

Model for magnetic mystery

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Today, the Moon has no magnetic field, but analyses of lunar rocks suggest that it did in the past. Did changes in the lunar interior create a magnetic dynamo billions of years ago?

Magnetic fields provide key information in reconstructing the evolutionary history of planetary bodies. Planets such as Earth and the gas giants have magnetic fields produced by self-sustaining dynamos that are a manifestation of the cooling of the deep planetary interior. In contrast, mystery surrounds the possible existence of a dynamo on the Moon. At present, the Moon has no internally generated magnetic field, but rock samples brought back by the Apollo missions bear evidence that the surface was magnetized in the past. On page 143 of this issue, Stegman and colleagues¹ revisit the question of dynamo generation on the Moon, making use of three-dimensional models that simulate the dynamics of the early lunar mantle.

On the surfaces of solid planets, some crustal rocks preserve the record of magnetic fields during earlier epochs of planetary history. The process of 'thermoremanent magnetization' occurs when certain volcanic rocks cool in the presence of a magnetic field. When the temperature falls past a value known as the Curie point, domains within magnetically susceptible rocks align and information on orientation and magnitude of the field at the time of cooling is preserved. For example, Earth's sea floor and the surface of Mars contain rocks that were magnetized in the presence of global magnetic fields generated by core dynamos, within the past 200 million years for Earth and over 4 billion years ago for Mars.

Although the Moon currently does not have an internally generated magnetic field, the Apollo samples show remanent magnetization that dates to between 3.6 billion and 3.9 billion years ago, half a billion to a billion years after the Moon formed. This is also the time of formation of the mare basalts — massive flood lavas that fill large impact basins on the near side of the Moon (Fig. 1). There has been much debate as to whether the lunar rocks were magnetized in the presence of a core dynamo because simulations have suggested that the interior would not have cooled rapidly enough to drive a dynamo².

The basic ingredients for dynamo action are an electrically conducting fluid within the planet (such as a liquid iron core), an energy source (such as convection arising from core cooling) and rotation (to organize the fluid motion). Various factors conspire against the idea of a vigorously convecting

Figure 1 The Moon's magnetic past. This image of the Moon, taken by the Galileo spacecraft en route to Jupiter, shows the bright highland areas, rich in anorthosite, and dark 'mare basalt' flood lavas. Stegman *et al.*¹ tie these features in to a model for how the Moon might have briefly generated a magnetic field 4 billion years ago.



primordial Moon, the most important of which are a small core and an 'inverted' thermal structure in the lunar interior. With regard to the latter, planets tend to be hot on the inside and cold on the outside, with internal heat being removed by convection. But analyses of Moon rocks have shown that the early Moon had a molten exterior. The pervasive presence of the rock anorthosite in the lunar highlands is evidence of this 'magma ocean' (Fig. 1).

A key aspect of the model of Stegman *et al.*¹ is that it takes into account the thermal and chemical consequences of the magma ocean. In a melting material that has the likely composition of the lunar mantle, minerals containing the lighter elements would float to the surface, forming the anorthosite crust. Left behind is a region enriched in heavy elements that is denser than its surroundings — so much so that previous simulations³ have shown it could sink to the deep lunar interior, possibly encircling the core. This layer would be rich in radioactive elements, such as uranium and thorium, which could produce sufficient heat as they decay to heat the Moon's interior significantly on timescales of hundreds of millions of years. In the model of Stegman *et al.*, the sunken residual material encircles the lunar core and insulates it from the rest of the mantle, trapping heat in the core and preventing the core from

cooling convectively, and also from developing a dynamo. But, after a period of time, the radiogenic material within this 'thermal blanket' decays and heats up. Eventually the material becomes more buoyant than its surroundings and rises towards the surface. With the removal of the thermal blanket, the core is then able to convect vigorously to cool itself, and this can produce a short-lived dynamo.

An essential element of the model is the timing. The length of time that it takes the thermal blanket to heat up and rise back towards the surface is broadly consistent with two important events in early lunar history — the eruption of the mare basalts onto the lunar surface and the magnetization of lunar rocks. Even so, the model is not without shortcomings. The early thermal and chemical structure of the Moon, which forms boundary conditions for the model, is highly uncertain. Although the core may be free to convect for the conditions assumed, the process may not be energetic enough to explain the magnitude of magnetization of lunar rocks. Even by adding additional energy associated with 'freezing out' the liquid iron core, the model can just barely explain the palaeointensity of recently reanalysed lunar samples (C. Johnson, personal communication).

Some researchers continue to doubt that an internal dynamo is required to explain the

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magnetization of the Moon, and favour an alternative idea — that the observed magnetic signature was generated in association with large impacts during early history. In this model, magnetization should be concentrated diametrically opposite to major impact basins. Satellite observations from the Lunar Prospector mission show concentrations of crustal magnetization at the antipodes of some but not all large impact structures¹.

Although the results of the current study are not proof of an early lunar dynamo, they do demonstrate that it is theoretically possible for a dynamo to explain both the timing of the observed magnetization of the lunar crust and the eruption of mare basalts. Fur-

ther simulations, continued analysis of the palaeomagnetic properties of lunar samples and low-altitude global mapping of the Moon's magnetic signature will be required for a true grasp of the elusive nature of lunar magnetism. ■

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2. Stevenson, D. J. *Icarus* **54**, 466–489 (1983).
3. Hess, P. C. & Parmentier, E. M. *Earth Planet. Sci. Lett.* **134**, 501–514 (1995).
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Developmental biology

A larval revelation

Thurston Lacalli

Identification of the previously unknown larval forms of the sea lilies, a group of marine invertebrates, is a refreshing reminder of the value of descriptive science in evolutionary studies.

The stalked crinoids, or sea lilies, are generally accepted as the most ancient of living echinoderms, with a fossil record extending back some 500 million years, almost to the base of the Palaeozoic^{1,2}. They live in deep water, and are difficult to collect in good enough condition for laboratory study. In consequence, their embryos and larvae have never been observed — until now, that is. On page 158 of this issue³, Nakano *et al.* describe how they took advantage of the local crinoid populations in two deep bays, southwest of Tokyo, where adult animals come to within 100 m of the surface. Using gill nets rather than dredges and trawls, and enlisting the help of local fishermen, the authors obtained healthy, gravid individuals that spawned in the lab and produced viable embryos and larvae.

The main significance of this discovery lies in the rich evolutionary connections of the phylum Echinodermata and the information that such 'missing' larval forms contain. The larvae of marine invertebrates are delightfully diverse morphologically, and often delicately beautiful. Most are small (less than 1 mm high) and use bands of cilia, arranged in diverse ways, for feeding and locomotion. There is frequently a 'type' larva for a given phylum, and similarities between larval forms can reveal evolutionary links between phyla that are not always evident from the morphology of the adult (Fig. 1). Zoologists with an evolutionary bent are thus keenly interested in any report of a previously undescribed larva, especially if it belongs to an organism as evidently ancient as the sea lilies.

Nakano *et al.*³ find that the development

of sea lilies resembles that of feather stars, their better-known shallow-water cousins, in having a stage known as a doliolaria (Fig. 2). The doliolaria is a yolky and rather featureless ovoid, with a regular series of four or five hoop-like ciliary bands, that settles without feeding and metamorphoses into the juvenile crinoid. In sea lilies, however, the doliolaria is preceded by a stage that has sinuous, longitudinally oriented ciliary bands. Although this stage also does not feed, it resembles the feeding larvae of other echinoderms — sea stars, sea urchins, brittle stars and sea cucumbers — which have ciliary bands arranged in sinuous patterns along the sides of the larval body. Of these, the newly discovered larva is most similar to the auricularia larva of sea cucumbers, although it is somewhat simpler in shape. This is consistent with its having secondarily lost the

ability to feed during evolution, something that has occurred repeatedly in other echinoderm lineages⁴.

The possession of a ciliated plankton-feeding larva has generally been thought to be a primitive feature of echinoderms, in part because a closely related group of marine invertebrates, the hemichordates, have a similar stage. It has always been something of an embarrassment, therefore, that no such larva was known from crinoids, ostensibly the most primitive group. The new results support the contention that the ancestral life history of echinoderms involved both an auricularia-like feeding stage and a non-feeding doliolaria. This is of broader significance for two reasons.

As 'basal' members of the Deuterostomia, the group of phyla to which vertebrates belong, echinoderms are a potential source of clues to the origin of chordates (the phylum that includes vertebrates). This is a major evolutionary puzzle, and several of the more reasonable explanations suggest that chordates are derived from larvae that were very like the auricularia. In the best known of these hypotheses, formulated by Walter Garstang in 1894, the characteristic dorsal nerve cord of chordates is generated by folding together the bilaterally paired, longitudinally oriented, ciliary bands of just such a larva. The idea that ciliary bands might convert directly into nerve cord in this way is now less widely accepted, but ciliary bands are the chief sites of nerve formation in auricularia-type larvae, so their involvement in the evolution of the chordate nervous system is nevertheless still a reasonable supposition.

The arrangement of the bands in ancestral larvae is thus a consideration in any serious attempt to reconstruct the events leading to the chordate condition. Circumferential doliolaria-type arrangements need to be considered as well as longitudinal ones. Converting the former into a nerve cord would require some rearrangement, but echinoderm larvae are accomplished at manipulating the patterning of epithelia and ciliary bands during development⁵. The evolutionary significance of this ability could be considerable but is not yet at all understood.

The second issue concerns the survival pattern of larval characters during evolution. If the possession of both an auricularia-like feeding stage and a doliolaria is ancestral, then among modern echinoderms the sea cucumbers preserve the primitive pattern most fully. Yet molecular phylogenies and morphological analyses based on adult characters routinely place sea cucumbers near the top of phylogenetic trees, as a modified (derived) 'crown' group^{6,7}. Determining whether morphological characters are primitive or derived has always been difficult. But the sea cucumber is a clear case of an organism that is considered advanced and



Figure 1 Picture of lily — the stalked crinoid *Metacrinus rotundus*. (Photo courtesy of S. Amemiya.)