EARTH HISTORY

Strange bedfellows

Donald J. DePaolo

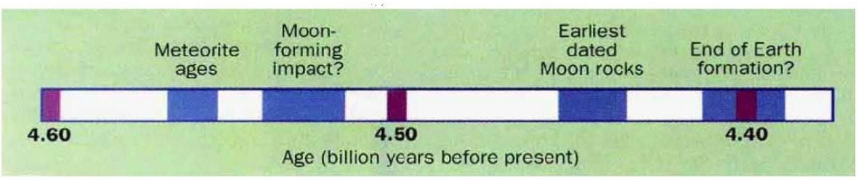
HOW long ago did the Earth start to form? Did the Moon form from the Earth? A report by Malcolm McCulloch in *Earth and Planetary Science Letters*[1] adds a new twist to both questions.

There are hardly two more fundamental questions that one could ask in Earth science, but convincing answers remain elusive. The difficulty in establishing the exact age of the Earth stems from the fact there there is no geological record for the time between the Earth's origin, presumably about 4.5 billion years ago, and the time represented by the oldest Earth rocks, which are 3.8 billion years old. Ironically, the hardest evidence about the exact age of the Earth may come from lunar rocks, the oldest of which is firmly dated at 4.44 billion years[2]. Now, the age of Moon rocks could conceivably have little to do with the age of the Earth, except that the preferred theory for the origin of the Moon is that it was produced from a giant meteorite impact with the Earth[3]. If the impact theory is accepted, then the Earth must have been around when the Moon formed, and its age must be bracketed by the age of the oldest Moon rocks and the age of the oldest meteorites, 4.56 billion years (see below).

ocean floor basalt. The seemingly simple measurement of one barite sample can be argued to give a better estimate of the $^{87}Sr/^{86}Sr$ of the Earth's mantle 3.45 billion years ago than was previously available from direct measurements on contemporaneous volcanic rocks.

McCulloch then argues that his measurement puts limits on the $^{87}Sr/^{86}Sr$ ratio that the Earth could have had when it finished accreting from solar nebular material. Specifically, he argues that the Earth must have continued accreting until 4.48 billion years ago in order to achieve such a high ratio of $^{87}Sr/^{86}Sr$, and at that time the Earth's $^{87}Sr/^{86}Sr$ ratio was much higher than the Moon's. Actually, his data can be reinterpreted as indicating that the *mean* time of Earth accretion was 4.48 billion years ago, and therefore that the end of Earth's accretion must have been even later. Although McCulloch's conclusion requires some assumptions, he has made his assumptions conservative enough that the conclusion appears robust.

The strontium ratio of the early Earth and the rubidium/strontium ratio of the Earth are particularly significant for the origin-of-the-Moon issue. The Rb/Sr ratio



As usual, however, the devil is at work in the details. If the Moon is made of Earth material, then one would expect the Moon to be similar in chemical composition to the outer parts of the Earth. Although it is indeed broadly similar[4], it differs in important ways, and proponents of the impact theory need to add some significant twists to the story to make it compatible with the geochemical differences between the Earth and Moon.

Malcolm McCulloch's new research[1] adds further fuel to the debate. McCulloch measured the strontium isotope composition of a barite (barium sulphate) deposit in Australia that is 3.45 billion years old. The barite measurement is significant because barite is a marine precipitate, and therefore its $^{87}Sr/^{86}Sr$ ratio can be argued to be representative of the $^{87}Sr/^{86}Sr$ of the world's oceans 3.45 billion years ago. The oceans, in turn, are likely to be representative of the Earth's mantle at that time because the oceanic strontium budget would have been dominated by hydrothermal exchange with

is a representation of the primary chemical difference between the Earth and the Moon. Relative to the Earth, the Moon is greatly depleted in 'volatile' elements (such as rubidium) in comparison with 'refractory' elements such as strontium. To make a consistent story from the impact theory, the Earth needs to have a low $^{87}Sr/^{86}Sr$ and Rb/Sr until the Moon forms, and then acquire additional Rb and ^{87}Sr-rich material so that it can end up having a higher Rb/Sr and a higher $^{87}Sr/^{86}Sr$ than the Moon. Although the picture becomes complicated, McCulloch's result implies that the Moon-forming giant impact probably occurred very early while the Earth was much smaller than it is now. Subsequently, the Earth must have continued growing to its present size, somehow accumulating new material that was able to bypass the nearby Moon.

Proponents of the giant impact theory generally believe that the impact occurred late in the accretion history of the Earth, when the planet was very close to its present size. A late impact is difficult to

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Earthrise from the Moon.

reconcile with the arguments put forward by McCulloch, unless the Moon is made up mainly of material from the impact body rather than from the Earth itself. This idea has its own problems, however, because it implies that the otherwise similar aspects of lunar and terrestrial geochemistry must be coincidental[5].

It is tempting, of course, to argue that the constraints described by McCulloch are not very strong and should be discounted. However, his result is consistent with other evidence that the Earth had a high initial value of $^{87}Sr/^{86}Sr$. In virtually all old terrestrial rocks, ranging in age from 1.8 to 3.5 billion years, the $^{87}Sr/^{86}Sr$ ratios are too high to be compatible with the idea that the Earth has a low, Moon-like initial value of $^{87}Sr/^{86}Sr$. Conservatives might argue that the high $^{87}Sr/^{86}Sr$ values found in old terrestrial rocks are not reliable, that they have been modified by subsequent processes. The problem with ignoring the existing data, however, is that a very large number of rocks have been studied over the past few decades, and no trace of the expected low $^{87}Sr/^{86}Sr$ values has been found.

The new barite measurement highlights the large degree of interrelation between models of Earth evolution, lunar origin and early Solar System evolution. Someone needs to find the elusive low-$^{87}Sr/^{86}Sr$ values in the Earth, or we are left to face the implications as described by McCulloch — a younger Earth, and an early giant impact. □

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