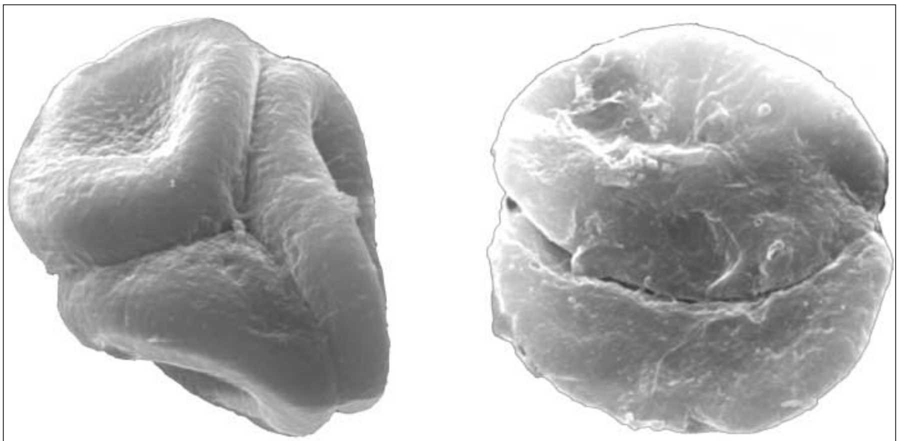

C. H. WELLMAN

Figure 1 **What the first land plants left behind. Evidence of the earliest land plants comes from spores extracted from 440–470-million-year-old rocks in Oman. The nature of the plants that produced these grains has remained a mystery, but Wellman *et al.*[1] have now found evidence that the spores were produced by minute land-dwelling plants that may have resembled liverworts. Unlike most of their modern counterparts, many of the earliest spores were dispersed in groups of four (tetrads; left) or in groups of two (diads; right). Spore diameter is 20 μm.**

spore-extraction methods to recover organic residues from Ordovician sediments collected from a borehole in Oman. When they passed the insoluble organic material through a series of sieves designed to trap plant fragments and spores of various sizes, the authors found many well-preserved spores — but they also found something much more intriguing. Trapped in the sieve containing the largest pores were elongated, disc-shaped objects that, on closer inspection, proved to be clumps of spores packaged in a type of cuticle. These fossil fragments are exciting because they resemble the spore-bearing organs of later land plants. So Wellman and colleagues' trawl through organic residues had netted a catch of the tiny plants that produced the spores. Although far from complete, these specimens indicate that the Ordovician spores were indeed produced by land plants and not by algae. But what did these early plants look like, and how are they related to modern plant forms?

The plants that produced the spores were certainly minute and probably simple, but these frustratingly incomplete fragments tell us little else. In a hunt for further clues, Wellman and colleagues looked in detail at the structure of the spore wall. They found a laminate interior resembling that of some living liverworts, which is consistent with other evidence[7,8] pointing to liverworts as the closest living relatives of the earliest land plants. Although intriguing, the spore-wall data are unlikely to win over the sceptics[6]. What we need now are more complete specimens of these tiny plants, and Wellman and colleagues' recovery techniques are clearly promising ways to achieve this.

One further issue raised by the new study is the possibility that plant life existed on land even before the Ordovician period. Could signs of plant life be awaiting discovery in even older rocks? Maybe so, according to one study[9]. These authors investigated the time of origin of land plants using a 'molecular clock' analysis, in which the timing of evolutionary divergence is inferred from comparisons of the gene sequences of living plant species. Controversially, this approach placed the common ancestor of all living land plants in the Precambrian period, around 700 million years ago. From a palaeontological perspective, the existence of land plants this long ago seems very unlikely. For one thing, there is no unequivocal evidence for land-plant spores in rocks predating the Ordovician period. Given the ubiquity of such spores in near-shore marine sediments throughout later periods, this dearth of microfossil data is telling. And different clocks tell different times — a more recent molecular analysis placed the origin of land plants close to the time predicted from the spore findings[10]. If plant life on land did predate the Ordovician period then it is very well hidden indeed. ■

Paul Kenrick is in the Department of Palaeontology, The Natural History Museum, Cromwell Road, London SW7 5BD, UK.
e-mail: P.Kenrick@nhm.ac.uk

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Global change

Probing early atmospheres

Stephen J. Mojzsis

Information about atmospheric conditions far back in Earth's history is embedded in the isotopic composition of fossil microbes. Such studies are technically demanding, but hold considerable promise.

What were atmospheric CO_2 concentrations like during the Proterozoic eon, the interval of Earth's history between about 2,500 million and 543 million years ago? The issue is germane to studies of the ancient biosphere because, owing to the way in which the Sun's composition and other properties evolved, its luminosity is thought to have increased gradually over time. Aside from a small contribution from internal heating that is driven by radioactive decay, the surface temperatures of a planet are governed by the amount of solar radiation it receives and how this interacts with the atmosphere. The fact that greenhouse gases, chiefly CO_2 (but also water vapour and methane), re-radiate infrared radiation to the surface keeps the present average surface temperature some 33 K above what it would otherwise be. Models of solar luminosity[1] indicate that if the greenhouse had not been much greater early in Earth's history, global glaciation should have held sway throughout the Proterozoic and the preceding Archaean eon, which stretches back to about 3,900 million years ago.

However, various lines of reasoning suggest that, over geological time, Earth has maintained surface pressures and temperatures that were conducive to the presence of liquid water, and thereby a global habitat for life. Carbon dioxide has always been an important greenhouse gas. But how much was present in the atmosphere during the Proterozoic, when the surface biosphere became transformed from a wholly microbial and anoxic world to an oxygenated domain poised for the emergence of diverse multicellular life?

On page 279 of this issue[2], Kaufman and Xiao describe their use of a novel approach to this question in comparing the carbon-isotope compositions of eukaryotic algal microfossils (acritarchs) to those of 'consanguineous carbonate' — that is, carbonate


SHUHAI XIAO

Figure 1 **Shot on site — an outcrop of the Ruyang Group in Shanxi Province, China.**

produced from CO_2 by inorganic processes at around the same time. They interpret well-characterized acritarchs, extracted from shales of the Ruyang Group in North China (Fig. 1), as representing the remains of marine organic matter produced during active photosynthesis[3]. The ages of the Ruyang Group rocks are only imprecisely known. But from correlation with the Roper Belt sediments of Western Australia, which contain similar fossil forms[4] and have recently been investigated for sulphur-isotope variability[5], they are estimated to be around 1,400 million years old — that is, mid-Proterozoic in age. Microbes are important players in long-term global biogeochemical cycles, not least by maintaining an oxygen-rich atmosphere through the oxygenic photosynthetic reaction:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

Because a short-circuit exists in the marine carbon cycle, whereby some organic carbon ($C_6H_{12}O_6$) is stored as sedimentary organic matter, a net leakage of oxygen to the atmosphere results. Carbonate carbon and organic molecules are respectively derived from CO_2 through precipitation in water and photosynthesis. Isotopic effects associated with these reactions lead to a fractionation of the $^{13}C/^{12}C$ ratio, between organic carbon and carbonate carbon that is in equilibrium with atmospheric CO_2, of about 25 parts per thousand (25‰). So organic materials are depleted in ^{13}C relative to consanguineous carbonate.

At present, marine photosynthesis responsible for about 99% of primary productivity is performed by single-celled eukaryotic algae using the Calvin cycle[6] — a major pathway for oxygenic photosynthesis. Kaufman and Xiao's approach[2] makes sense, because the source carbon in photosynthesis is CO_2, and the morphologically complex organisms found in the Ruyang shales are reasonably interpreted as eukaryotic organisms that used the Calvin cycle. As a result, it becomes possible to estimate the CO_2 concentration in the system using the magnitude of carbon-isotope fractionation (ϵ_p) between organic carbon and carbonate. This tactic works if the carbon-isotopic composition of individual acritarchs can be measured.

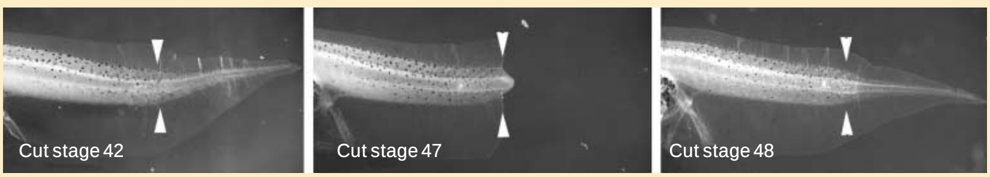
For this purpose, Kaufman and Xiao used an ion-microprobe technique, in which a beam of caesium ions is focused on minute carbonaceous particles to measure their $^{13}C/^{12}C$ ratio at high mass resolution. This is an improvement over attempts to measure carbon isotopes in individual microfossils[7]. Kaufman and Xiao isolated the acritarchs from the Ruyang shales by acid extraction, allowing for rapid repeat carbon-isotope measurements of separate fossils and ensuring

Developmental biology

A tadpole's tale

If tadpoles of the African clawed toad *Xenopus laevis* lose their tail, they can usually make another — but not always. So say Caroline W. Beck and colleagues, who have identified a 'refractory period' during which tails cannot regenerate (*Dev. Cell* **5,** 429–439; 2003). Studies of this down-time have provided insight into the molecular mechanisms that underlie tail regeneration.

The ability to regenerate limbs is scattered throughout the animal kingdom, even occurring in the adults of some species — certain lizards, for instance. But the phenomenon is not well understood at the molecular level. Beck *et al.* have used a variety of new molecular techniques to tackle this question.



The authors started by investigating tail regeneration at different stages of tadpole development. They found that 3 and 7 days into development, at stages 42 and 48, around two-thirds of the tadpoles could regrow their tails after amputation (see picture; the arrowheads represent the position at which the tail was amputated). At stage 49 and beyond, that figure was near 100%. But at stages 46 and 47, only a very few of the tails regenerated (although the tadpoles developed into froglets normally).

What's going on during this refractory period? A look at the regenerating tails showed that a thin skin formed over the cut stump, and that unspecialized cells accumulated beneath the skin; these later began to produce the spinal cord, muscle cells and other cells required for tail formation. This did not occur in the non-regenerating tails.

Proteins involved in the bone morphogenetic protein (BMP) and Notch signalling pathways are required for embryonic tail development. Might they also be expressed in regenerating tails? Beck *et al.* show that they are, but that they are not expressed in tails amputated during the refractory period. If, however, the BMP receptor is forcibly expressed during this period, tail regeneration occurs in nearly all cases. Further findings hint that the BMP pathway activates the Notch pathway to regenerate the spinal cord, but works independently of Notch to regenerate muscle. Whether these molecular events underlie the remarkable phenomenon of regeneration more generally remains to be seen. **Amanda Tromans** sample homogeneity, so it can be argued that no significant amount of secondary organic matter has affected the isotopic composition of the primary photosynthetic product.

Analyses of the $^{13}C/^{12}C$ of individual acritarchs, coupled with calculated magnitudes of ϵ_p depending on the CO_2 levels of the growth medium and volume/surface-ratio estimates of the original algal forms, suggest that, around 1,400 million years ago, CO_2 levels were at least 10 times and possibly more than 200 times higher than at present. The results agree broadly with studies[8] on the iron mineralogy of 'weathering profiles' (palaeosols), estimated at 2,750 million years old, which placed a minimum value for CO_2 of about 100 times those of today. But is this enough CO_2 to have kept the Proterozoic in a suitable greenhouse state?

Models of solar evolution[9] indicate that the Sun was only about 88% of its present luminosity at the time of deposition of the Ruyang Group. A typical solution to why there was no planetary freeze throughout the Archaean and Proterozoic is to invoke the existence of CO_2 levels on the early Earth of around 1,000 times present levels[10]. Such a CO_2-rich atmosphere can be qualitatively justified by theoretical feedback mechanisms that link increased volcanism and decreased continental weathering resulting in mineral dissolution in liquid water, and thereby to higher atmospheric CO_2 concentrations.

The new results[2] appear to be close to the limits required in atmospheric models to overcome diminished solar luminosity[11]. Other workers have proposed that a combination of gases, probably including a large contribution from methane produced by living organisms, kept the early Earth from being permanently frozen over[12]. But once free oxygen became a major atmospheric constituent between 2,300 million and 2,100 million years ago, it shortened the photochemical lifetime of methane, diminishing its greenhouse influence. All in all, it would seem that the imposition of high, steady-state concentrations of CO_2 is consistent with the temperature record of a mostly ice-free Proterozoic.

Studies of the early Earth are dogged by the meagre evidence available: discontinuities punctuate the entire sweep of the ancient rock record. But they can be tackled by intertwining strands of evidence from, for instance, geochemistry, geophysics, 'fossil morphometrics' and analyses of the molecular phylogenetic relationships between living organisms. 'Geobiology' is an innovative and inspiring venture in the Earth sciences[13], and by linking metabolism to CO_2 concentrations, Kaufman and Xiao have provided a promising way of improving our understanding. The way forward is to pursue independent proxy measures of atmospheric CO_2 levels, and the isotopic payload of fossil microbes may prove an excellent source of such measures. ■

Stephen J. Mojzsis is in the Department of Geological Sciences, Center for Astrobiology, University of Colorado, Boulder, Colorado 80309-0399, USA.
e-mail: mojzsis@colorado.edu

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Viral genetics

Deadly partnerships

Steven A. Frank

Pairs of viral genomes work together to destroy their hosts more quickly. How this might occur remains unknown, but study of the phenomenon should provide insight into how genetic systems evolve.

Early in the history of life, different copies of replicating nucleic acids must have existed near each other. Some of these genomes probably parasitized their neighbours by becoming shorter, dropping essential information and using proteins encoded by the full-length molecules. The shorter parasitic genomes might have replicated faster and out-competed their fully endowed neighbours. Other pairs probably complemented each other to mutual benefit, favouring some method for the pair to disperse together. Viral systems provide our best window back through time, allowing us to glimpse how multi-copy genetic systems might have evolved. There are many known examples of shortened viral genomes exploiting functional partners[1], but writing in the *Proceedings of the Royal Society*, López-Ferber and colleagues[2] now show that defective viral genomes are not always parasitic. They provide evidence that shortened

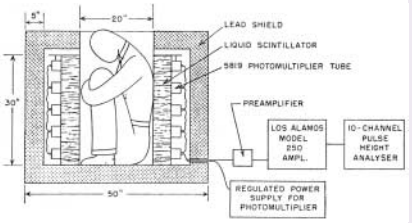
NATURE

100 YEARS AGO

From the study of rays of measurable wavelengths we have lately sailed under the guidance of M. Henri Becquerel into another region where it is doubtful whether all the rays conform to the undulatory theory. In fact some of the rays are believed to be charged particles of matter, charged, that is to say, with electricity. Beyond doubt they are possessed of very extraordinary properties, inasmuch as they are able to penetrate the clothing, celluloid, gutta percha, glass, and various metals. They are, moreover, endowed with a no less remarkable physiological action, producing blisters and ulcerations in the flesh which are difficult to heal… From this we can quite understand that there is no exaggeration in the statement attributed to the discoverer, Prof. Curie,… that he would not care to trust himself in a room with a kilogram of pure radium, because it would doubtless destroy his eyesight, burn all the skin off his body, and probably kill him.
From *Nature* 17 September 1903.

50 YEARS AGO

In the course of developing equipment for other problems, we have made some measurements of the total radioactivity content of several humans and a dog, using a technique which may have other applications in biophysics… (See Fig. 1). A dog of approximately 35 lb. weight was anaesthetized and counted in the small insert. A solution containing 0.1 μC. radium



in equilibrium with its decay products was injected into the femoral vein, and (five min. after injection) the dog was again 'counted'… The large insert was used for the measurements on humans, who were able by doubling up to be entirely within the insert… In the absence of the radium group, the potassium content of the body can be measured with good accuracy, and it is quite conceivable that application of these techniques could yield important results in the study of the role of potassium in the metabolic process. F. Reines, C. L. Cowan *et al.*
From *Nature* 19 September 1953.