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Carbonatite – an overlooked karstic rock (and its relationship to Life, the Universe and Everything)

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Abstract: This Report aims to raise awareness among karst specialists of the existence and nature of a relatively rare, dominantly carbonate, rock-type – carbonatite. This originated in upper mantle melts at high temperatures, but after rising to the lithosphere, it is capable of hosting the development of karstic landforms.

A second aspect of the Report looks more widely at what appears to be an inextricably linked relationship between sedimentary limestone and the development of life. Indeed, the Earth seems to have had such a favourable and extremely rare astronomical and geological history, which was absolutely dependent on the presence of the Moon, that life and biotic sedimentary limestone here might be unique in our galaxy, and perhaps universally. If any calcium carbonate, necessary for the development of early cyanobacterial life, was present on Earth at its creation, it would have been in the form of a carbonatite, because the collision that created the Moon melted the lithosphere.

Keywords: Scotland, stromatolite, life on Earth, subducted limestone, karst, Moon, extra-terrestrial.

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Introduction

Carbonatites could have been the oldest form of calcium carbonate on Earth and pre-date the production of sedimentary and metamorphic limestones. Some younger occurrences in Scotland are discussed and the various biotic and abiotic limestone formational processes are summarized. The first stromatolitic structures were deposited at an age of 3.7 billion years (Ga), and the ages of the various younger karstic sedimentary and marble limestone outcrops are considered, including those in Scotland. The origin of life depended partly upon the availability of calcium carbonate, but this seems to be rare or non-existent elsewhere in the Solar System. Furthermore, development of life on Earth depended on many favourable circumstances, some hinging upon the fortuitous presence of the relatively large Moon. This ensures the regularity of the seasons and causes the large tides in the oceans, which were even larger previously. It is also shown that without the Moon, the Earth would have become tidally locked to face the same way towards the Sun, thereby preventing the geological, environmental and biological development of the known Earth history. The absence of similar relationships in possible habitable zones in the observed exoplanets suggests that extra-terrestrial life and biotic sedimentary limestone are probably non-existent elsewhere in the galaxy.

Carbonatite

Carbonatites are complex igneous rocks that comprise mainly calcium carbonate (Ford and Williams, 2007, p24). Globally, they remain relatively rare. Whereas only some 330 occurrences with surface areas between 1 and 20km^2 were recorded by Pyle (1990), Yaxley *et al*. (2022, p.262) recognized: *"…more than 600 carbonatites in the geological record…"*. Considered together, these represent possibly as little as 1% of all the igneous rocks currently recognized at outcrop. They occur within diverse tectonic situations, which include intrusive, extrusive, volcanic and pyroclastic settings. There is a broad consensus, as described for example by Amsellem *et al*. (2023), that many carbonatites originated as a result of fractional crystallization and/or liquid immiscibility effects, including transformations within upper-mantle melts at temperatures greater than 1315ºC. From their trace element isotopic compositions, however, most of them appear to have formed as shallow melts of subducted limestones, which typically melt at 825ºC, and which subsequently cooled and solidified on ascending back into the lithosphere. Approximately 90% of all dated carbonatites occur within Precambrian cratons. The oldest recognized examples are aged *c*.3Ga, and are located on ancient "shield" areas of western Australia, Canada and southern Greenland (Gibson *et al*., 2024, citing many other authors).

A suite of small blocks of drifted, originally intrusive, orange-brown carbonatite lies beside the northeastern shore of Loch Urigill (Fig.1) in Assynt in Sutherland, Scotland (Young *et al*., 1994). This is within a few kilometres of the Knockan caving area on the outcrop of the sedimentary Durness Group limestone of Mid Cambrian to Mid Ordovician age (Lawson and Dowswell, 2022; Faulkner, 2023). Currently, the carbonatite blocks rest some 400m southwest of the Borralan Intrusion granite and syenite pluton, which intruded the Moine Thrust Zone 439−430 million years (Ma) ago. The plutonic magma was emplaced within the grey limestone sequence, which has turned white locally as a result of contact metamorphism, as revealed by the celebrated geological mapping of Peach *et al*. (1892).

The Loch Urigill carbonatite appears to be only its second known occurrence in Britain (Figure 1 *in* Gibson *et al.,* 2024,), although that small-scale map shows another occurrence at the southern tip of Ireland. At Loch Urigill, the carbonatite blocks cover only a small, 150m^2, area within ground where the bedrock is mostly buried beneath thick peat. One of the loose blocks occupies a shallow swallow-hole (Young *et al*., 1994), which presumably formed within the Durness Group limestone.

Elsewhere in northern Scotland, the first reported British carbonatites were recognized as a suite of carbonate veins within the Great Glen Fault Zone near Inverness (Fig.1)(Garson *et al.,* 1984). Considering more widely, the only carbonatite karst system reported anywhere is formed in the 1.8Ga Cargill Alkalic Complex, which is intruded into a rift system at Kapuskasing, Ontario, Canada (Sandvik and Erdosh, 1977; Erdosh, 1979). It is small and locally confined, but is associated with a well-developed karst topography.

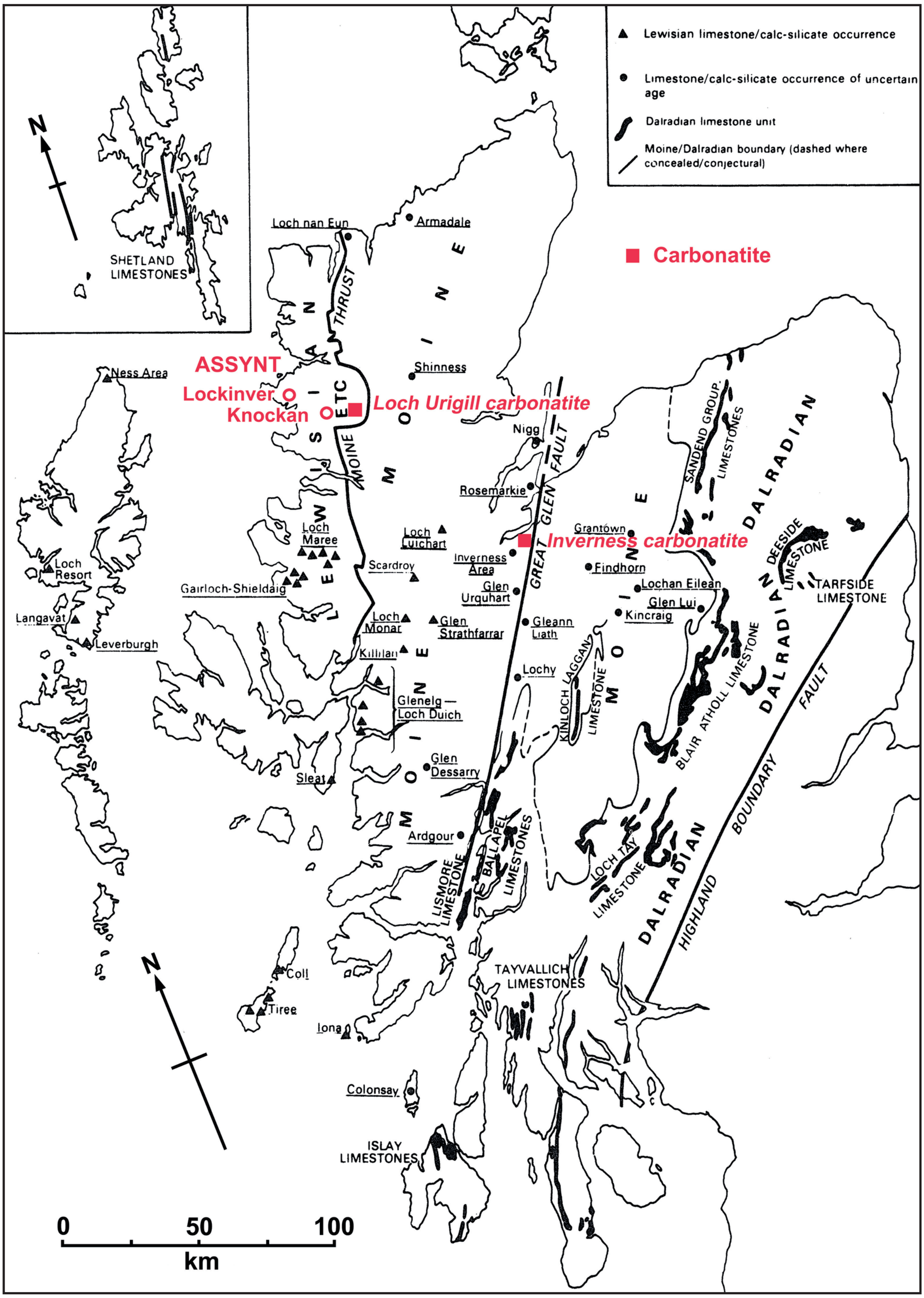

Figure 1: *Locations of carbonatites, and outcrops of marble within the Lewisian Complex and the Moinian and Dalradian supergroups of northwestern Scotland.*
Based upon Rock, 1989, Fig.1, with the permission of the British Geological Survey.

Limestone formation

Rock composed of $CaCO_3$ forms and re-forms by a variety of mechanisms, of which carbonatite production is perhaps the most extreme example. The dissolutional chemical properties of low-magnesian calcites (<4% $MgCO_3$, limestone's most stable chemistry) are similar, such that under comparable conditions they can all host the formation of caves and karst features within similar timescales. A brief summary of possible biotic or abiotic limestone formation processes, followed by subsequent lithification where appropriate, includes:

- Marine precipitation and sedimentation in shallower parts of seas and oceans at lower latitudes. Away from brackish coastlines, these are commonly saturated with $CaCO_3$ above the Calcite Compensation Depth. Below that depth, more CO_2 and calcite can dissolve in seawater at the prevailing lower temperature.
- Terrestrial lacustrine precipitation and sedimentation, perhaps assisted by evaporation.
- Underground (endokarst) speleothem, and terrestrial (exokarst) travertine and tufa, deposition.
- Regional and/or contact metamorphism of sedimentary carbonates at pressures from 1−10kbar and temperatures >200ºC, to create "marbles".
- Contact metamorphism of regionally-metamorphosed carbonates at a temperature that reduces with distance from a rising igneous pluton and becomes ineffective at *c.*1.5km.
- Igneous melting of subducted sedimentary, metamorphic or igneous limestones into the mantle, leading to the creation of carbonatites on subsequent ascent.

Additionally, $CaCO_3$ can be created by abiotic chemical reactions, perhaps forming oolite or chalk:

- Chemical weathering, or mechanical weathering followed by dissolution, of all types of limestone outcrops when subjected to acid rain, such as carbonic acid in rainwater. Calcium bicarbonate in solution then flows downstream into lakes and oceans, where it can precipitate as $CaCO_3$.
- Reaction of mantle-derived CO_2 with silicates to create non-sedimentary carbonates and silica (SiO_2). (Atmospheric CO_2 might be removed similarly in the future, to help reduce the effects of global warming).
- Similar reactions during atmospheric weathering of silicate rocks by acid rain also produce calcium bicarbonate in solution (Berner *et al.*, 1983). This important process has largely been ignored in the literature and textbooks on karst processes.

Limestone and life

Interesting quandaries and questions concern the ages of the various types of limestones and whether they were deposited or altered under chemogenic/abiotic conditions or deposited from biogenic/biotic components, such as calcitic plankton. Intriguingly, the histories of sedimentary limestones and life on Earth are inextricably linked, so that it is natural to enquire: which came first? The oldest known life forms were probably colonies of cyanobacteria that created reef-mat mounds of biogenic limestone stromatolites aged at 3.7Ga in West Greenland (Van Kranendonk *et al*., 2025) and at *c.*3.5Ga in western Australia (Hickman-Lewis *et al*., 2023). No known carbonate accumulations thicker than 100m are known that are older than 2.95Ga, but *c.*400m-thick biotic outcrops have been dated to >2.85Ga in Ontario, Canada (Fralick *et al.,* 2025). The oldest known *terrestrial* (rather than marine) possible stromatolites on Earth, and the oldest known sedimentary limestone and possible stromatolites in Europe, are from the ≤1.177Ga-old sedimentary *lacustrine* rocks of the Clachtoll and Bay of Stoer formations in northwest Scotland. These occur within thin (<1m thick), impure, Stoer Group limestones, north and south of Lochinver, on the west coast of Sutherland (Fig.1), including at Stoer, Clachtoll and Enard Bay (Gibbons and Harris, 1994, p.17; Turnbull *et al*., 1996; Brasier *et al*., 2017). The Stoer Group overlies older basement rocks of the Lewisian Gneiss Complex, which contain some marbles, and underlies sandstones of the Torridonian Supergroup. However, unambiguous microfossils are absent in the examined specimens, where visible geometries could be explained by abiotic sedimentary processes. This led Brasier *et al*. (2019) to doubt a genuine biogenic stromatolitic nature. Stromatolites of 750−653Ma age do occur, however, in weakly metamorphic Dalradian Supergroup rocks on the islands of Islay and Lismore (Fig.1)(Stephenson and Gould, 1995, pp.49 and 74−77). Earth's primitive atmosphere was initially anoxic, but release of oxygen by stromatolitic photosynthesis gradually raised oxygen levels, enabling the Cambrian evolutions of plant and animal life in the oceans and then on land. Nevertheless, other intriguing questions remain: what was the origin of the $CaCO_3$ of which the stromatolites are composed? Was there any abiotic sedimentation of limestones resulting from the chemical weathering of carbonates and silicates, when the atmosphere was still anoxic and believed to contain high levels of volcanically sourced CO_2?

An early comprehensive review of the limestones of Scotland was provided by Robertson *et al*. (1949). Rock (1989) later gave updates for metamorphic "limestones" within the Lewisian Complex and Moine Supergroup outcrops of the Highlands and Islands. His Table 1 includes ≥8 "pure" limestone outcrops, within a list of >60 impure metalimestones and metadolostones, and calc-silicate skarns. These rocks are of Lewisian Complex age, varying from perhaps 2.9–1.2Ga, and are among the oldest high-grade metamorphic limestones yet recognized on the planet. As well as forming the basements of the Torridonian Supergroup and the Moine Thrust Zone, these Lewisian rocks also occur as inliers within the younger rocks. Some outcrops of the Lewisian marbles are narrow (mostly <100m wide) and up to 10km long, but they are commonly far shorter and/or discontinuous. According to Mykura (1976, Figure 5), seven narrow marble outcrops occur on the Walls Peninsula of Shetland, within other calcareous rocks of probable Lewisian age.

Rocks of the Lewisian Complex are among the oldest in Britain and collectively have experienced many episodes of orogenic mountain building and metamorphism during subduction (Johnstone and Mykura, 1989). If any evidence of palaeokarstic activity is present within the Lewisian marbles, it could pre-date that surviving in Archean rocks of >2.5Ga age in the Canadian Shield (Ford and Williams, 2007, pp37–38) or of 2.3Ga age in the Transvaal of South Africa (Palmer, 2007, p.353). Almost certainly, however, palaeokarstic voids in marble could not have survived the conditions and processes associated with high-grade metamorphism. Any indications of speleogenetic dissolution would therefore date from a time between the age of metamorphism and that of the oldest palaeokarstic sediments. The possibly oldest example of an open cave formed in non-carbonatite karst rock might be one within 1.2Ga-old Grenville-age marble in the Adirondack Mountains of New York State, USA (Palmer, 2007, Figure 2.42, p.353). Caves are also known in marbles on the Baltic Shield in Sweden, which are >1Ga in age (Faulkner, 2018). Hence, if any caves exist within any Lewisian marbles older than 1.2Ga, they could occupy a special place in the world, as being formed in the oldest known non-igneous karst rocks. So far, only a 1m-long, 15cm-wide, karst 'through-conduit' guided by a fracture, and several small dolines, sinks, risings and enigmatic tors, have been reported in the Lewisian Complex marbles (Faulkner, 2019). Open cave passages in younger marbles are well-known world-wide, including in the Appin and Argyll groups of the Dalradian Supergroup between the Great Glen Fault and the Highland Boundary Fault in Scotland (Fig.1). In the metamorphic North Atlantic Caledonides, and probably also more generally, such caves must also post-date early regional metamorphism. However, they were commonly enlarged by dissolution that occurred far more recently, during Quaternary deglaciations, along fractures that were close enough to the surface to have been created by deglacial isostatic uplift (Faulkner, 2007).

It seems unlikely that recognizable parts of any organic species, including extremophiles, could survive temperatures associated with igneous or high-grade metamorphic calcite, so that recycling of such limestones should be regarded as abiotic. Evidence of microbial life can, however, survive in limestones recycled through low-grade greenschist-facies regional or contact metamorphism. Many marine and lacustrine sedimentary systems, terrestrial tufas and some speleothems were certainly biotic, where fossiliferous sediments incorporated the calcium carbonate remains of various organisms. Even in such a realm, however, deposits from chemical weathering, lacustrine precipitates promoted by evaporation, some surface travertines, and most underground speleothems remain primarily or completely abiotic.

A possibly unique example of limestone sedimentation is a large (>330,000km^2) and thick (>500m) porous limestone deposit of early Cretaceous age. It lies within what have now become deep basins, offshore from Brazil and Angola, which resulted from the effects of the rifting that formed the South Atlantic (Wright, 2022). The deposit was probably precipitated on land in the waters of a terrestrial lake, partly assisted by evaporation. Reservoirs within the sequence now host major oilfields. Although this deposit was not described as a carbonatite, Wright (2022) assumed, in a 'deep lake model', that tectonic and volcanic CO_2 venting from the mantle, which perhaps originated from older recycled limestone, was a critical factor in determining the composition of rising carbonate fluids. Microbialites are rare within these deposits, and only typical in the top 20−30m. Thus, most of the deposition was chemogenic, and similar to extensive abiotic marine carbonate precipitation that was occurring from Archean times through to the Palaeoproterozoic, presumably caused by the chemical weathering of outcrops of carbonates and silicates. It might be an interesting exercise to compare the characteristics and numbers of caves and karst extents formed in the majority biotic outcrops with those in the outcrops of minority abiotic limestone deposits.

The Earth−Moon system

The Earth is an incredibly special and possibly unique planet, with many fortunate 'Goldilocks' attributes that acted in favour of life and sedimentary limestone developing. However, it took about 1Ga for cyanobacterial life to start and be deposited as stromatolites, another 3Ga for animal life to develop, and then another *c.*0.5Ga for human civilization to become more impactful to the planet than geological and biological processes. This might be the fastest possible evolutionary timescale, but 4.498Ga, the probable age of the Earth since the formation of the Moon (Nimmo *et al.,* 2024), is a large proportion (33%) of the *c.*13.7Ga age of our galaxy (which is nearly as old as the Universe itself), showing how rare it must be for biotic sedimentary limestone and animal life to be produced.

Apart from the size of the Earth, which permits the retention of an atmosphere, the distance to the Sun, which commonly allowed maintenance of liquid oceans, and plate tectonics, which contributed to evolution, the major Goldilocks benefit is the presence of the relatively large Moon. This stabilizes the rotational axial tilt (obliquity) of the Earth at 22.1º−24.5º to its orbital perpendicular, whilst also stabilizing the precession and eccentricity Milankovitch cycles, and generates two thirds of the tidal energy. Without the Moon, the rotating Earth's tilt would vary sporadically up to 85º, removing the seasons and creating a completely different climate and geological history (Rast *et al.*, 2017), but an even greater influence is discussed below.

The lunar effects would have been even stronger when the Moon had just been formed by the collision between the proto-Earth and a Mars-sized body called Theia – probably *c.*70Ma after the formation of the Sun, which has an age of 4.568Ga. At that time, the Earth's rotation period was *c.*6 hours and the distance of the centre of the Moon from the centre of the Earth was only about five times the radius of the Earth, i.e. *c.*32,000km (Nimmo *et al.,* 2024). At that time, the lunar orbital period is calculated herein to be *c.*16 hours.

Frictional tidal forces acting on the oceans and lithosphere have lengthened the Earth 'day' ever since, reaching *c.*18 hours at an age of 0.9Ga (Sonett *et al*., 1996), when the lunar distance is calculated to be *c.*324,000km and its orbital period to be 21.2 (24-hour) days. The Moon's initial rapid rotation rate was similarly reduced, to become tidally locked to face the same way towards the Earth, soon after its formation and perhaps whilst still molten. As a consequence of the Earth's reducing rotation rate, the lunar distance and 'month' increased, to conserve angular momentum. The Moon was *c.*120,000km away *c.*217Ma after the Sun's formation, at an age of 4.351Ga, when its surface was re-melted by tidal heating (Nimmo *et al.,* 2024), with a calculated lunar orbital period of *c.*4.8 days. It was *c.*240,000km away at 3.5Ga (from Bills and Ray, 1999, Figure 2) – when deposition of stromatolites began – with a calculated lunar period of *c.*13.5 days. Its present distance is 384,400km, with a month of 27.5 days and an Earth day of 24 hours.

Calculated values for angular momentum, lunar orbital period and the Earth rotational period are shown in Table 1 for each of the five stages discussed above, at ages of *c.*4498, *c.*4351, *c.*3500, *c.*900 and *c.*0Ma. The textbook equations used are:

Lunar orbital period:

$P = 2\pi(D^3/GM)^{0.5}$ in 24-hour days, ***where:***

$D =$ distance between the centres of the Earth and the Moon (km)

$G =$ Gravitational constant

$= 6.674\times10^{-11} m^3kg^{-1}s^{-2}$

$= 6.674\times10^{-20} km^3kg^{-1}s^{-2}$

$M =$ Mass of the Earth (kg).

Lunar orbital angular momentum:

$L_o = 2\pi mfD^2$ $kgkm^2s^{-1}$, ***where:***

$m =$ mass of the Moon (kg)

$f =$ Moon orbital frequency

$= 1/P$ (s^{-1})

$D =$ distance between the centres of the Earth and the Moon (km).

The Moon's rotational angular momentum has remained insignificant, and is ignored.

Earth rotational angular momentum:

$L_r = 4\pi Mfr^2/5$ $kgkm^2s^{-1}$, ***where:***

$M =$ mass of the Earth (kg)

$f =$ Earth rotational frequency

$= 1/P$ (s^{-1})

$r =$ Earth radius (km).

Derived Earth-rotation periods P were commonly obtained by ensuring that the total angular momentum, $L = L_o + L_r$, remained constant at the present amount, as shown in Table 1, (except that at 900Ma, the derived D was obtained from the cited P of 18 hours). The present astronomical masses, Earth radius and mean distance apart are under constant refinement. The values used in Table 1 (and Table 2) are taken from the Internet, and any small improvements in accuracy will have negligible effects on the values derived from them. The evolution of the Earth−Moon system is illustrated graphically in Figure 2. The timescales indicated might be approximate, because the rate of tidal dissipation has been anomalously high during the last 1.6Ga (Bills and Ray, 1999), as also shown in Figure 2.

Body	Mass M or m	D	r	Lunar orbital or Earth rotational period P = 1/f	Lunar orbital or Earth rotational frequency f	Lunar orbital angular momentum $L_o = 2\pi m f D^2$	Earth rotational angular momentum $L_r = 4\pi M f r^2/5$	Total angular momentum $L = L_o + L_r$	*c.*Age
	kg	km	km	24-hour day	s^{-1}	$kgkm^2s^{-1}$	$kgkm^2s^{-1}$	$kgkm^2s^{-1}$	Ma
$Moon_{orb}$	7.348E+22	32000		0.6594	1.7553E−05	8.2981E+27		3.5827167E+28	4498
$Earth_{rot}$	5.972E+24		6378	0.2567	4.5088E−05		2.7529E+28		
$Moon_{orb}$	7.348E+22	120000		4.7884	2.4171E−06	1.6069E+28		3.5827167E+28	4351
$Earth_{rot}$	5.972E+24		6378	0.3577	3.2360E−05		1.9758E+28		
$Moon_{orb}$	7.348E+22	240000		13.5435	8.5458E−07	2.2725E+28		3.5827167E+28	3500
$Earth_{rot}$	5.972E+24		6378	0.5394	2.1459E−05		1.3102E+28		
$Moon_{orb}$	7.348E+22	324012		21.2449	5.4479E−07	2.6405E+28		3.5827167E+28	900
$Earth_{rot}$	5.972E+24		6378	0.7500	1.5432E−05		9.4223E+27		
$Moon_{orb}$	7.348E+22	384400		27.4530	4.2160E−07	2.8760E+28		3.5827167E+28	0
$Earth_{rot}$	5.972E+24		6378	1.0000	1.1574E−05		7.0667E+27		

Table 1 (above)*:*
Angular momentum during the evolution of the Earth–Moon system.

No doubt the frictional tidal forces depended upon the oceanic and glacial state of the Earth, so that they would be minimized at the times of a Snowball Earth, for example. Importantly, since its creation, the Earth has been becoming more tidally locked to face the Moon rather than the Sun, because the Moon still exerts the greater tidal influence, by a factor of two.

Considered broadly, the Earth's initial rotational angular momentum and the Moon's, smaller, initial orbital angular momentum have swapped over since their creation. This means that the Moon has become apparently the only known satellite to have an orbital angular momentum that is greater than its planet's rotational angular momentum. The transfer process will continue, unless the Moon drifts far enough away from the Earth for influence of the Sun to become dominant.

Tidal locking

Table 2 illustrates the various relevant tidal accelerations that can cause phase lock resonance in the Solar System inner planets and their natural satellites, and for the Earth–Moon system at the five discussed stages of its evolution. For each calculation, the first body is subject to the gravitational attraction from the second body. The mass of the first body is not applicable, only its radius. Using equations provided by Sawicki (1999):

Tidal Acceleration = $1000GM((1/D^2) - (1/(D + r)^2))$ ms^{-2}, where:
G = Gravitational constant, M = Mass of the second body (kg), D = distance between the centres of the two bodies (km) and r = the radius of the first body (km).

Approximate Tidal Acceleration = $2000GMr/D^3$ ms^{-2}, a good approximation, if r/D <0.4%.

Lunar orbital period ('month') = $2\pi(D^3/GM)^{0.5}$ (24-hour days), as calculated in Table 1.

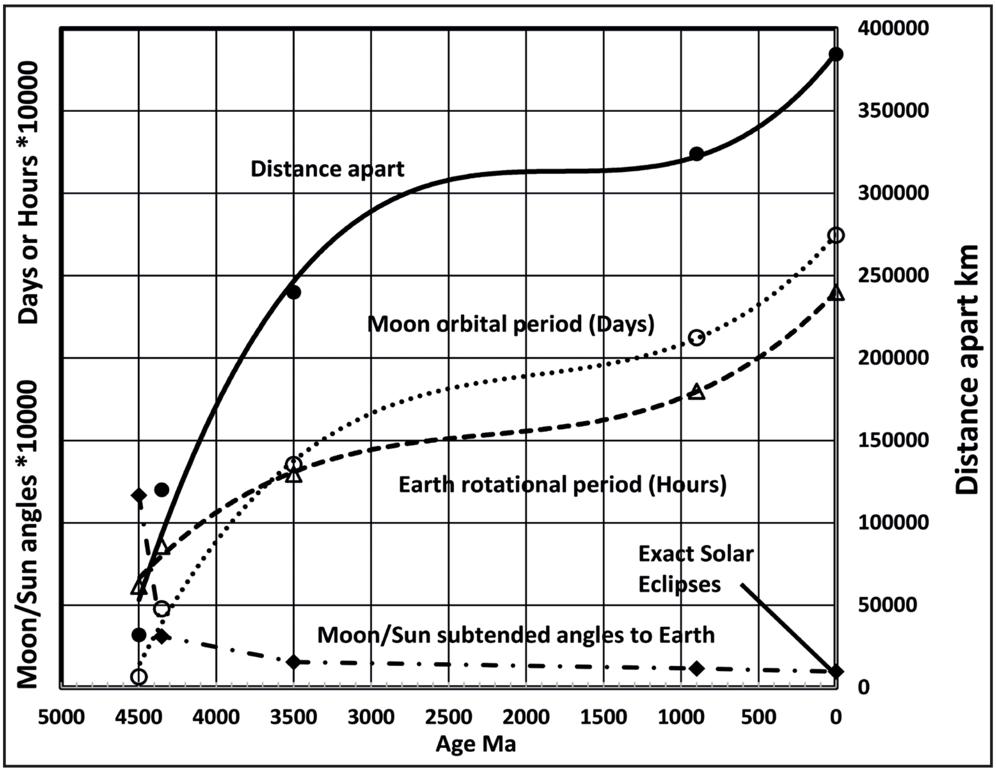

Figure 2*:*
The evolution of the Earth–Moon system. Trendlines shown are for the five indicated stages, as discussed in the text.

First body	First body radius	Second body	Second body mass	Mean distance between body centres	Lunar 'month' (24-hour days)	r/D	Tidal Acceleration	Approximate Tidal Acceleration	Phase lock resonance to Sun or planet?	Age
	r km		M kg	D km			ms^{-2}	ms^{-2}		Ma
Mercury	2439	Sun	1.989E+30	5.800E+07		0.000042	3.3187E−06	3.3189E−06	Yes	0
Venus	6052	Sun	1.989E+30	1.075E+08		0.000056	1.2933E−06	1.2934E−06	Yes	0
Earth	6378	Sun	1.989E+30	1.496E+08		0.000043	5.0566E−07	5.0569E−07	No	0
Earth	6378	Moon	7.348E+22	3.200E+04	0.66	0.199313	1.4595E−03	1.9090E−03	Towards Moon	4498
Moon	1738	Earth	5.972E+24	3.200E+04		0.054297	3.9060E−02	4.2269E−02	Yes	
Earth	6378	Moon	7.348E+22	1.200E+05	4.79	0.053150	3.3506E−05	3.6200E−05	Towards Moon	4351
Moon	1738	Earth	5.972E+24	1.200E+05		0.014479	7.8447E−04	8.0155E−04	Yes	
Earth	6378	Moon	7.348E+22	2.400E+05	13.54	0.026575	4.3508E−06	4.5250E−06	Towards Moon	3500
Moon	1738	Earth	5.972E+24	2.400E+05		0.007240	9.9116E−05	1.0019E−04	Yes	
Earth	6378	Moon	7.348E+22	3.240E+05	21.24	0.019684	1.7860E−06	1.8389E−06	Towards Moon	900
Moon	1738	Earth	5.972E+24	3.240E+05		0.005362	4.0394E−05	4.0719E−05	Yes	
Earth	6378	Moon	7.348E+22	3.844E+05	27.45	0.016592	1.0745E−06	1.1013E−06	Towards Moon	0
Moon	1738	Earth	5.972E+24	3.844E+05		0.004520	2.4221E−05	2.4385E−05	Yes	
Mars	3397	Sun	1.989E+30	2.280E+08		0.000015	7.6095E−08	7.6096E−08	Not yet	0
Mars	3397	Phobos	1.080E+16	9.377E+03		0.362269	3.7802E−09	5.9394E−09	Slightly opposed by Phobos and Deimos orbits	0
Mars	3397	Deimos	1.480E+15	2.346E+04		0.144800	4.2529E−11	5.1974E−11		0
Phobos	11.1	Mars	6.420E+23	9.377E+03		0.001184	1.1516E−03	1.1537E−03	Yes	0
Deimos	6.3	Mars	6.420E+23	2.346E+04		0.000269	4.1796E−05	4.1813E−05	Yes	0

***Table 2**: Solar System tidal accelerations and phase locking.*

From Table 2, it is seen that, since the formation of the Solar System, tidal accelerations $\geq 10^{-6}ms^{-2}$ have caused the phase lock resonance of Mercury and Venus (which have no natural satellites) to the Sun, the Moon to the Earth, and Phobos and Deimos to Mars. (For comparison, the gravitational acceleration, g, at the surface of the Earth = $9.81ms^{-2}$).

The Earth, at $0.5\times10^{-6}ms^{-2}$, and Mars, at $7.6\times10^{-8}ms^{-2}$, are not (yet) locked to the Sun. However, the Earth's tidal acceleration towards the Moon has always been $\geq 10^{-6}ms^{-2}$, which has prevented locking to the Sun. Without the Moon, it is highly likely that the Earth would also have achieved a phase lock resonance with the Sun during its geological history, especially considering its large tidal oceans, which were absent on Mercury and Venus. This has been confirmed by modelling (Barnes, 2017). Thus, quite apart from stabilizing the Milankovitch cycles of a rotating planet, the Moon has prevented the Earth from locking one hot side towards the Sun, with the far side frozen.

Large astronomical changes in the Earth−Moon system have rarely been considered when attempting to deduce the geological history of the Earth. The distance of the Earth from the Sun has also increased slightly since its creation, as the Sun has lost mass and the Earth's rotational angular momentum has reduced. However, the Earth's global temperature has been variable and its history has been punctuated by glaciations. It also depended on competitions among heat radiated from the Earth after its hot collisional formation, internal nuclear radiation, atmospheric greenhouse gases, and solar output. The approximate tidal acceleration at the Earth caused by the Moon is inversely proportional to their distance apart cubed (above). Hence, when the Moon was 240,000km from the Earth, 3.5Ga before now, the tidal acceleration was four times greater than it is currently.

Thus, for most of geological history, during the development of life and sedimentary limestone, there were much larger tides in the oceans. Research into how these larger tides would have influenced both coastal erosion and the deposition of limestone and sandstone is awaited. Such large tides in more mobile oceans would have had significant impacts on geomorphic evolution and enhanced the conveyance of new life forms around the globe, promoting biological evolution.

Simple calculations show that the relative size of the Moon to the Sun, when viewed from the Earth, has reduced continuously as the Moon moved farther away. From an initially huge apparent size ratio of *c*.12, it reduced to *c*.1.6 at an age of 3500Ma, and to *c*.1.2 at 900Ma. It is now 1.0, so that we live at the time of an extraordinary coincidence that gives us exact solar eclipses, as also shown in Fig.2. If the Earth's tidal acceleration towards the Moon were to reduce to $<0.5\times10^{-6}ms^{-2}$ (at a lunar distance of *c*.500,000km), the Sun would become dominant tidally. However, the apparent size ratio would reduce only to *c*.0.75.

On the other hand, if the relatively large and close Moon had not existed, the early oceans would have had lower tides and would have been less mobile. They would probably have ceased to exist in liquid form when the Earth became phase locked to the Sun, thereby preventing the creation of any form of, at least, animal life.

At present, 79% of the calcium that flows down rivers to the oceans comes from calcite (plus some dolomite) weathered by acid rain, rather than from weathered calcium silicates (Berner *et al*., 1983, Table 1). If this dominance persisted throughout geological history, most of the existing limestone has been present on Earth, as $CaCO_3$ in some form, since its formation. Because the collision that changed the proto-Earth to the Earth appears to have melted the lithosphere, it could follow that most of the limestone originated as carbonatite!

Extra-terrestrial life and limestone?

The relationships between sedimentary limestone and life on Earth lead to questions about the possible extra-terrestrial existence of such rocks and organisms. Apparently, deposits of $CaCO_3$ have been identified in 3–5% of the "soil" around the Phoenix lander site on Mars (Boynton *et al*., 2009). Magnesite ($MgCO_3$) accounts for a few percent of the Mars surface dust, and bright carbonate veins have been detected on an asteroid (King, 2023). However, the common absence of limestone in any form at outcrop on Mars, which had rivers and oceans for a short time, is intriguing. The absence of sedimentary deposits on the Moon is understandable, given its arid surface. However, the apparent absence of any significant carbonatite there and of limestone outcrops on Mars hints that carbonatite was also absent on the early Earth. In that case, perhaps limestone on Earth did originate by the weathering of igneous calcium silicates in an anoxic atmosphere with high levels of carbon dioxide, although, paradoxically, this does not seem to have occurred on Mars. Apart from on Earth, nowhere in the Solar System seems suitably hospitable to support life that might lead to the formation of biogenic sedimentary limestone, either now or in the Past. This leads inevitably to a prediction that not one single strand of the complex DNA molecule (which comprises the elements C, H, N and O), will ever be found elsewhere in this planetary system.

Farther afield, despite *c*.6000 exoplanets orbiting *c*.4000 other stars now being identified, few appear to be in a habitable zone with liquid water, none have significant oxygen in an atmosphere, and there are still no confirmed exomoons. Hence, no exoplanet–exomoon systems are known with gravitational relationships comparable to those for the Earth and Moon. Without such strong oceanic tides, stabilizing associations to ensure regular seasons, and the avoidance of tidal locking to the local star, the existence of any forms of multicellular life and hence of biogenic sedimentary limestone seems unlikely. Indeed, without a large moon, tidal locking (with only a little liquid water in a narrow twilight zone) before the development of life and biotic limestone seems inevitable, and Barnes (2017) predicted that nearly all potentially habitable exoplanets became tidally locked within 1Ga. Further, the presence of a significant satellite to a rocky inner planet might be unlikely anyway, from the local evidence. There are no moons around Mercury and Venus, only the Moon around the Earth (which was produced by a rare chance collision), and only two tiny asteroids captured by Mars. To be candidates for developing life and biogenic limestone, exosystems would need to have characteristics fairly similar to the Sun–Earth–Moon system, so that the exomoon would probably look larger than the local star, when viewed from the exoplanet. However, the early presence of abiotic sedimentary limestone produced by the weathering of calcium silicates on exoplanets, even without large exomoons, but with otherwise habitable attributes, remains feasible. Thus, such exoplanets could contain dissolutional limestone caves and karst, even without developing life.

The obvious conclusion from the above discussion is that other animal life in our galaxy, and perhaps in the Universe, is either non-existent, or, perhaps, just extremely rare. It follows that the likelihood of other so-called "intelligent life" is vanishingly small, in agreement with the conclusion by Mills *et al.* (2025). Indeed, despite radio telescopes listening for intelligible signals for more than 60 years, nothing confirmed as even possibly intelligible has been reported. Expeditions to other galaxies, or even to other stars, to search for extra-terrestrial life, limestone or karst caves, seem permanently impractical with present technology, as it would take far longer than a human lifetime to get there. As well as living on a possibly unique planet, cavers are extremely fortunate to be able to explore so many caves formed within several types of limestone, which might not exist anywhere else. Ultimately, most of these caves depend, as does the human race, upon the development of life and biotic sedimentary limestone on the Earth, as part of the special Earth–Moon system.

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References

Amsellem, E, Schiller, M, Klausen, M, Bouyon, A, Rojas, V, and Bizzarro, M, 2023. Origin of carbonatites and associated silicate rocks revealed by Mg triple-isotope approach. *Chemical Geology*, Vol.636, 121663.

Barnes, R, 2017. Tidal locking of habitable exoplanets. *Celestial Mechanics Dynamical Astronomy*, Vol.129, 509–536.

Berner, R A, Lasaga, A C, and Garrels, R M, 1983. The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years. *American Journal of Science*, Vol.283, 641–683.

Bills, B G and Ray, R D, 1999. Lunar orbital evolution: a synthesis of recent results. *Geophysical Research Letters*, Vol.26(19) 3045–3048.

Boynton, W V and 13 others, 2009. Evidence for calcium carbonate at the Mars Phoenix landing site. *Science,* Vol.325, 61–67.

Brasier, A T and 4 others, 2017. Evaluating evidence from the Torridonian Supergroup (Scotland, UK) for eukaryotic life on land in the Proterozoic. *Geological Society Special Publication* 448, 121–144.

Brasier, A T and 10 others, 2019. Detecting ancient life: Investigating the nature and origin of possible stromatolites and associated calcite from a one billion year old lake. *Precambrian Research*, Vol.328, 309–320.

Erdosh, G, 1979. The Ontario carbonatite province and its phosphate potential. *Economic Geology*, Vol.74(2), 331–338.

Faulkner, T, 2007. The one-eighth relationship that constrains deglacial seismicity and cave development in Caledonide marbles. *Acta Carsologica*, Vol.36(2), 195–202.

Faulkner, T, 2018. The ages of the Scandinavian caves. *Norsk Grotteblad*, (70), 15–33 and 40.

Faulkner, T, 2019. Are there any caves in Lewisian marbles? *Grampian Speleological Group Bulletin*, Vol.3(1), 13–17 and 23.

Faulkner, T, 2023. Turnalt Pothole re-located and small caves at Knockan. *Grampian Speleological Group Bulletin*, Vol.4(5), 11–14 and 23.

Ford, D and Williams, P, 2007. *Karst hydrogeology and geomorphology*. [Wiley.] 562pp.

Fralick, P and 9 others, 2025. Earth's earliest known extensive, thick carbonate platform suggested by new age constraints. *Earth and Planetary Science Letters,* Vol.656, 119273.

Garson, M S, Coats, J S, Rock, N M S, and Deans, T, 1984. Fenites, breccia dykes, albitites, and carbonatitic veins near the Great Glen Fault, Inverness, Scotland. *Journal of the Geological Society*, Vol.141, 711–732.

Gibbons, W and Harris, A L (eds), 1994. A revised correlation of Precambrian rocks in the British Isles. *Geological Society Special Report,* 22. 110pp.

Gibson, S, McKenzie, D, and Lebedev, S, 2024. The distribution and generation of carbonatites. *Geology*, Vol.52(9), 667–671.

Hickman-Lewis, K and 11 others, 2023. Advanced two-and three-dimensional insights into Earth's oldest stromatolites (ca. 3.5 Ga): Prospects for the search for life on Mars. *Geology*, Vol.51(1), 33–38.

Johnstone, G S and Mykura, W, 1989. *British Regional Geology: The Northern Highlands of Scotland*. Fourth Edition. [HMSO.] 219pp.

King, A J, 2023. Carbonate's fluid history. *Nature Geoscience*, Vol.16, p.941.

Lawson, T J and Dowswell, P N F, 2022. Caves of Assynt. [Grampian Speleological Group.] 211pp.

Mills, D B, Macalady, J L, Frank, A, and Wright, J T, 2025. A reassessment of the "hard-steps" model for the evolution of intelligent life. *Science Advances,* Vol.11, No.7, eads5698. 17pp.

Mykura, W, 1976. *British Regional Geology: Orkney and Shetland*. [HMSO.] 149pp.

Nimmo, F, Kleine, T, and Morbidelli, A, 2024. Tidally driven remelting around 4.35 billion years ago indicates the Moon is old. *Nature*, Vol.636 (8043), 598–602.

Palmer, A N, 2007. *Cave Geology*. [Cave Books.] 454pp.

Peach, B N, Horne, J and others, 1892 [and later revisions]. 1-inch [1: 63,360] geological map sheet: Assynt District. [British Geological Survey.]

Pyle, D M, 1990. Review of Bell, K. (Ed.) 1989. *Carbonatites. Genesis and Evolution*. [Unwin Hyman.] xix+618pp. *Geological Magazine*, Vol.127(5), 467–469.

Rast, R and 5 others, 2017. Effects of the Moon on the Earth in the Past, Present and Future. *University of Saskatchewan Undergraduate Research Journal*, Vol.4(2) 1–10.

Robertson, T, Simpson, J B, and Anderson, J G C, 1949. *The Limestones of Scotland*. [HMSO.] 221pp.

Rock, N M S, 1989. Aspects of the limestones of the Highlands and Islands of Scotland. *British Geological Survey Report Series,* CG16(12). [London:HMSO.] 33pp.

Sandvik, P O and Erdosh, G, 1977. Geology of the Cargill phosphate deposit in northern Ontario. *Canadian Institute of Mining and Metallurgy, Bulletin*, 70, 90–96.

Sawicki, M, 1999. (latest revision: 2005). Myths about gravity and tides. *The Physics Teacher*, Vol.37, 438–441.

Sonett, C P and 4 others, 1996. Late Proterozoic and Paleozoic tides, retreat of the Moon, and rotation of the Earth. *Science*, Vol.273, 100–104.

Stephenson, D and Gould, D, 1995. *British Regional Geology: The Grampian Highlands*. Fourth Edition. [HMSO.] 262pp.

Turnbull, M J M, Whitehouse, M J, and Moorbath, S, 1996. New isotopic age determinations for the Torridonian, NW Scotland. *Journal of the Geological Society*, Vol.153, 955–964.

Van Kranendonk, M J, Nutman, A P, Friend, C R L, and Bennett, V C, 2025. A review of 3.7Ga stromatolites from the Isua Supracrustal Belt, West Greenland. *Earth-Science Reviews*, Vol.262, 105034.

Wright, V P, 2022. The mantle, CO_2 and the giant Aptian chemogenic lacustrine carbonate factory of the South Atlantic: Some carbonates are made, not born. *Sedimentology*, Vol.69, 47–73.

Yaxley, G M, Anenburg, M, Tappe, S, Decree, S, and Guzmics, T, 2022. Carbonatites: Classification, Sources, Evolution, and Emplacement. *Annual Review of Earth and Planetary Sciences*, Vol.50, 261–293.

Young, B N, Parsons, I, and Threadgold, R, 1994. Carbonatite near the Loch Borralan intrusion, Assynt. *Journal of the Geological Society*, Vol.151, 945–954.