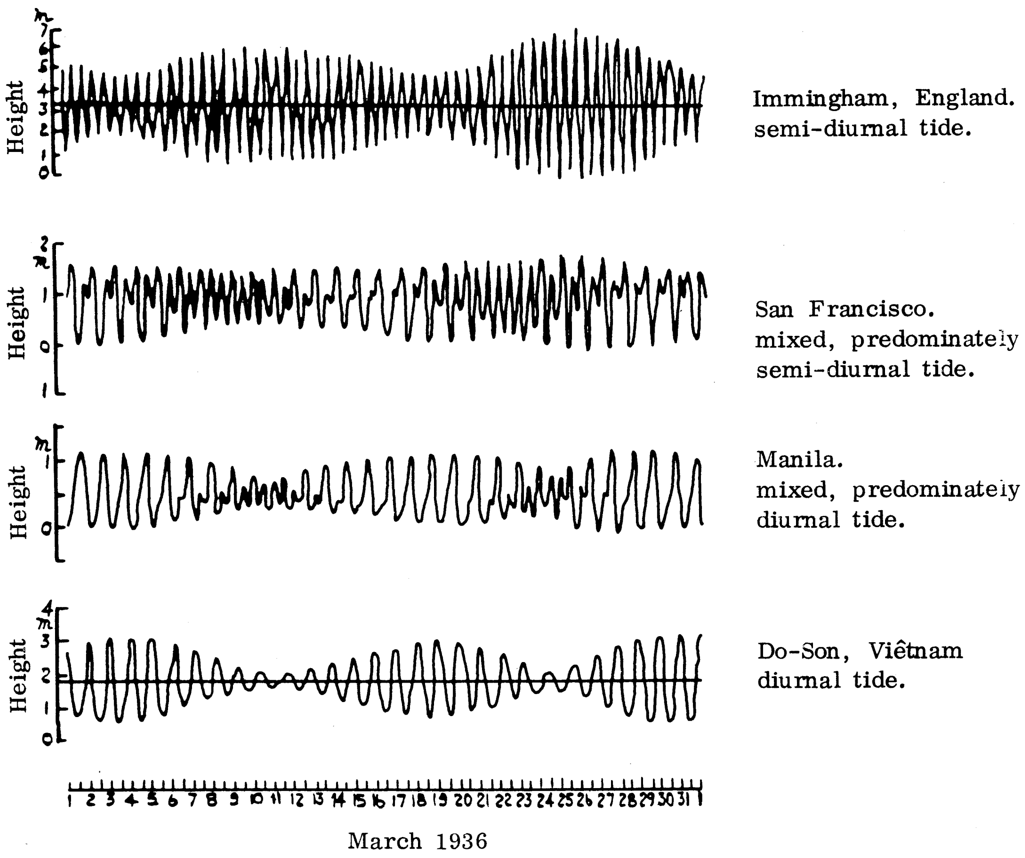
The 'equilibrium' tidal theory was first developed by Sir Isaac Newton in his book "Principia". Galileo had, prior to Newton, given a good empirical account of tides but his theoretical analysis was faulty. Bernoulli vindicated the Newtonian theory in the eighteenth century and the accepted theory became the Newton-Bernoulli equilibrium theory of tides. Since this time the theory has been challenged by Laplace, with his dynamical theory of tides and by Kelvin, who attempted to modify severely the Newtonian theory. Both these challenges were endeavouring to reconcile the huge discrepancy between theory and observation, but both failed. The Newtonian model is, however, sufficient for the purposes of this paper and further details can be found in Darwin (1898, pp. 135-147) and Tricker (1964, pp. 4-13). The latter offers a particularly good elementary mathematical treatment. More modern tidal theory is dealt with at a popular level by Russell and Macmillan (1952, pp. 214-251), and more rigorously by Dean (1966). Reservations as regards the whole of present-day tidal theory have been expressed by Michelson (1974).

Tides in practice

Tides are, in reality, waves with a typical period of twelve hours twenty-five minutes, and with a wavelength of half the circumference of the earth, about 21,300 kilometres. From the equilibrium tidal theory of Newton the maximum and minimum tidal ranges at the spring and neap tides can be calculated as seventy-nine cms. and thirty-one cms. respectively (Pattullo. 1966, p. 917). The spring tide is that which occurs when the tides induced by the sun and moon reinforce each other, while the neap tide occurs when the two tides are in opposition. These extremes should only be found where the sun and moon can be directly overhead; elsewhere the variation in tidal range should be more restricted. Values similar to the calculated ones are found on isolated oceanic islands, where the tidal range is between ninety and sixty cms (Darwin, 1898). Elsewhere in the world the observed tides have little in common with those of theory.

Two classes of effects lead to the departure from theory. First, physical conditions and constraints on earth act in ways that create diversity; amplification of tidal range due to resonance effects takes place, for example, in the Bay of Fundy (Swift, 1966); amplification due to water depth shallowing is found in narrow seas, estuaries and on broad continental shelves, while meteorological tides can arise from high winds. All these agents act in localised areas, whereas the second class of effects, contributing to worldwide tidal variations, are more systematic. These are astronomical effects, caused by the complex motions of the sun and the moon, coupled with geographical variations due to the tide inducing bodies being at different elevations with respect to different latitudes on earth. The forces causing the tides can therefore be broken up into numerous separate components. These components can be classified into three groups on the basis of their periodicities: long-period, diurnal and semi-diurnal. The relative importance of these groups varies geographically, with a tendency for low latitudes to exhibit semi-diurnal tides (Pattullo, 1966, p. 914, his fig. 3), so monthly tidal curves show markedly different patterns from one place to another. For example, text-fig. 5 shows tidal curves from four different areas of the world illustrating these variations. Marmer (1926, pp. 61-75) considers the above variations at greater length.

The totality of the above effects results in worldwide variations in tidal range of two orders of magnitude: from twenty cms in enclosed basins such as the Mediterranean Sea to nearly twenty metres in the Bay of Fundy (Pattullo, 1966, p. 919). Variations in tidal



Text-fig. 5. Tidal curves for various tidal groups. The heights refer to arbitary zero points for each location. (After Pattullo, 1966).

periodicity along the complete spectrum from diurnal to semi-diurnal tides also exist. With such variability being found today, any changes in tidal range over geological time would obviously have to have been of several orders of magnitude to be picked up unambiguously in the geological record.

Tidal sediments today

Tidal sediments are those sediments which possess a majority of depositional and sedimentary features which are the result of tidal action. Environments in which tidal sedimentation is important are beaches, tidal flats and shallow marine deposits. Beaches are strongly overprinted with the effect, however, of wave action. More importantly, the dominant waves which rework sediments on beaches are produced by storms and therefore of meteorological origin. Shallow marine sediments are influenced by the interaction of waves, tides and oceanic circulation (Allen, 1970, p.150; Kukal, 1971, p. 210). Tidal flats are usually protected from both wave action and oceanic circulation due to their situation in bays, and represent the only areas where sedimentary patterns are almost solely attributable to tidal causes.

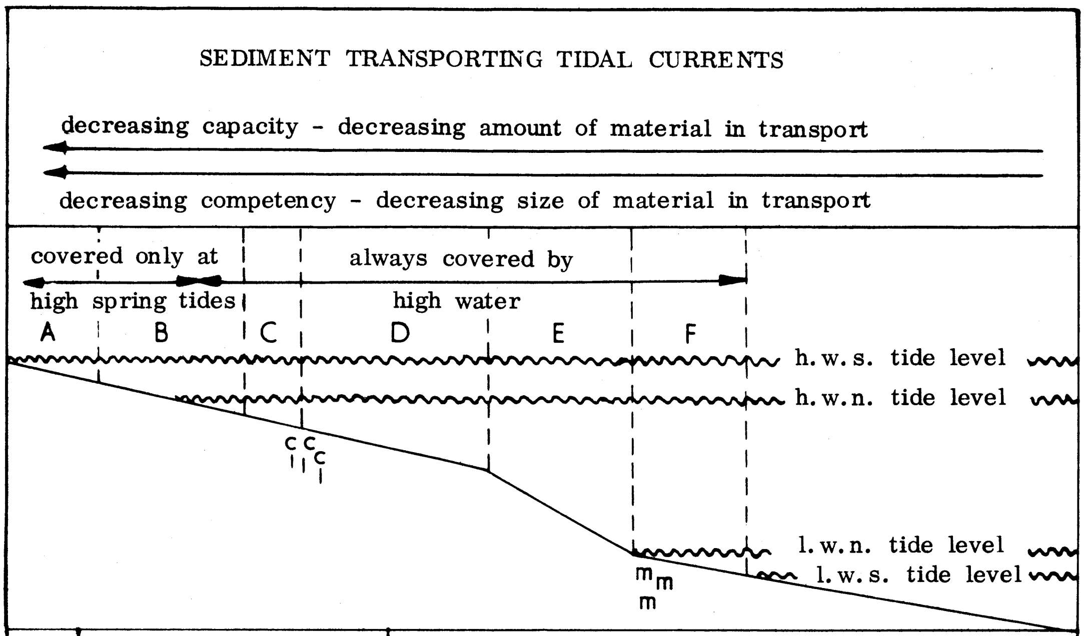
Tidal flats are marshy or muddy areas which are covered and uncovered by the rise and fall of the tide. They occur today only on submergent coastlines with a constant or recurrent positive movement of sea-level (Kukal, 1971. p. 264). Examples of modern tidal flats include the Wash of eastern England (Evans, 1958, 1965), the Bay of Fundy in Nova Scotia (Klein, 1963a., 1970a) and the Wadden Sea of the Netherlands and Germany (Van Straaten, 1961; Reineck, 1969). All other areas of tidal flats lack comprehensive study. The Wash and Wadden Sea show very similar tidal ranges, whereas the Bay of Fundy is dissimilar in this respect and so may be expected to exhibit markedly different sedimentary characteristics.

These areas are all clastic dominated sedimentary environments, little work having been done on those with carbonate precipitation. Both Klein (1967) and Evans (1970) consider that, despite the great differences in origin of clastic and carbonate sediments, the patterns of dispersal and the resulting sedimentary facies patterns show striking similarities for like tidal ranges. In the case of the carbonate environments, the tidal marsh zone appears to be replaced by broad sabkhas and supratidal areas in which penecontemporaneous dolomite is formed. Since this paper was prepared, Lucia (1972) has presented his work on carbonate shore-line sedimentation. Both clastic and carbonate areas show a general decrease in grain size landwards. Table 1 lists the rock equivalents for clastic and carbonate rocks in tidal flat environments.

Table 1 Comparative clastic and carbonate rock types found in tidal flat environments

Clastic	**Carbonate**
Sandstone	Limestone consisting of sand-sized particles
Siltstone	Limestone consisting of silt-sized particles
Mudstone	Dolomite
Coal	Evaporites

Research on the above named areas indicates that intertidal sedimentation is characterised by a distinct zonation of sedimentary environments from high to low tide level. The sedimentary zones are crosscut by deposits associated with tidal creeks. The sediments of each zone can be distinguished on the basis of composition, texture, sedimentary structures and included organisms. Evans (1965) identified six sub-environments in the intertidal environment of the Wash, excluding tidal creeks. These are shown in text-fig. 6, where brief characteristics of the sedimentary environments are also given. In the southern North Sea of the Netherlands and Germany four sub-environments have been distinguished (Van Straaten, 1954a; Van Straaten and Kuenen, 1958; Reineck, 1963, 1967). These two classifications are



A	salt marsh	no reworking by waves or organisms; fairly slow sedimentation; sediment bound by plants; filter effect on plants
B	higher mud flats	very limited reworking by waves & organisms; fairly rapid sedimentation; sediment bound by algae.
C	inner sand flats	limited reworking by waves; extensive reworking by *corophium*; slow sedimentation.
D	*Arenicola* sand flats	extensive reworking by waves & *arenicola*; slow sedimentation.
E	lower mud flats	little reworking by waves or organisms; rapid sedimentation.
F	lower sand flats	little or no organic reworking, minor wave-action; strong tidal currents slow sedimentation.
c	*Cardium edule*	organisms extracting suspended clay from seawater (l.e. filter feeders).
l	*Lutraria elliptica*	
m	*Mytilus edulis*	

h.w.s. - high water spring
h.w.n. - high water neap
l.w.s. - low water spring
l.w.n. - low water neap

Text-fig. 6. A schematic representation of the six sub-environments and the dynamics of sedimentation in the Wash. (Source Evans (1965), with permission of the Geological Society of London).

compared in text-fig. 7 and shown to be broadly similar. Each sub-environment grades into adjacent ones. Text-figs. 6 and 7 show the relationship of the sub-environments and the tidal levels.

The mechanism of tidal sedimentation was divided by Van Straaten (1961) into two types: 'lateral' and 'vertical'. The former occurs predominately in lower tidal flat areas on the sides of migrating channels and gullies and results in beds that are gently inclined. Deposition is rapid, but ephemeral due to subsequent erosion. Reineck (1960) estimated that only 1/10,000 to 1/100,000 of sediment deposited in tidal flat areas is, in fact, eventually preserved. Vertical sedimentation is found mainly on the higher parts of tidal flats, outside the influence of the shifting gullies and channels, and consists of a slow accumulation of sand and mud, the sand often being supplied by current ripple migration from gullies. The two mechanisms are shown in text-fig. 8, which also illustrates other facets of the tidal flat environment. Lateral and vertical processes of sedimentation are not mutually exclusive; both often occur together.

Klein and Sanders (1964) consider the distinctive features of tidal flat sediments result directly from the intensity of the reworking mechanisms, which consist of Van Straaten's lateral sedimentation and organic activity. The importance of bioturbation in the zone of vertical sedimentation should not be disregarded. Van Straaten (1952) estimated that the entire layer of sandy sediment above the feeding level of organisms is reworked every twenty months.

Van Straaten and Kuenen (1958) postulated two mechanisms which work in tandem to explain the seaward coarsening of sediments mentioned above. These two mechanisms are *settling lag* and *scour lag*. The first is particles settling out from a waning current, which are not deposited vertically but carried along in the current direction a distance proportional to the settling velocity of the particle in question from the point at which the current is no longer competent to carry the particle. Scour lag occurs because the maximum current velocity which allows sedimentation is lower than the minimum current velocity needed for erosion of the same material to take place. This means that once a particle is deposited on a waning current it will not become re-entrained when a current sweeps over it with the same velocity as that of the current which allowed deposition to occur.

The Wadden Sea and Wash having been compared, the Bay of Fundy can now be shown to be notably different. Klein (1967) went as far as to divide intertidal sediments into two distinct groups, Wadden-type and Fundy-type. The tidal flat environment in the Bay of Fundy consists of four sub-environments (Klein, 1963a). These sub-environments will be briefly described as, unlike those of the Wash and Wadden Sea, they cannot easily be represented diagrammatically. The four sub-environments are as follows:

1. Wave-cut Benches

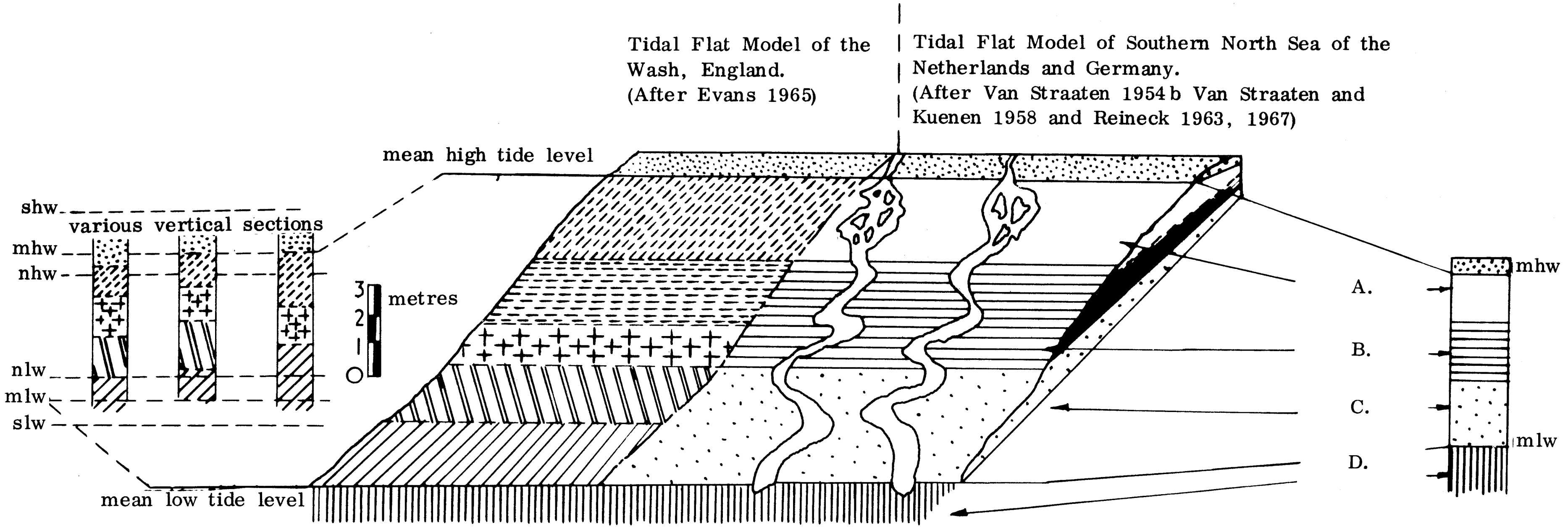
Tidal sediments in this environment constitute seventy-five per cent of the total and are formed by the undercutting of sea cliffs. Only a thin veneer of sediment is present on the benches and this correlates very closely in type with the underlying bedrock. The dominant action here is wave motion and this results in the widespread occurrence of oscillation ripples. Rhombic shaped interference ripples are also characteristic, with near shore clay accumulation. (Van Straaten and Kuenen, 1958).

2. Estuarine Clay Flats

These sediments consist of clay and silt with rare shells. No stratification or ripples can be seen, except for a few oscillation ripples near the high tide mark.

3. In the lee of bedrock islands

The sediments of this environment are closely analogous to the tidal flats of the Wadden Sea, and sediments similar to both the high and low tidal flats of the Wadden Sea can be distinguished. In this environment are found the only examples of lateral sedimentation in the whole Bay of Fundy area.



Key

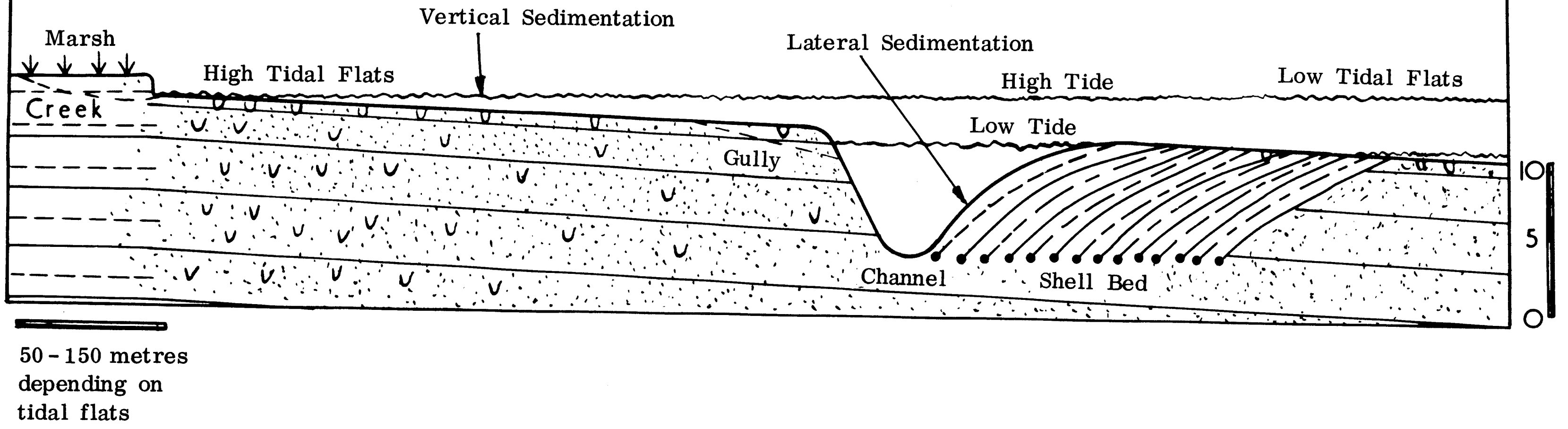
░	salt marsh	▨	lower sand flat
▒	high mud flats	☐	high tidal flat - mud
▦	inner sand flats	☰	mid-flat - interbedded sand and mud
✚	*Arenicola* sand flats	⁚	low tidal flat-sand
▧	lower mud flats	▥	subtidal sand

Abbreviations

shw.	spring high water	slw.	spring low water
mhw.	mean high water	mlw.	mean low water
nhw.	neap high water	nhw.	neap low water

A. Suspension Dominant Transport
B. Transitional Transport
C. Bedload Dominant Transport and Emergence Run Off
D. Bedload Dominant Transport

Text-fig. 7. A sedimentary model for determining tidal range in the past. Clastic intertidal sedimentation models of the north sea coast of the Wash and the Netherlands and Germany. (After Klein 1971, with permission of Geological Society of America).



Text-fig. 8. Vertical and lateral sedimentation in tidal flats; in this idealised cross-section of a tidal flat environment, V shows the varying intensity of bioturbation on sediment structure in high parts of flats (with slow, continuous deposition), and in low parts of flats, where sediments are frequently reworked by shifting gullies.

4. Tidal Marsh

The Bay of Fundy tidal marsh sediments exhibit little evidence of stratification, but otherwise resemble those of the Wadden Sea.

The differences between the Wadden Sea tidal flats and those of the Bay of Fundy are manifest but the underlying cause of these differences is not quite so obvious. The traces of what appears to be Wadden-type sedimentation on the sheltered sides of bedrock islands suggest that a large part of the explanation can be attributed to the higher current velocities in the Bay of Fundy which result from the higher tidal range. Klein (1967) lists a number of factors thought to influence sedimentation in coastal areas, such as bottom slope, tidal range, fetch, coastal morphology, climate, organisms, and long term position of the sea. These factors and also provenance are compared for the three areas of the Wash, the Wadden Sea and the Bay of Fundy in table 2.

The table illustrates clearly that tidal-range and provenance are the two factors which differ markedly between the areas. The tidal range is over two and a half times larger in the Bay of Fundy than in either of the other two areas, although the provenance does show a minimum correlation as Pleistocene sediments are present in all three areas. The tidal range is related to current velocity, as the higher the range the greater the volume of water which must be moved in a fixed time, therefore the higher the current velocities. Klein (1970a) records tidal current surface velocities of up to 280 cms sec^{-1} and bottom velocities of 110 cms sec^{-1} in the Bay of Fundy, and concludes that tidal current transport is the dominant process of sand deposition.

Klein and Sanders (1964) in their comparison of tidal flat sediments in the Bay of Fundy and Dutch Wadden Sea did not isolate one factor as determining the differences between the two areas, rather suggesting that the differences were explicable on the basis of the interaction of a number of factors. But the sedimentary environments are so different in the two areas that there seems to be strong support for the hypothesis that tidal range and hence current velocity are the primary factors in determining sedimentary facies in intertidal areas. Obviously other factors do come into play to a limited extent and these may reinforce or weaken the influence of tidal range on the environment: for example, emergent coastlines would reinforce tidal influences.

Table 2 A comparison of the factors effecting sedimentation in three areas of intertidal sedimentation

Factor	The Wadden Sea	The Wash	Bay of Fundy
Bottom Slope	All shallow and similar: 1:100 to 1:450		
Tidal Range	2.8 - 4.5 M (1)	6.7 M (2)	17.0 M (3)
Fetch	All fairly restricted in length		
Coastal Morphology	Low-lying	Low-lying	More prominent
Climate	All cool temperate maritime		
Organisms	As far as known, all similar		
Provenance	Pleistocene from floor of the North Sea (4)	Pleistocene from floor of the North Sea (2)	Pleistocene, Carboniferous and Triassic rocks (5)
Long term position of the sea	Slight transgression	Moderate regression	Slight transgression occurring today

(1) Van Straaten (1961)
(2) Evans (1965)
(3) Swift (1966)
(4) Van Straaten (1954b)
(5) Klein (1970a)

The dominance of tidal influence is very important when looking at tidal deposits in the geological record and this fact will be used later. Swift (1966) concluded that the reason the Bay of Fundy has an atypical tidal range of high magnitude is that the shape of the Bay is such that tidal resonance takes place, enhancing the tidal height by strong reinforcement. This means that the Bay can be considered as a relic tidal flat environment of a past time when, if ever, the tidal range throughout the world was an order of magnitude higher than it is today.

Criteria for identifying tidal sediments in the past

The most obvious way of identifying tidal sediments in the stratigraphical column is by the use of diagnostic sedimentary structures, coupled with other available evidence for origin. Unfortunately there is no unique structure or set of structures which will result in a reliable identification. The best single criterion was considered by Van Straaten (1961) to be the presence of tidal channel deposits. Klein (1963b) distinguished between river, estuarine and tidal channel deposits in the geological past by means of the composition of the coarse grained material or lag found in the channel bottom. River channels contain lag deposits which consist of chips of clay eroded from semi-consolidated clay beds at the time of deposition; estuary channels contain both 'clay-chip' and shell lag deposits, while in tidal channels only shell lag deposits are found.

However, Van Straaten (1961) pointed out that there are few, if any, sedimentological features which taken alone could prove that sedimentary rocks originated in a tidal environment. He concluded that it is necessary to study all the characteristics of a rock, both organic and inorganic - and if possible, the underlying, overlying and adjoining rocks - before coming to a final decision. Klein (1971) holds similar views to those of Van Straaten and considers that sediments deposited by tidal currents can only be identified by a combination of features. In his process-response model, Klein identifies ten phases of tidal sediment transport, in both clastic and carbonate environments, which he considers are characterised by a distinct combination of sedimentary structures, vertical sequences, textures and lithologies. In his table 1, Klein gives in all fifty-nine criteria for recognising tidal sediments. Tidal sediments are subdivided on the basis of structures indicating exposure, evaporation and late-stage emergence run-off prior to exposure.

Other criteria besides those above have been advanced as aiding in the establishment of a tidal origin for certain rocks. Van Straaten (1954b, pp. 88-93) lists factors useful for distinguishing between sub-environments in modern tidal flats, but many of these are equally applicable to indurated rocks. Klein (1970b, his table 2) lists thirty-six factors in a comparison of the lower fine-grained quartzite (Dalradian) of Islay and other rocks from tidal environments. Klein (1970a) and Swett et al. (1971) give thirteen and nine criteria respectively for the characterisation of tidal sediments.

Besides sedimentary structures, other corroborative criteria are available. Palaeontological evidence is often useful, but the reliability of this evidence falls in the Paleozoic, and all but vanishes in the Pre-Cambrian. Trace fossil communities provide another approach. Seilacher (1967) considers trace fossils useful tools in paleobathymetry, suggesting that in very shallow environments protective burrows, which are deep and vertical, predominate over other kinds of trace fossils. These protective burrows constitute Seilacher's skolithos trace fossil facies, characteristic of littoral environments. Two specific trace fossils, *Corophium volutator* and *Callianassa* burrows, thought by Seilacher to be specifically intertidal, however, can be also subtidal.

Geochemical analysis of the trace-element content of rocks is a recently introduced technique, which is thought to indicate paleosalinities. Shaw and Bugry (1966) consider that the higher the boron content in a rock, the higher the salinity of the water in which the sediment was deposited. Other trace-elements besides boron have been proposed as better discriminants, but the state of the art at the moment is such that whichever discriminant is used, great caution is required in interpretation. Krejci-Graf (1964) said of these techniques, " . . theoretical difficulties are not always practical obstacles. . " but these difficulties do tend to be rather disconcerting.

With the above variety of criteria available, there would seem to be little difficulty in unambiguously identifying tidal environments in the geological record. However, a number of problems do arise. Firstly, ancient and modern environments cannot be studied in the same way (table 3); secondly, diagenetic modifications of sedimentary rocks with age may have altered the characteristic features beyond recognition; thirdly, organic activity has changed over geological time; and fourthly, tidal variations may, with time, have been such as to cast doubt on the applicability of the Huttonian Principle of Uniformitarianism. Nevertheless, bearing in mind these reservations there does at least seem to be a reliable base of criteria for the identification of tidal sediments.

Table 3 Limitations inherent in research methods for comparing ancient and modern environments

Recent Sediments	**Ancient Sediments**
Mainly occur as thin layers over large areas	Mainly vertical sections of restricted horizontal extent
Environment studied in a horizontal sense	Lateral facies variation is limited by size of outcrop
Time correlation of sedimentary deposits by age is easily established	Time correlation is virtually impossible
Environment is complete in the spatial aspect	Environment normally found as sporadic outcrops which may grossly misrepresent original proportions of various facies

(Modified from Kukal ((1971, his table 200))

Paleotides from theory

The basis of tidal theory is Newton's Law of Gravitation which is encapsulated in equation (1), F being related to tidal height, as explained in the section concerning the causes of tides.

$$F = \frac{GMm}{r^2} \qquad (1)$$

F = force
G = the Universal Gravitational Constant
M = the mass of the tide inducing body
m = the mass of the particle being affected
r = the distance away of the tide inducing body

If m is assumed to be a constant of unit mass, it can clearly be seen that a change in any of the other physical properties on the right hand side of the equation will affect property F. A number of theories have been proposed which imply changes in the physical parameters in question. These will now be considered and the resulting effects on paleotides evaluated.

G - the Universal Gravitational Constant

Variation in G was first proposed by Dirac (1937, 1938) who suggested that G was inversely proportional to the age of the universe. Since then, further research has led to a position where four alternatives need consideration: first, G is constant; second, Dirac and Jordan's hypothesis that G is decreasing by 1 or 2 parts in 10^{10} per year; third, the Brans-Dicke and Hoyle-Narlikar hypotheses which require a decrease of between 1 and 5 parts in 10^{11} per year (Wesson, 1973); and fourth, that G varies as a function of both time and space (Steiner, 1967). This last suggestion implies that an oscillation in the value of G, occurs superimposed on its secular decrease.

From astronomical data available of solar eclipses in the Pre-Christian era, Dicke (1966) calculated that, at the earth's present rate of deceleration, allowing for tidal friction which will be discussed later, G was decreasing by 3.8 parts in 10^{11} per year. Stewart (1970, 1972) suggested a number of gravity sensitive geological indicators, including sediment compaction, diaper movement and change in depth of fossil footprints, but all he could conclude was that if G was changing, it had been changing by less than 4 parts in 10^8 per year over the last twenty-six million years. Wesson (1973), in a lengthy review article concerning cosmologies with implicit G variations, was unable to conclude that G was even varying. It therefore seems that, if G has been decreasing, the rate has been very low - around 3 or 4 parts in 10^{11} or less.

Table 4 illustrates the effect, changes in G of this rate, would have had on tides in the past. The results given in the table are based on equations (2) and (3). The first is given by Dicke (1962a, p. 46) and the second by Alfvén and Arrhenius (1969).

$r \propto 1/G$ (2) r is the distance away of the tide-inducing body

$f \propto (Ro/R)^3$ (3) f is tidal height

Ro is distance away of the tide-inducing body today

R is distance away of the tide-inducing body in the past

Table 4 Paleotides compared with those of today, assuming G to be changing constantly at the rate postulated by Dicke (1966)

	Today	0.6 aeons ago (1)	3.0 aeons ago
G	1.00	1.02	1.11
Earth Moon distance	1.00	0.98	0.90
Earth-Sun distance	1.00	0.98	0.90
Tidal height	1.00	1.07	1.38

(1) Throughout this paper 1.0 aeon equals 10^9 years
Today's values are all taken as unity, and the tidal heights derived are those of the theoretical equilibrium tide

The assumption made in deriving the figures in table 4 is that the contraction of the earth's radius in the past due to G being higher was negligible. This assumption is supported by Dicke (1962b) who gives equation (4):

$$dr = 0.1\ ((Go - G)/G) \quad (4)$$

dr is change in earth's radius compared to today

G is value of G in the past

Go is value of G today

With the rate of change of G postulated, the change in radius of the earth would have been negligible in its effects on tides. Therefore, accepting the value postulated by Dicke as indicating an upper limit as regards the rate of change of G, it has been shown that tides in the past are unaffected on a significant scale.

M - the mass of the tide inducing body

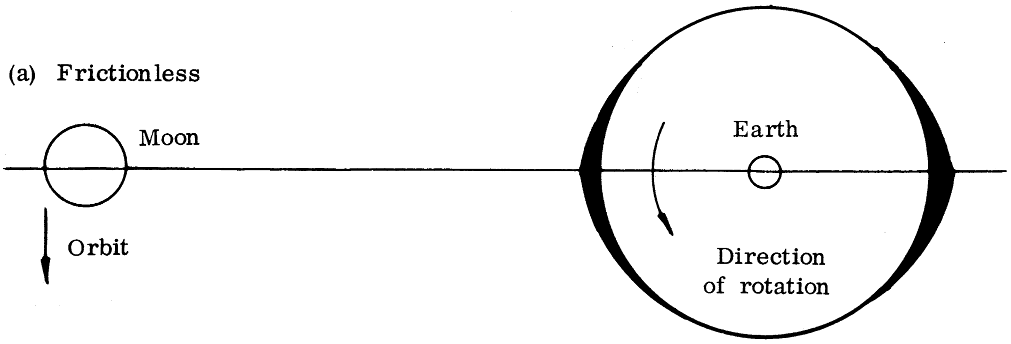
A significant increase in mass of any of the bodies in the solar system due to meteoric bombardment and cosmic dust settling has been discredited by Garrels and Mackenzie (1971, p. 111). Kapp (1960) put forward a theory which suggested all mass concentrations in the universe were losing mass fairly rapidly due to a constant creation of matter per unit volume and a constant extinction per unit mass. The rate proposed meant that the earth, sun and moon would have had masses of between ten and one thousand times their present mass four aeons ago. Holmes (1965, p. 985) pointed out that the implied volume change was far too high to be geologically acceptable. Wesson (1973, p. 9) neatly summarises present opinion when he says Kapp's theory is almost certainly wrong, while other theories postulate rates of continuous matter creation which are insufficient to affect the mass of the moon or earth noticeably. Hence mass changes with time have not significantly affected tides.

r - the distance away of the tide inducing body

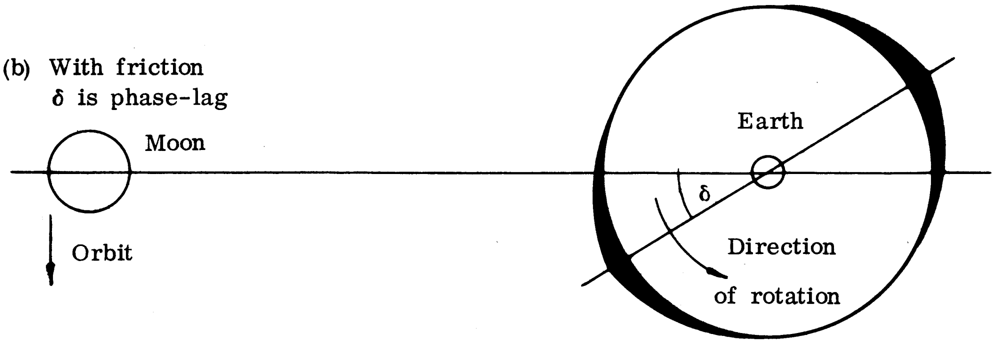
Theory

Since George Darwin's work (1879, 1880) it has been known that the distance between the earth and the moon has been changing, at least on the geological timescale. The reason for this change is illustrated in text-fig. 9. The upper diagram shows the situation which would prevail if the earth was perfectly elastic in its solid parts and perfectly fluid in its liquid parts. The tidal bulges would then be in perfect alignment with the line between the centres of the earth and moon, and no torque would be introduced into the system. However, as friction accompanies tidal deformation, the rotation of the earth causes the tidal bulges to be carried forward, resulting in the situation as shown in the lower diagram. This means that tides are not highest when the moon is directly overhead but at some earlier time.

(a) Frictionless



(b) With friction
δ is phase-lag



Text-fig. 9. A schematic representation of the mechanism causing tidal friction. The diagrams are greatly exaggerated.

The gravitational attraction of the two bulges is therefore asymmetrical to the line of centres. There is a stronger forward attraction from the bulge nearest the moon than a retarding one from the bulge furthest away and this results in a torque on the earth and an equal and opposite torque on the moon. This main pair of torques is supplemented by subsidiary ones, induced in the system by the mutual interaction of the earth, sun and moon. The net result of all these torques is that the earth's rotation is slowed but, more significant from the paleotidal aspect, the moon is hurried on in its orbit, in consequence spiralling very slowly out into space. As the moon retreats from the earth, the tidal range will decrease in consequence. Two popular accounts are given by Darwin (1898, pp. 238-284) and Kopal (1971) of tidal friction; its occurrence within the solid earth has been proposed by Bostrom (1971) as a mechanism for continental drift.

Results

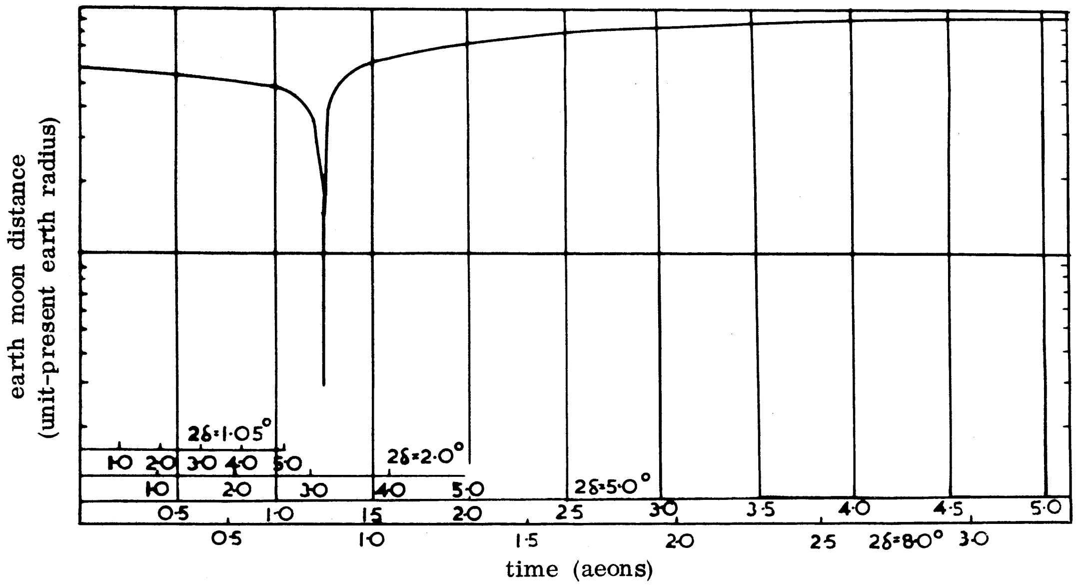
Attempts have recently been made to extrapolate back from the present in order to sketch the dynamic history of the moon's orbit. The calculations indicate that at some period in the past a close approach of the moon to the earth took place. When this happened, it is thought that the inclination of the moon's orbital plane to that of the earth increased rapidly, resulting finally in the orbital plane of the moon passing over the earth's poles - an event which would convert the moon's prograde orbit into a retrograde one. Once in a retrograde orbit, tidal friction begins to work in reverse and so, as extrapolation back continues, the moon recedes from the earth. This can be seen by imagining that the moon's orbit, as shown in the lower part of text-fig. 9, is the reverse of that shown. Then the closer tidal bulge would be slowing it down while the more remote bulge would be attempting less successfully to accelerate it.

Gerstenkorn (1955, 1967), MacDonald (1964), Goldreich (1966), and Chevallier and Cailleux (1972) all accept the concept of a close approach by the moon, differing only in regard to when and at what distance this happened. Gerstenkorn (1955) stated that the calculations indicated that the moon must originally have been captured in an extended retrograde orbit. The results of Gerstenkorn's and MacDonald's calculations are shown in Table 5. Text-figs. 10 and 11 show the earth-moon distance and the length of the month in the past from some other calculations by MacDonald (1966). The tidal heights have been calculated by the author from the distance data using equation (3). The results cited in the table correspond closely with those of Goldreich (1966) and Gerstenkorn (1967), the main reason for the differences observed being the various assumptions made about the past value of the phase lag. This is the angular amount by which the tidal bulge is ahead of the moon in its orbit. This is shown in the lower half of text-fig. 9 as the angle δ.

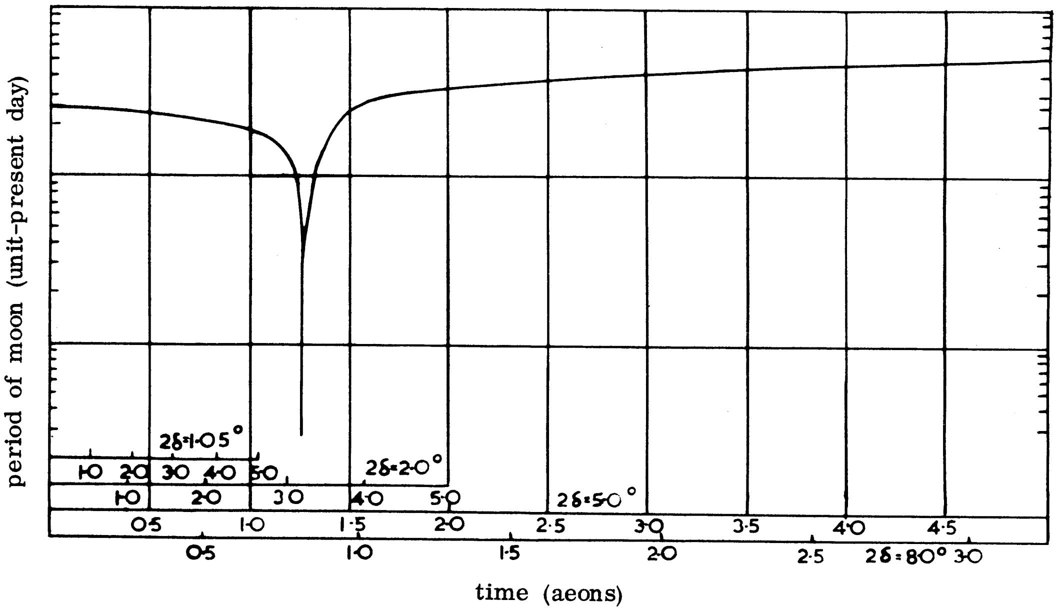
Table 5 Parameters postulated for the close approach of the Moon

	Time of closest approach (in Aeons)	Distance at this time (in earth radii)	Length of day (in hours)	Length of month (in hours)	Tidal height (today's equilibrium tidal height taken as unity)
MacDonald (1964, his table 2)	1.8	2.72	4.9	30.2	11,300
Gerstenkorn (1955)	1.4	2.89	4.8	6.8	9,400

The only arguments that have been advanced against tidal friction are those of Engels (1880), which today would be considered invalid, and that based on magnetohydrodynamic theory. This is the study of the motions of electrically conducting fluids in the presence of electric and magnetic fields, and it does suggest that it might be possible for energy transfer to take place between parts of the solar system without affecting the angular momentum of the



Text-fig. 10. The earth-moon distance in the past. (After MacDonald, 1966).



Text-fig. 11. The length of the month in the past. (After MacDonald, 1966).

individual bodies. This theory is described fairly simply in Dungay (1958), but the implications for tidal friction are obscure. Observation apparently shows that tidal friction has occurred at the rates postulated and astronomers working on the earth-moon system continue to ignore magnetohydrodynamic theory.

The work of Wells (1963), Scrutton (1964) and others on growth rings in fossils lends credence to tidal friction (text-fig. 12). This shows the length of the day based on paleontological evidence since the Cambrian, along with theoretical values derived on the basis of a number of alternative sets of assumptions. The reason these results are important is that the earth's rotation is arrested simultaneously with the acceleration of the lunar orbit, and so evidence of the former supports the hypothesis of tidal friction being an agent in altering the moon's orbital radius.

Problems

Two points of criticism arise: firstly, a common supposition is that the phase lag was always constant in the past. Different values are put into the calculations (text-figs. 10 and 11) but not ones that vary with time. Today's value is thought to be 2.25°. (MacDonald, 1966, p. 180). The phase lag depends on the amount of friction occurring at any one time and this is attributable to two components: that due to bodily tides, and that due to tidal dissipation in shallow seas. Munk (1968, p. 357) considers two thirds of tidal friction today to be that occurring in shallow seas, and suggests that this proportion might change in step with the variation in the area of shallow seas throughout the world. Pannella *et al.* (1968) produce evidence for a variation in phase lag with time (text-fig. 13), showing that the rate of change of the synodic month has not been constant, the synodic month being the interval between two successive full moons. If the phase lag had been constant, it would have been expected that the rate of change of the synodic month would also have been constant. Therefore the time-scale could be significantly in error. Alfvén and Arrhenius (1969) suggest that phase lag today is an exceptionally high value.

The second point of criticism is that the moon may have joined the system more recently than the postulated time of close approach. If this was so, that awesome period in earth history, with 7 km. high tides sweeping round an earth with a five hour day and accompanied by a moon having a seven hour polar orbit obliterating half the sky, may have been avoided. This would imply a non-catastrophic origin of the earth-moon system, as there are no signs in the geological record of a recent catastropic origin. A number of these non-catastrophic theories are considered, along with their implications for paleotides, in Table 6, (p. 225).

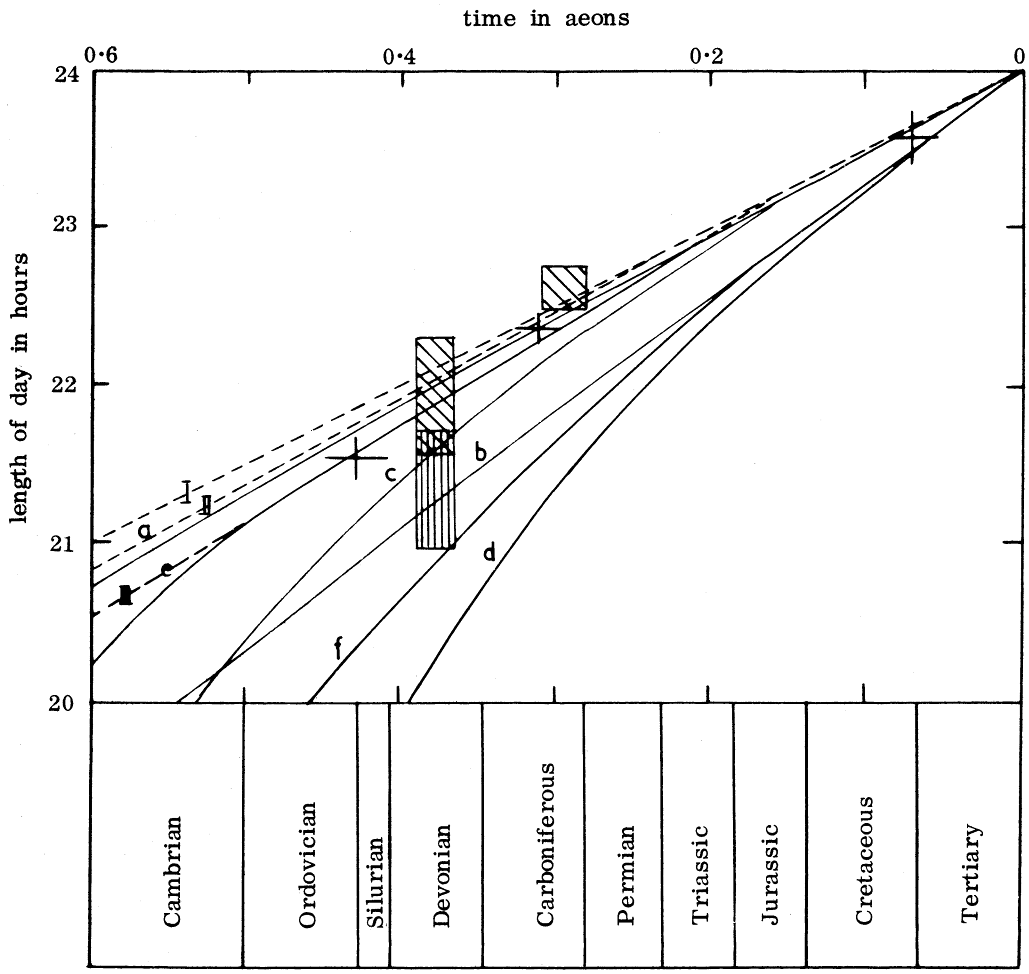
The tidal ranges given in Table 6 are obviously at a maximum at the time or origin of the system, and begin to decay immediately with the action of tidal friction.

All the variable factors in equation (1) have now been considered, but one other factor needs examination:

Variation in tidal force due to an expansion of the Earth

The explanation why earth expansion is a factor influencing paleotides can be seen by looking again at text-fig. 1 (p. 206). Should the earth expand with time, the distance AB would decrease while the distance AE would increase, combined with an increase in the angle OAE. These effects would result in an increased equilibrium tidal height, as the horizontal tide generating forces shown in text-fig. 3 would be strengthened, provided the orbits of the tide inducing bodies remains unchanged.

Two hypotheses have been proposed which require an expansion of the earth. First, Halm (1935) suggested that the earth's original density was much higher than today's and, since the time of formation, the material constituting the earth has been expanding in volume and decreasing in density. Geological evidence in support of this hypothesis was given by

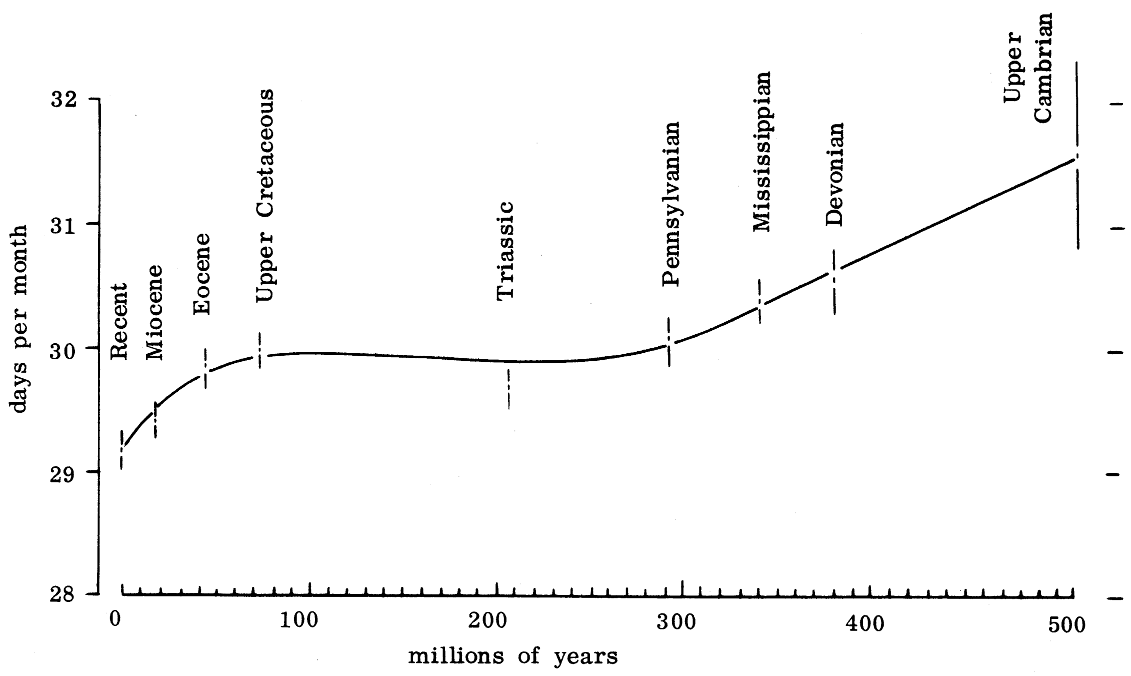


▨ Wells (1963) Results

▥ Scrutton (1964) Results

\+ Unpublished Results of Wells (From Munk (1968, fig. 3)
and for Cretaceous result Berry and Barker (1968)
Lines a to f from Lamar and Merifield (1967
Lines I - III from Munk (1968)

Text-fig. 12. The length of the day from fossil evidence, with some plots of the theoretical variation with various tidal friction models. (After Lamar and Merifield 1967) (With permission of the Geological Society of America).



limited eperic seas: wide continental shelves large Atlantic Ocean.	limited eperic seas with no Atlantic ocean: change (in Cretaceous) to widespread eperic seas bordered in part by narrow Atlantic Ocean	very extensive eperic seas adjacent to Pacific Ocean
Cenozoic	Mesozoic	Paleozoic

Text-fig. 13. The variation in the length of the synodic month. (Source: Pannella *et al.* (1968), with permission of *Science*. Copyright 1968 by the American Association for the Advancement of Science).

Table 6. Some non-catastrophic theories concerning the origin of the earth-moon system and the implications for paleotides

	Time ago (in Aeons)	Distance (in earth radii)	Tidal height (1)
GOLDREICH (1966)			
Formation of the moon by the accretion of many small satellites ...	1.5 (a)	10 - 30	150 - 5.0
MACDONALD (1966)			
(a) Captive in an extended prograde orbit ...	1.0	40 - 45	2.5 - 2.0
(b) Moon formed by accretion of 6 - 10 small satellites ...	1.1	40	2.5
GERSTENKORN (1967)			
Capture, without the aid of tidal friction in a prograde orbit ...	1.0 (2)	30 - 45	5.0 - 2.0
ALFVÉN and ARRHENIUS (1969)			
Protracted evolution of the orbit, as close approach prevented by resonating periods of orbit of moon with earth's rotation period ...	1.0 - 2.0 (2)	10+	less than 150

(1) Tidal height compared to today's equilibrium tidal height, which is taken as unity, the height in the past being determined by equation (5).

(2) Not given in paper in question, but estimated by author.

$$f = 5/16 + 11/(16r^3) \qquad (5)$$

f = tidal height in past

r = distance of tide inducing body from the earth, if today's distance is considered as unity.

Egyed (1956). If expansion had taken place, the length of the day would be increasing, and Holmes (1965, pp. 972-974) uses Wells' (1963) data on growth rings in corals, which suggests a 401 day Devonian year as support for the expanding earth model above. The work of Wells and others on growth banding in fossils is now considered as evidence in favour of tidal friction, and Halm's hypothesis has now been superseded by the second hypothesis in favour of earth expansion.

This second hypothesis is that previously examined under the heading "G - The Universal Gravitational Constant'. Any decrease in G would result in an expansion of the earth accompanied by a partially counterbalancing expansion in both the moon's orbit and the earth's orbit around the sun. But, as was noted in the above-mentioned section, Dicke (1962b) concludes that changes in G were too small for this effect to be noticeable in changing tidal heights. The question as to whether or not the earth is expanding is of no concern here. Even accepting that G is varying at the rate suggested by Wesson (1973), for instance, tidal heights are unaffected to the extent required for unambiguous recognition of this quantitative change in the geological record. This can be seen by comparing the tidal heights given in Tables 4 and 5. If variations in G led, in total, to increases in tidal heights of ten or one hundred times greater than those envisaged in Table 4, they would still be barely distinguishable from tides of today. This expansion would, however, produce a whole range of other effects on the rock record. Jordan (1971) has discussed these at length.

In conclusion, it can be seen that, of these theories which have been discussed with regard to their effects on tides, the one with the major effect is that related to tidal friction. The various theories on the origin of the earth-moon system involved a change in the height of the tides ranging from 2.0 to 11,300 times today's value. Although it would be impossible to detect changes at the lower end of this scale, it should be possible to put some constraints on these figures from geological evidence of paleotides.

Ancient Tidal Sediments

The preservation potential of tidal sediments is thought to be very low (Kukal, 1971, p.386). Despite this, numerous examples are known of tidal sediments preserved as rocks. Klein (1970c) states that at least 428 different rock exposures have yielded evidence of being of a tidal or intertidal origin. Here is not the place to discuss these in detail. The vast majority of them have features very similar to those found in the Wadden-type area today (Klein, 1967). The only two ancient counterparts of the Fundy-type area are the worldwide transgression of Cambrian shelf sediments on Pre-Cambrian crystalline rocks, and the shallow marine transgression of Upper Llandovery age in the Welsh borderland (Klein, 1964). A comparison of thirty-one ancient tidal deposits is given by Klein (1970b, his table 2). This great predominance of ancient tidal sediments of a similar type to the Wadden Sea type of today is borne out in the literature (Van Straaten, 1954a; Pannekoek, 1960; Klein, 1967 and Wunderlich, 1970)

The conclusion could be drawn that tidal sedimentation has remained virtually unchanged throughout time. But this may be an over-simplification as two alternative conclusions are possible. First, there exists today a very large spectrum of tidal intensities, evidenced by tidal range variations; this was probably true in former times (Table 8, p. 229), but a certain portion of the spectrum could have a high preservation potential while other parts are rarely preserved. Thus, even if the spectrum of tidal ranges changes, the type of sediments preserved may remain the same. The second alternative is that tidal sediments, which were laid down by exceptionally high tides, are preserved in the rocks record, but that a quantitative change in tidal height leads to a qualitative change in sedimentary features, and hence these deposits fail to be recognised for what they are.

The first possibility, by reason of its negative nature, is not open to discussion, but the second can be examined. The great predominance of quartzites in the early Paleozoic and late Pre-Cambrian could provide evidence of much greater scouring power at this time - the result of higher tides. Klein (1970a); Hargreaves (1970) and Swett *et al.* (1971) all consider these quartzites to be of tidal origin. The genesis of many mineralogically mature marine sandstones could be related to paleotidal processes, in that these sandstones, by being subjected to greatly enhanced scouring action, would rapidly attain maturity (Swett *et al.* 1971). Until recently no satisfactory mechanism was available, but now higher tides in late Pre-Cambrian or early Paleozoic times offer a solution. These quartzites are by no means limited to this part of the geological column, but what has been difficult to explain is their greater abundance at this particular time. Tidal scour is inversely proportional to the sixth power of the distance of the tide inducing body (MacDonald, 1964). So, if at this time the moon was only half as far away as now, the scour would be sixty-four times greater. It is probable that a smaller increase in scouring power than this would be sufficient to solve the quartzite problem.

Paleotides

Initial Research

The first workers to gueest, for geological reasons, that tides might have been higher in the past were Ball (1881) and Hull (1881). Ball's suggestion was that higher tides, owing to their enhanced erosion capacities, would explain the thicknesses of sediments in the Lower Paleozoic; while Hull considered higher tides, for a similar reason, would explain the unconformities at the base of the Cambrian, Devonian and Triassic - although the latter two unconformities are not considered today to be very conspicuous. Eckermann (1937) investigated the possibility of higher tides in the Pre-Cambrian, with inconclusive results.

Recent Work

Olson (1968, 1970, 1972) suggested a close approach of the moon to the earth at the end of the Pre-Cambrian, based on measurements of gravel thickness in the past, implying tides of up to three km. in range. This is illustrated in text-fig. 14, where it can be seen that the trend in conglomerate thickness reaches a peak about six or seven hundred million years ago. Olson, in his 1972 paper, moderates his value for tidal range in the late Pre-Cambrian to 100 m. These conglomerates, thought by Olson to represent tidal deposits in extremely fast currents of up to fifty m. sec^{-1}, have in many cases been described as tillites or tilloids. A tillite deposit is thought of as a deposit of definite glacial origin, whereas a tilloid is a deposit of unknown or questionable origin closely resembling a till.

Schermerhorn and Stanton (1963) give a good example of a late Pre-Cambrian conglomerate in a paper re-interpreting a supposed tillite deposit in the West Congo geosyncline as a tilloid submarine mudflow deposit, but much of their evidence would lend itself to an interpretation along the lines Olson envisages. This would necessitate a re-examination of evidence for a worldwide late Pre-Cambrian glaciation.

One of Olson's other suggestions is that the close approach of the moon would explain the Lipalian interval, an interval immediately preceding the Cambrian which is supposedly missing throughout the world in the geological record. Cloud (1968a) criticised this work for a number of reasons, while Munk (1968) dismissed it by recording that the Lipalian interval has now been bridged in a large number of areas. Olson's papers are the only ones which postulate tidal ranges of anything near the height required for a lunar approach along the lines the tidal friction model gives, but at the moment Olson's work has little support.

Cloud (1968b) suggested that paleotidal heights were around five or six metres in the early Pre-Cambrian. Table 7 shows an updated version of Cloud's results, which were based on stromatolites, domed sedimentary structures of algal origin.

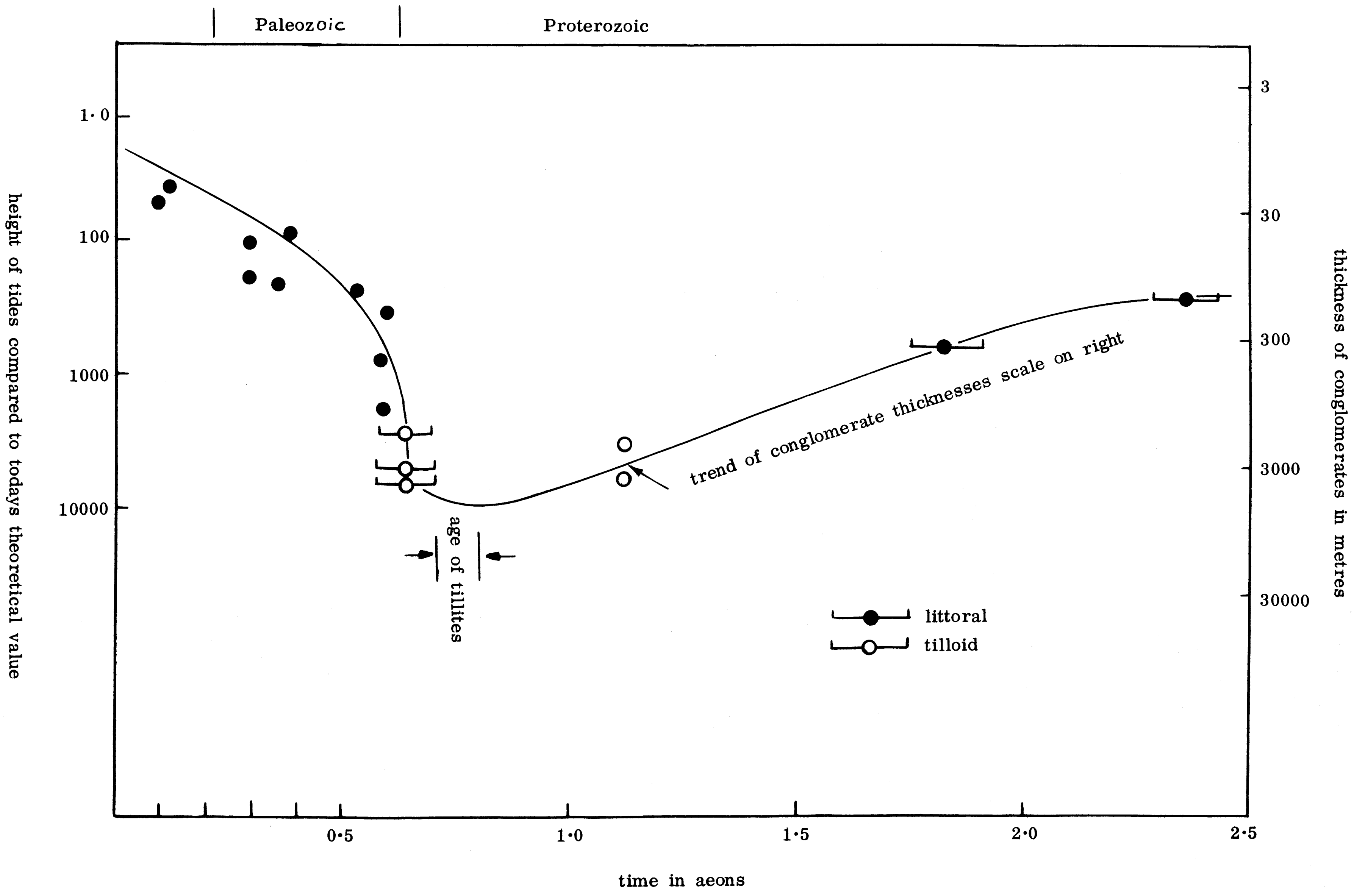
Table 7 Maximum stromatolite heights in the past (after Cloud (1968a)

Age (aeons)		Height (metres)
0.0		0.7
0.5 - 1.1	(1)	6.0
Older than 1.1		5.0
1.5 - 1.7		2.5 - 3.00
Older than 2.0		2.5 - 3.00
1.95 - 2.3	(2)	0.1 - 0.4
Older than 2.7	(3)	0.04 - 0.6

(1) This result comes from the Otavi Series which Cloud (1968b) dates as Proterozoic. Alfvén and Arrhenius (1969) give the age quoted.

(2) Additional result from Button (1971)

(3) Additional result for which Engel et al. (1968) give a figure for the height of 0.04 m, while Walter (1970) disagrees, giving a value of 0.6 m.



Text-fig. 14. Tidal heights in the past, from conglomerate thickness after Olson (1970), his figure 3. Reprinted with permission of the New York Academy of Sciences.

Both Cloud and Kukal (1971, p. 63) assume stromatolites to be intertidal. Caution is needed in the interpretation of Cloud's results for although he claims they are obtained from areas of stromatolites too great to be due to local exceptionally high tides, other objections arise. Walker (1970) argued that stromatolites are sub-tidal and further, he reports a stromatolite fifteen metres high in the Middle Cambrian from near Lake Baikal in Russia. If the specimen is not exceptional, the postulated tidal height should be corroborated in the Cambrian from other sources.

Another problem with using maximum stromatolite heights as a measure of tidal range is that some of these results could be spurious as the area the specimens came from could have been a submergent coastline, which would indicate anomalously high tides. Evidence of English stromatolites on submergent coastlines has been reported by Dr. M. R. Leeder (personal communication). Cloud's results seem therefore to be of use only as a broad guideline, since the criticisms above and the wide spectrum of tidal ranges found today suggest that the fine variations shown by Cloud should not now be taken too literally.

Klein (1972a) has reported some preliminary results of paleotidal ranges, obtained by using the model he published in 1971; these are given in Table 8 :

Table 8 Paleotidal Ranges (after Klein, 1972a)

	Range (in metres)
Late Pre-Cambrian	0.3 - 13.0
Cambrian	1.1 - 7.9
Silurian	3.3 - 6.1
Devonian	1.0 - 8.9
Jurassic	0.8 - 4.1
Holocene (Today)	0.0 - 17.0

The table was based on 428 samples, whose time-stratigraphical distribution was correlated with the length of time represented by various geological periods, i. e. the proportion of samples in any particular period was proportional to the length of the period and nothing else. This suggests that tidal sedimentation has existed since earliest Pre-Cambrian times, 3.2 aeons ago (Klein, 1970c) as this is as far back the sampling went. The results in Table 8 show that tidal range has changed little, if at all, over the period investigated, although Klein does consider that the results show a narrower spectrum of tidal ranges in the past than today (written communication).

Klein's model is illustrated in text-fig. 7 (p. 213). A fining-upward sequence, in prograding tidal-flat deposits, contains a record of tidal range at the time of deposition. The position of the mean low tide is considered to be represented by the sandstone member of the sequence and is found at the contact between sandstones showing features indicative of bedload transport only, and those indicating a combination of bedload transport and late stage emergence run-off features. The mean high water mark is the contact of the sandstones with the overlying tidal marsh. The vertical distance between these two is the mean tidal range. As sandstones compact little, later burial by other sediments should not greatly alter this vertical distance. Olson (1972) and Klein (1972b) discuss this at length.

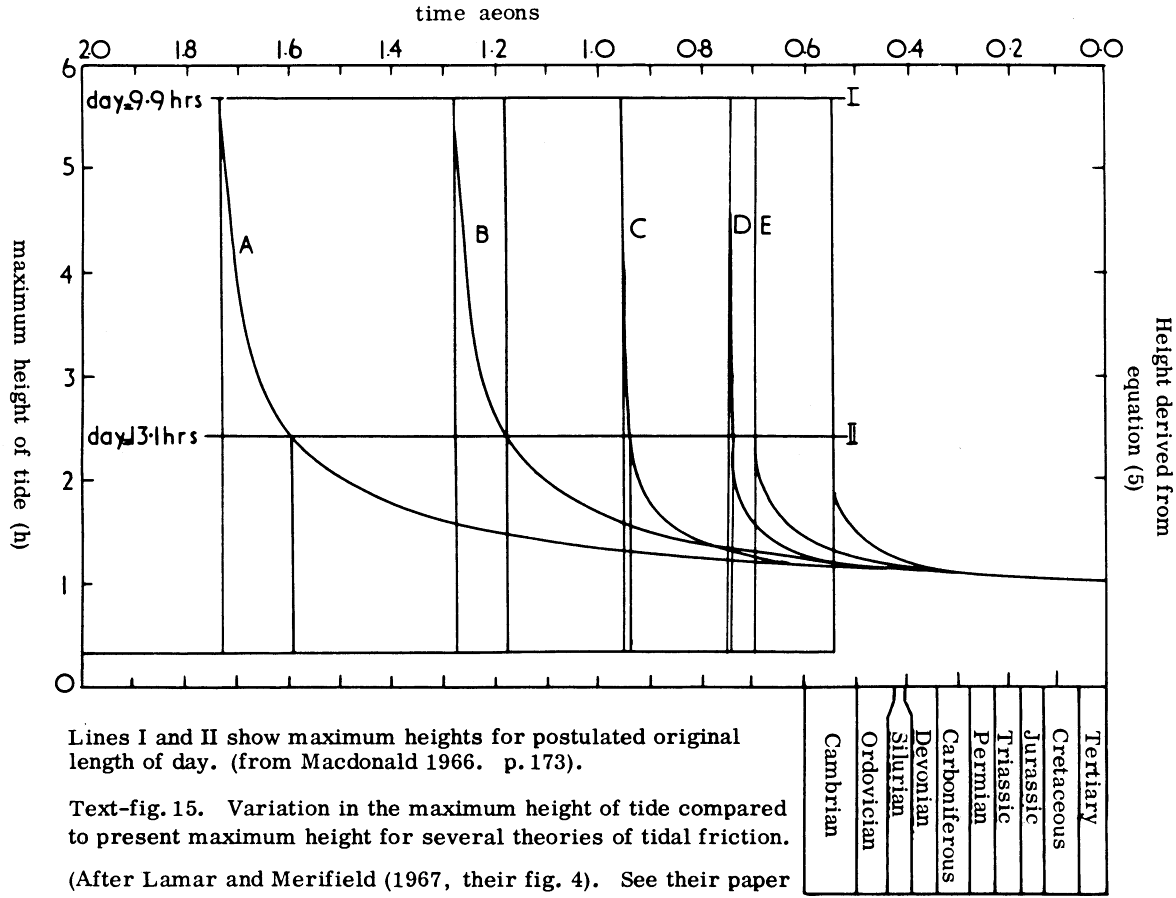
Tides higher than those found today have been postulated as occurring around the end of the Pre-Cambrian (Lamar and Merifield, 1967; Merifield and Lamar, 1968, 1970). In the first of these papers the suggestion is made that the evolution of hard shelled organisms in the Cambrian was a response to the sudden onset of strong tidal currents and exposure at low tide, caused by lunar capture. Text-fig. 15 shows the variation of tidal height with time deduced. The data in the 1967 paper has been slightly modified by Lamar *et al.* 1970.

Support for the idea of higher tides in former times is given by Oparin (1952, p. 98) who suggested that tremendous bodily tides in the Archean caused very deep seated rocks to be erupted, and Trechmann (1955) who suggested that mountain building was linked with lunar gravitation.

The next steps

Klein (1971) has supplied a model for clastic paleotidal ranges, and recently a model has been proposed for carbonate paleotidal ranges. Ginsburg *et al.* (1970) have reported that a zonation of carbonate intertidal areas can be obtained on the basis of organisms, textures, structures and stromatolite morphology. This zonation is linked to the percentage of the year which an area is exposed to the atmosphere, with ninety per cent exposure being considered the high water mark and fifteen per cent the low water mark. Thus, in prograding carbonate intertidal areas, a vertical succession is produced, which like the model for clastic intertidal areas, contains a measure of the tidal range at the time of deposition.

Another approach which offers some hope for the determination of paleotide ranges



Lines I and II show maximum heights for postulated original length of day. (from Macdonald 1966. p. 173).

Text-fig. 15. Variation in the maximum height of tide compared to present maximum height for several theories of tidal friction.

(After Lamar and Merifield (1967, their fig. 4). See their paper for assumptions for various tidal friction models).

(with permission of The Geological Society of America) is by the inspection of growth rings in fossils. Tidal rhythm cycles have been reported by a number of scientists. Barker (1964) identifies five cyclic groupings of growth layers in molluscs, three of which were said to be tidal. These are shown in Table 9:

Table 9 The various rhythms in mollusc growth rings (based on Barker, 1964)

Order	Environmental periodicity reflected
First	Annual changes in temperature and salinity
Second	Equinoctial tides and storms
Third	Fortnightly tidal cycle
Fourth	Day and night
Fifth	Daily tidal rhythm

The work on the periodicities exhibited in the shells of the various fossil phyla can be paralleled by similar studies on stromatolites, which show a characteristic lamination in cross-section (Kukal, 1971, pp. 62-63). In recent forms the laminae consist of either consolidated layers, or fine and coarse alternating layers, indicating a periodicity control. Pannella (1972) claims that monthly tidal growth patterns are recorded in fossil stromatolites as old as 2.2 aeons, indicating that the earth-moon system has been in existence at least since the early Proterozoic. Pannella's results at a more detailed level were inconclusive but the hope remains that stromatolites could become important tools in geochronometry.

This method does have difficulties associated with it. Stromatolites apart, the technique is confined to the Phanerozoic, whilst tides are not quite as beautifully periodic as first imagined (text-fig. 5, p. 209) and mixed tidal areas or an eccentric lunar orbit might yield anomalous results. Finally, in all this work, the length of the year is used as a frame of reference for lower order periodicities and considered implicitly to be constant, whereas it is likely that tidal friction between the earth and the sun is slowly lengthening the year.

Summary and conclusions

The first few sections of this paper are simply reviews of present knowledge in a number of areas associated with the geology of tides. It is only when paleotides and the history of the earth-moon system are considered that the paper departs from being simply a review. This latter section has been approached very much as Rubey (1951) approached his work on the geological history of sea-water. It is primarily intended here to ask the questions, while trying to put some constraints on the answers. The lack of research in the field of paleotides, and the complex interactions between scientific disciplines which are rarely considered in conjunction, means that the conclusions reached should be treated with a degree of scepticism perhaps not normally associated with geological work.

Bearing in mind the above caveat, it can be said that tidal sediments today are sufficiently well documented for their identification in the geological column to be possible with a reasonable degree of certainty. Little is known in quantitative terms of the tides which produced them. The possibility arises that not all past tidal sediments are recognised for what they are, as quantitative changes in tidal range have led to qualitative changes in sedimentary structures, due to enhanced current velocities. Olson's work (1970) suggests that tilloid deposits of great age may be of tidal origin. Experiments with flume tanks using very high flow velocities might support Olson's hypothesis, or could lead to the formation of other sedimentary structures which could be looked for in both the literature and sedimentary rocks.

The research work which has been done, results in two apparently incompatible results being obtained. The geologists, apart from Olson, suggest that although tidal heights in the past were apparently higher at times than those of today, this was only by a factor of two or so, whereas many of the astronomers' theories require tidal heights four orders of magnitude greater than those of today.

If the evidence of the geologists is accepted, no close approach of the moon can have occurred within the last three aeons, but the theory of tidal friction demands that a close approach to the earth should have happened within the last two aeons. It therefore seems that the moon cannot have been in orbit round the earth since early in earth history, implying that the earth-moon system must have had a non-catastrophic origin along the lines of one of the theories proposed in Table 6, (p. 225).

Three basic theories of non-catastrophic lunar origin late in earth history have been postulated. Firstly, an aggregation of a number of smaller satellites over a period of time as proposed by Goldreich (1966) and Alfvén and Arrhenius (1972). This aggregation would imply some lunar rocks with ages around the time of supposed aggregation, but Mason and Melson (1970, pp. 76-77) report only ages between 2.7 and 4.4 aeons, while Tera *et al.* (1974) fix the date of the moon's terminal cataclysm around 3.9 aeons. Therefore aggregation is excluded as a viable theory on the same grounds as the above. If the moon was formed by aggregation more than two aeons ago in orbit round the earth, it must have endured a close approach to the earth, for which there is no evidence.

The second theory - capture at a distance - has been criticised on many grounds by both Goldreich (1966) and Gerstenkorn (1967), whilst a third theory (Alvén and Arrhenius, 1969) suffers from a complete lack of theoretical and observational backing.

If, instead of accepting the evidence of the geologists, that of the astronomers is preferred, the consequences are that evidence of tremendous tides should exist and needs to be found; but more importantly, one of the philosophical groundrules of geology has been violated. The Lyellian version of uniformitarianism states that geological processes have always proceeded at the same rate as those observable today. This will no longer be true and a great deal of geological work will have to be re-evaluated.

One way out of these difficulties is to attempt to solve the time-scale problem which lies behind all the difficulties, as then both geological and astronomical theories are congruent. The time-scale problem can be solved by postulating that the radioactivity decay constants are dependent on the age of the universe. Dicke (1959) suggested a similar relationship but only for the beta-decay constant, while the alpha-decay constant was invariant. Kanasewich and Savage (1969) attempted to test this hypothesis of Dicke but found no evidence in its favour. However, should both constants vary at the same rate, the techniques used by Kanasewich and Savage would not have been capable of detecting the change.

If, in fact, the two constants vary in unison, catastrophical theories of the evolution of the lunar orbit can be revived but the implications for the scientific world would be traumatic. The evidence to support the assertion that the radioactive decay constants may vary with the age of the universe is that sedimentation rates throughout the geological column increase the closer to the present day that they are measured. Kay (1955) gives the following figures: sedimentation rate from Cambrian to today is average of 0.004 mm year^{-1}, while the sedimentation rate for the last million years is 0.3 - 0.4 mm year^{-1}. Holmes (1965, p. 227) also gives the theory some support when he gives figures of movement rate along the San Andreas fault since the late Jurassic. At that time the rate of movement was 1.20 km per million years, whereas the rate today is 16.0 km per million years.

If it is assumed that sedimentation rates and movements along the San Andreas fault have been approximately constant throughout geological history, then time was apparently passing faster than today in earlier epochs, on the basis of radioactive dating, suggesting a slowing of decay rates with time.

This paper does reveal that geologists and astronomers need to co-operate more closely in the future in order to give each other a sense of perspective. Today the two disciplines seem to be at an impasse with respect to each other, a situation which bodes ill for both. How this impasse is going to be overcome is not clear at the moment but cracks are appearing in the facade of scientific unity, and pressure seems to be building up which may shatter asunder both geology and astronomy. The ad hoc nature at the moment of theories of lunar origin, such as those of Singer (1972) and Alfvén and Arrhenius (1972), involving chains of interlocking coincidences of extremely low probability, are reminiscent of astronomical work in the pre-Keplerian age when more and more epicycles were continually added to an already over-ponderous astronomical world view. If Kuhn's (1970) vision of how science moves is correct, geology and astronomy may need a revolution.

Tides may seem to have been forgotten, but the above discussion should illustrate how important the study of the tides of antiquity could be to geology and other sciences.

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