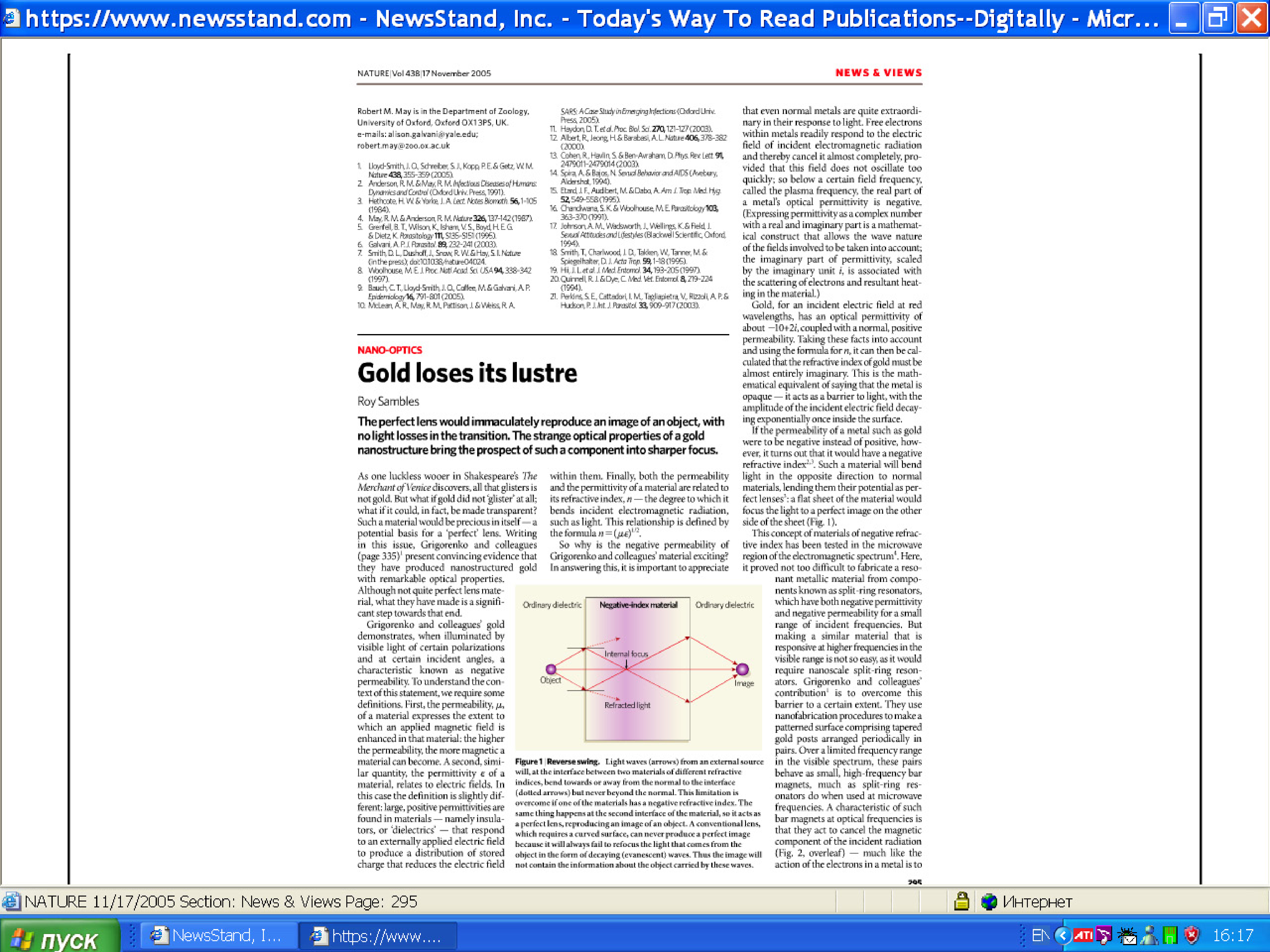

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NANO-OPTICS

Gold loses its lustre

Roy Sambles

The perfect lens would immaculately reproduce an image of an object, with no light losses in the transition. The strange optical properties of a gold nanostructure bring the prospect of such a component into sharper focus.

As one luckless wooer in Shakespeare's *The Merchant of Venice* discovers, all that glisters is not gold. But what if gold did not 'glister' at all; what if it could, in fact, be made transparent? Such a material would be precious in itself — a potential basis for a 'perfect' lens. Writing in this issue, Grigorenko and colleagues (page 335)[1] present convincing evidence that they have produced nanostructured gold with remarkable optical properties. Although not quite perfect lens material, what they have made is a significant step towards that end.

Grigorenko and colleagues' gold demonstrates, when illuminated by visible light of certain polarizations and at certain incident angles, a characteristic known as negative permeability. To understand the context of this statement, we require some definitions. First, the permeability, μ, of a material expresses the extent to which an applied magnetic field is enhanced in that material: the higher the permeability, the more magnetic a material can become. A second, similar quantity, the permittivity ε of a material, relates to electric fields. In this case the definition is slightly different: large, positive permittivities are found in materials — namely insulators, or 'dielectrics' — that respond to an externally applied electric field to produce a distribution of stored charge that reduces the electric field within them. Finally, both the permeability and the permittivity of a material are related to its refractive index, n — the degree to which it bends incident electromagnetic radiation, such as light. This relationship is defined by the formula $n=(\mu\varepsilon)^{1/2}$.

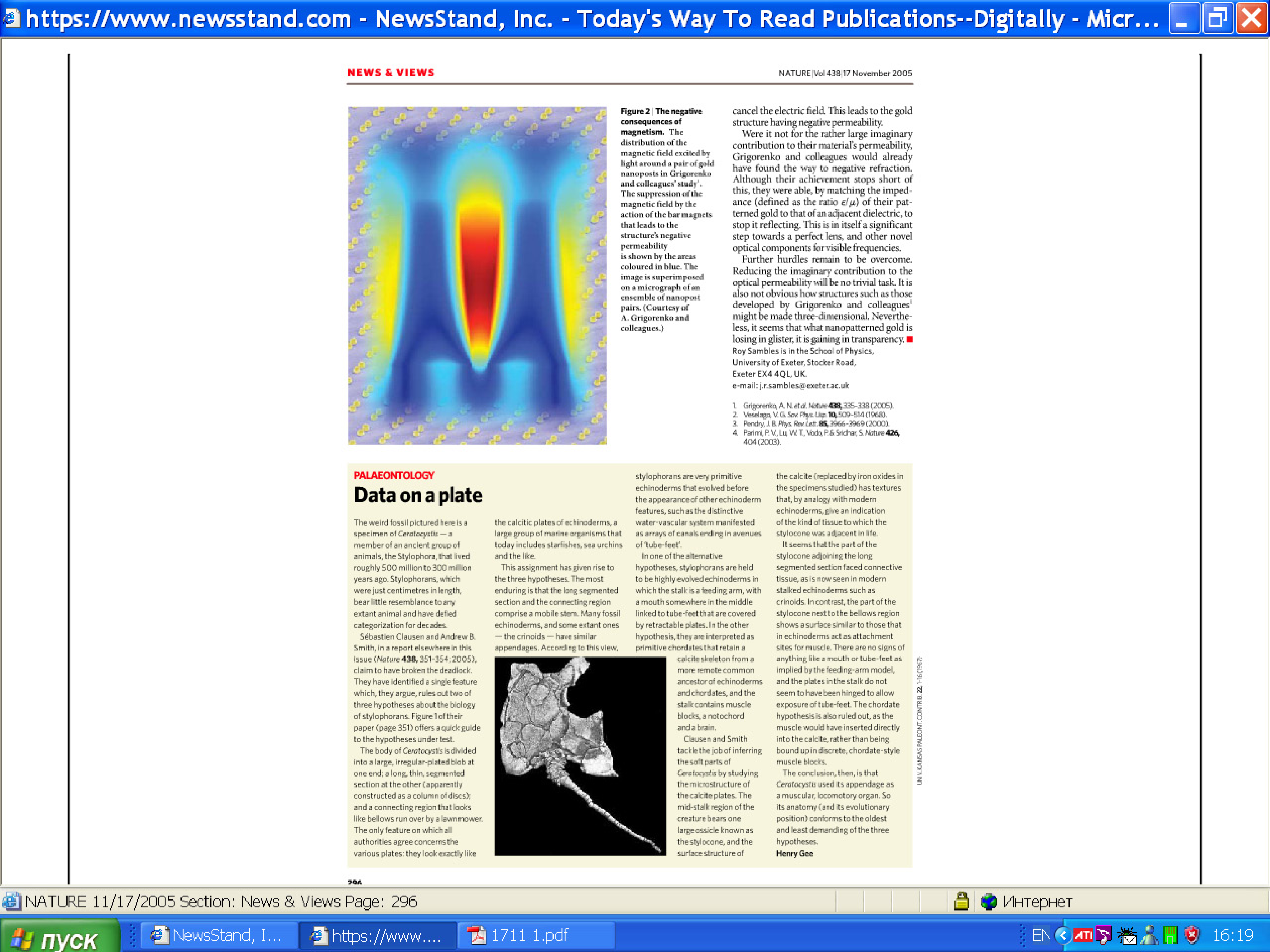
So why is the negative permeability of Grigorenko and colleagues' material exciting? In answering this, it is important to appreciate that even normal metals are quite extraordinary in their response to light. Free electrons within metals readily respond to the electric field of incident electromagnetic radiation and thereby cancel it almost completely, provided that this field does not oscillate too quickly; so below a certain field frequency, called the plasma frequency, the real part of a metal's optical permittivity is negative. (Expressing permittivity as a complex number with a real and imaginary part is a mathematical construct that allows the wave nature of the fields involved to be taken into account; the imaginary part of permittivity, scaled by the imaginary unit i, is associated with the scattering of electrons and resultant heating in the material.)

Gold, for an incident electric field at red wavelengths, has an optical permittivity of about $-10+2i$, coupled with a normal, positive permeability. Taking these facts into account and using the formula for n, it can then be calculated that the refractive index of gold must be almost entirely imaginary. This is the mathematical equivalent of saying that the metal is opaque — it acts as a barrier to light, with the amplitude of the incident electric field decaying exponentially once inside the surface.

If the permeability of a metal such as gold were to be negative instead of positive, however, it turns out that it would have a negative refractive index[2,3]. Such a material will bend light in the opposite direction to normal materials, lending them their potential as perfect lenses[3]: a flat sheet of the material would focus the light to a perfect image on the other side of the sheet (Fig. 1).

This concept of materials of negative refractive index has been tested in the microwave region of the electromagnetic spectrum[4]. Here, it proved not too difficult to fabricate a resonant metallic material from components known as split-ring resonators, which have both negative permittivity and negative permeability for a small range of incident frequencies. But making a similar material that is responsive at higher frequencies in the visible range is not so easy, as it would require nanoscale split-ring resonators. Grigorenko and colleagues' contribution[1] is to overcome this barrier to a certain extent. They use nanofabrication procedures to make a patterned surface comprising tapered gold posts arranged periodically in pairs. Over a limited frequency range in the visible spectrum, these pairs behave as small, high-frequency bar magnets, much as split-ring resonators do when used at microwave frequencies. A characteristic of such bar magnets at optical frequencies is that they act to cancel the magnetic component of the incident radiation (Fig. 2, overleaf) — much like the action of the electrons in a metal is to

Figure 1 | Reverse swing. Light waves (arrows) from an external source will, at the interface between two materials of different refractive indices, bend towards or away from the normal to the interface (dotted arrows) but never beyond the normal. This limitation is overcome if one of the materials has a negative refractive index. The same thing happens at the second interface of the material, so it acts as a perfect lens, reproducing an image of an object. A conventional lens, which requires a curved surface, can never produce a perfect image because it will always fail to refocus the light that comes from the object in the form of decaying (evanescent) waves. Thus the image will not contain the information about the object carried by these waves.



cancel the electric field. This leads to the gold structure having negative permeability.

Were it not for the rather large imaginary contribution to their material's permeability, Grigorenko and colleagues would already have found the way to negative refraction. Although their achievement stops short of this, they were able, by matching the impedance (defined as the ratio ϵ/μ) of their patterned gold to that of an adjacent dielectric, to stop it reflecting. This is in itself a significant step towards a perfect lens, and other novel optical components for visible frequencies.

Further hurdles remain to be overcome. Reducing the imaginary contribution to the optical permeability will be no trivial task. It is also not obvious how structures such as those developed by Grigorenko and colleagues[1] might be made three-dimensional. Nevertheless, it seems that what nanopatterned gold is losing in glister, it is gaining in transparency. ■

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Figure 2 | The negative consequences of magnetism. The distribution of the magnetic field excited by light around a pair of gold nanoposts in Grigorenko and colleagues' study[1]. The suppression of the magnetic field by the action of the bar magnets that leads to the structure's negative permeability is shown by the areas coloured in blue. The image is superimposed on a micrograph of an ensemble of nanopost pairs. (Courtesy of A. Grigorenko and colleagues.)

PALAEONTOLOGY

Data on a plate

The weird fossil pictured here is a specimen of *Ceratocystis* — a member of an ancient group of animals, the Stylophora, that lived roughly 500 million to 300 million years ago. Stylophorans, which were just centimetres in length, bear little resemblance to any extant animal and have defied categorization for decades.

Sébastien Clausen and Andrew B. Smith, in a report elsewhere in this issue (*Nature* **438,** 351–354; 2005), claim to have broken the deadlock. They have identified a single feature which, they argue, rules out two of three hypotheses about the biology of stylophorans. Figure 1 of their paper (page 351) offers a quick guide to the hypotheses under test.

The body of *Ceratocystis* is divided into a large, irregular-plated blob at one end; a long, thin, segmented section at the other (apparently constructed as a column of discs); and a connecting region that looks like bellows run over by a lawnmower. The only feature on which all authorities agree concerns the various plates: they look exactly like the calcitic plates of echinoderms, a large group of marine organisms that today includes starfishes, sea urchins and the like.

This assignment has given rise to the three hypotheses. The most enduring is that the long segmented section and the connecting region comprise a mobile stem. Many fossil echinoderms, and some extant ones — the crinoids — have similar appendages. According to this view, stylophorans are very primitive echinoderms that evolved before the appearance of other echinoderm features, such as the distinctive water-vascular system manifested as arrays of canals ending in avenues of 'tube-feet'.

In one of the alternative hypotheses, stylophorans are held to be highly evolved echinoderms in which the stalk is a feeding arm, with a mouth somewhere in the middle linked to tube-feet that are covered by retractable plates. In the other hypothesis, they are interpreted as primitive chordates that retain a calcite skeleton from a more remote common ancestor of echinoderms and chordates, and the stalk contains muscle blocks, a notochord and a brain.

Clausen and Smith tackle the job of inferring the soft parts of *Ceratocystis* by studying the microstructure of the calcite plates. The mid-stalk region of the creature bears one large ossicle known as the stylocone, and the surface structure of the calcite (replaced by iron oxides in the specimens studied) has textures that, by analogy with modern echinoderms, give an indication of the kind of tissue to which the stylocone was adjacent in life.

It seems that the part of the stylocone adjoining the long segmented section faced connective tissue, as is now seen in modern stalked echinoderms such as crinoids. In contrast, the part of the stylocone next to the bellows region shows a surface similar to those that in echinoderms act as attachment sites for muscle. There are no signs of anything like a mouth or tube-feet as implied by the feeding-arm model, and the plates in the stalk do not seem to have been hinged to allow exposure of tube-feet. The chordate hypothesis is also ruled out, as the muscle would have inserted directly into the calcite, rather than being bound up in discrete, chordate-style muscle blocks.

The conclusion, then, is that *Ceratocystis* used its appendage as a muscular, locomotory organ. So its anatomy (and its evolutionary position) conforms to the oldest and least demanding of the three hypotheses.

Henry Gee

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