At the Dawn of Archaic Sex

Birth, and copulation, and death.
That's all the facts when you come to brass tacks:
Birth, and copulation, and death
I've been born, and once is enough.

T.S. Eliot
'*Sweeney Agonistes*'

So when and why did organisms first start reproducing by sex? By 'sex' here we mean that instead of simply shedding or budding off a piece of themselves to create a new identical form of life (a clone having the exact same DNA as the original), two organisms decided to get together and share their genetic material to create a more genetically variable kind of offspring.

Most primitive forms of life can be divided into those that lack a nucleus in their cells (prokaryotes) and those with a nucleus (eukaryotes). Most organisms that we associate with today – the complex multicellular animals and plants (called 'metazoans') – are eukaryotes which contain nuclear DNA inside them. Most eukaryotic organisms undergo sexual reproduction, the sharing of genetic material to make a new generation, although some can reproduce asexually by budding off identical clones. Some animals like hydras (a relative of the jellyfish) can reproduce sexually or bud off clones depending on food availability. 'Sex' in the biological sense is really defined by the process of meiosis and gametogenesis, when cells divide in such a way to produce gametes (for example, egg or sperm cells) by halving their chromosomes. When male and female gametes from different organisms unite, the chromosome halves recombine to begin making a genetically unique new organism. So how can fossils shed light on such microscopic and delicate processes that took place not just million of years ago, but probably a billion or more years gone by?

To try to answer this question, it might help to briefly look at the life of a truly extraordinary man named Reginald Sprigg, whose work in the field of geology begat a whole new field of study that has since revolutionized our understanding of the early evolution of multicellular organisms. Born in 1919 in Stansbury, on South Australia's Yorke Peninsula, Reg collected fossils and shells from his local beach as a boy and later become fascinated by minerals through a chance meeting with an old miner. Studying science at Adelaide University, he was fortunate to learn under greats such as Sir Douglas Mawson and Professor Cecil Madigan, both veterans of Antarctic exploration. Mawson is quoted as saying that Sprigg was his 'best ever student'. Sprigg was inquisitive and liked to question and challenge the views of his professors at time when it was not common to do so.

After he graduated in zoology in 1941, with honors in geology, Sprigg was brought on board an Australian Government top-secret project searching for Australian uranium deposits. This was wartime, and a great race had begun to develop and utilize the secret properties of uranium. It would result in the first atomic bombs being built, and ultimately end the war in the Pacific through the horrific events at Hiroshima and Nagasaki. Reg worked on several key deposits in Australia and was sent to study uranium deposits in the USA, Europe and the UK in order to extend his knowledge of the geological settings of uranium-bearing ores. On his return to Australia in 1950 he was perhaps the world's most highly regarded source on the subject.

Despite his groundbreaking work, forces within the Australian Government hindered his work, keeping information from him. In the end he handed his uranium studies over to others and switched his brilliant mind to working on petroleum exploration. But a discovery he stumbled upon during his uranium field work in the Ediacara Hills of the South Australia's Flinders Ranges remains a legacy. At the time he determined that the strange fossils were probably of Early Cambrian age (about 540 million years old), both through his geological mapping of the area and also because at the time no large metazoan (multicellular) fossils such as the ones he had found had ever been found in the older Precambrian rocks. Reg identified the fossils as being impressions of jellyfish and first exhibited them at an ANZAAS (Australian and New Zealand Association for the Advancement of Science) meeting in 1946. Recognizing the significance of the very old age of these finds, he published two important papers in the *Transaction of the Royal Society of South Australia* in 1947 and 1949, describing various species of early jellyfishes from his new sites.

Enter Martin Glaessner, Bohemian-born paleontologist extraordinaire. Trained in Vienna, Professor Martin Glaessner had fled Nazi Germany with his Russian ballerina wife during the war years to find work in New Guinea with Shell before ultimately arriving in Australia. After a stint in Melbourne he settled into a steady job at the University of Adelaide, where the Ediacara Hills fossils found by Reg Sprigg caught his attention. In 1958 Glaessner published a paper similar to Sprigg's on new forms of Lower Cambrian (that is, lower in rock strata) fossils from Ediacara, but in that year everything would change when a discovery from the other side of the world would show the Ediacaran fossils in a whole new light.

When Dr Trevor Ford from Leicester University published the first account of undoubted Precambrian-age fossils from a site in the Charnwood Forest of England in 1958, he described a frond-like organism he named *Charnia masoni*, similar forms of which were known at Ediacara. Martin Glaessner then went to print with his landmark paper in *Nature* on Precambrian jellyfish and other coelenterates (the phylum which jellyfish and sea-anemones belong) from Ediacara, Africa (Namibia) and England, announcing to the world that the oldest known assemblage of fossils came from Australia. This was soon followed by an article about these ancient fossils which nabbed him the cover of *Scientific American* in 1961. The Ediacaran fossils have been studied and collected intensely ever since, and still they keep shedding their secrets. Today these fossils are known as the 'Ediacaran Biota' and are accurately dated at around 560 million years old, well before the explosion of life occurred in the Cambrian period 540 million years ago.

Reg Sprigg's legacy lives on in the naming of a new geological time period, the first one to be described in over a century. The Ediacaran period was formally established in 2004, delineating an age range of 542 to 635 million years ago. This is now widely known as the time when multicellular life first emerged in a variety of shapes and sizes. And this means that for such diversity to occur at this time in life, sex must have evolved.

The man who would discover sex in the Ediacaran fossil record first started collecting in the Ediacara Hills back in 1971, but would not realize his discovery until 2008. Dr Jim Gehling, a colleague and friend who is now curator at the South Australian Museum in Adelaide, began working on the Ediacaran fossils in 1971, tracing out layers containing the fossils in other regions of the Flinders Ranges. In 1972, he and fellow worker Colin

Ford found a remarkable new site where fossils showed what appeared to be frond-like organisms with the broad base of the animal that held it to the sea-floor in the same bedding planes. These fossils challenged previous interpretations by Glaessner that the Ediacaran fossils were washed-up remains on intertidal flats. Gehling's work hinted that they could be much deeper water dwellers. The debate about Ediacaran organisms, what they actually are and how deep they lived goes on to this day, and one very recent discovery made international headlines when published in *Science* in 2008: it announced the discovery of the origin of sex.

The paper by Mary Droser and Jim Gehling described a new kind of organism from the Ediacara site which they named *Funisia*. *Funisia* was a worm-like tubular organism, the fossils of which are found abundantly at the Ediacara sites, so much so that different stages of its growth can be studied and measured in detail. Droser and Gehling identified that these organisms were budding off 'sprats', or juveniles from the adult, which were all at a similar growth stage. Hence instead of shedding or budding asexually (shedding identical clones of itself), as expected for primitive organisms of this period, it is likely that the 'sprats' developed all at the same time due to an act that begat them all: sex. Put simply, if they were budding asexually then a wider range of sizes would be expected in the juveniles. The fact that they were always at the same size suggested an act that was timed, a mutual shedding of sperm and eggs into the water as occurs for corals.

A *London Times* story about the discovery explained that 'the knobbly animal, named *Funisia dorothea*, is thought most likely to have reproduced in a similar way to modern corals and sponges, but little else is understood of its biology.' And, of course, the journalist went on to ask the scientists if the *Funisia* would have enjoyed sex:

'Sex for the creature would have been functional rather than a social affair,' Professor Droser, of the University of California, Riverside, said. 'I think they would have been way too basic to have enjoyed the sex. I don't think they would wind around each other. But I could be wrong – I would like to think they enjoyed it.'

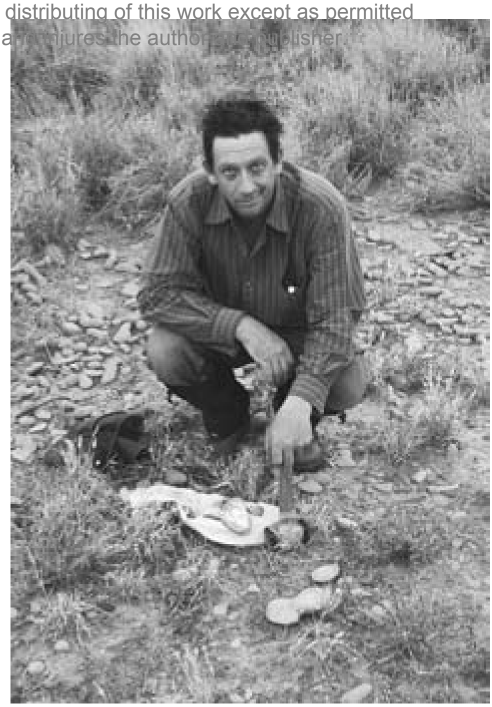
These Ediacaran fossils provide circumstantial evidence, given the rigorous analysis of data carried out by the scientists, of a very early sexual reproductive event occurring in a similar way to how corals and sponges shed their gametes into the water before a period of new growth. This begs the question: could this form of sexual reproduction have been going on even further back in time?

The oldest known eukaryotic fossils are possibly the weird spirals resembling swirling party streamers known as *Grypania*, which have been found in rocks as old as 1.8 billion years in sites in both Michigan and Montana in the USA. One theory is that they are giant algae but others hold they could be large cyanobacteria, which in colonies build mounds of layered structures called stromatolites by trapping floating particles of sediment (excellent examples of these can be found alive today at Hamlin Bay in Western Australia). Bacteria do not use sex to reproduce; they just clone themselves. But it is more likely, given the rarity of large coil-shaped bacteria today, that the fossils are indeed algae, which all reproduce by sexual means, so *Grypania* could represent the oldest fossil evidence we have of sexually reproducing organisms?

Yet fossils can be more than just the remains of once-living creatures. Sometimes chemicals leave us traces of where life was before, like a ghost in the rocks. For example, in 1999 Jochen Brocks of the then Australian Geological Survey Organisation in Canberra and his colleagues pushed back the tentative origin of eukaryotes to about 2.7 billion years ago from their identification of complex biomarkers in the form of certain lipids (fats) in rocks of the Western Australian Pilbara region, which are unique in their chemical signature to those of living eukaryotic tissues. In August 2008 Birger Rasmussen of Curtin University in Western Australia and his colleagues published an important paper in *Nature* that critically reassessed the ages of biomarkers for eukaryotic cells. Their work shot down this earlier age of 2.7 billion years by chemical arguments that the biomarkers entered the rocks after metamorphic events – rocks being heated and crushed at great temperature and pressure. Their new estimates for the origins of reliable eukaryotic fossils now rest at 1.78 to 1.68 billion years ago, and this date, dear readers, is where we must currently park the idea of when sex first possibly began.

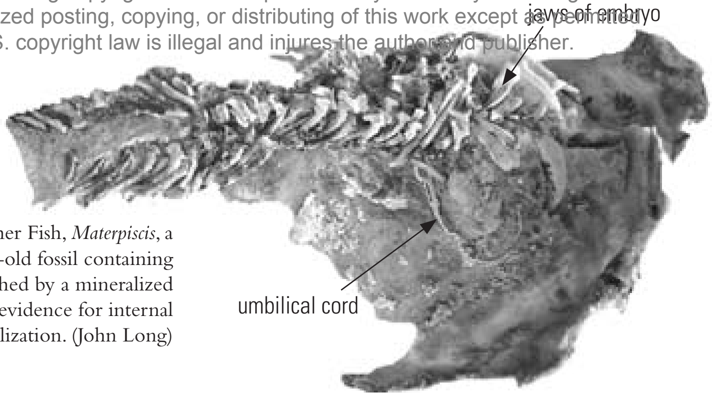
The age-old question that follows this is *why* did sexual reproduction begin? Why didn't life just keep evolving with simple cloning and asexual budding systems? Wouldn't it be easier if we were all like little freshwater hydras, where instead of performing complex mating rituals we humans simply grew a rather large lump on our bodies which eventually budded off like a festered sore, and from it emerged a perfect clone of ourselves? Maybe easier, but no fun at all, especially as we would all look the same

The Argentine lake duck, *Oxyura vittata*, sports the longest penis relative to body size of any vertebrate animal, this one measuring 1.3 feet (42.5 centimeters) extended. (Courtesy Dr Kevin McCracken, Alaska)



The author at the Gogo fossil site, in northern Western Australia in 2008. The rounded limestone concretions on the ground sometimes contain fossil fishes. (Peter Long)

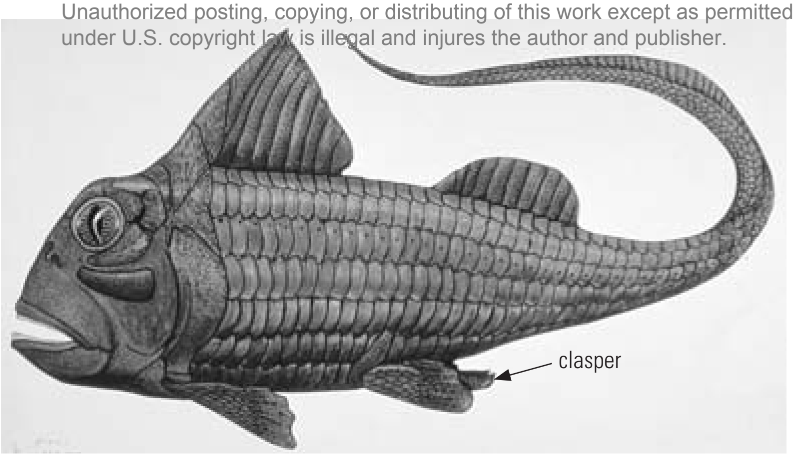
An adult male Californian gray whale, *Eschrichtius robustus*, displaying his penis in San Ignacio Lagoon, Mexico. (© Michael S. Nolan/SeaPics.com)



The Mother Fish, *Materpiscis*, a 380-million-year-old fossil containing an embryo attached by a mineralized umbilical cord – evidence for internal fertilization. (John Long)

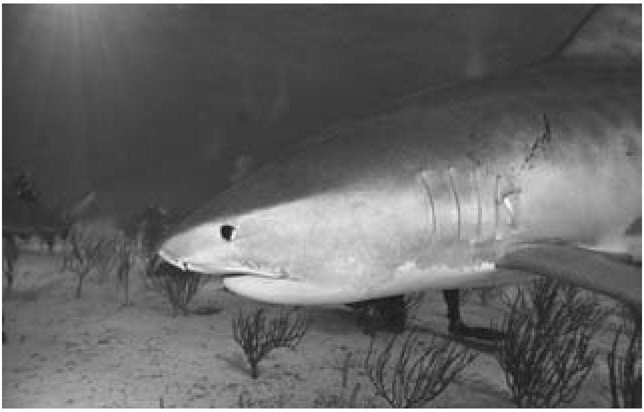
The pelvic girdle and clasper of *Incisoscutum*, an arthrodire placoderm from Gogo. The long basipterygium has the clasper fused to the end of it. (Sexual organs arrowed.) (John Long)

A placoderm fossil from Victoria, *Austrophyllolepis*, showing long pelvic girdle (basipterygium), indicating it mated by copulation. (Sexual organs arrowed.) (John Long)



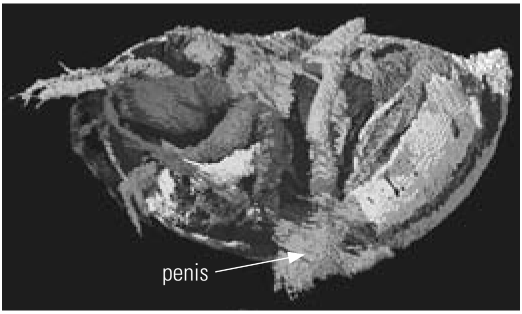
A male Gogo ptyctodontid fish, *Campbellodus,* showing clasper attached to pelvic fin. (Sexual organs arrowed.) (John Long)

A mating pair of nurse sharks, *Ginglymostoma cirratum*, in the Florida Keys, US. Sharks and rays all mate by copulation using claspers. (© Jeffrey C. Carrier/SeaPics.com)

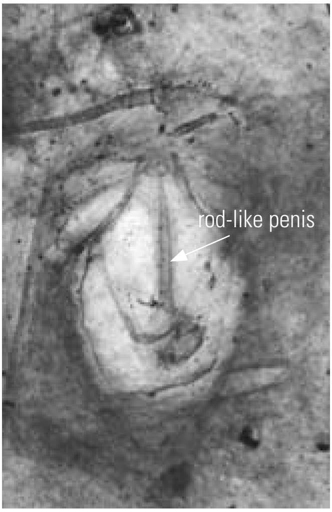


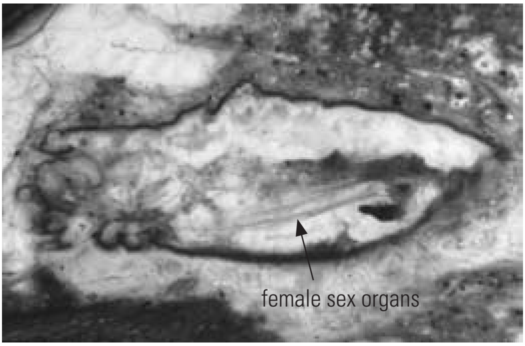
You can see the mating scars on the flank of this female tiger shark, *Galeocerdo cuvieri*.

The grunion run, a mating frenzy of ray-finned fishes which mass-spawn under the full moon in summer.



A CT scan image of a remarkable 425-million-year-old fossil bivalved crustacean (ostracod) with penis preserved (arrowed), dubbed by tabloids as 'the world's oldest willy'. (Courtesy Dr David Siveter)



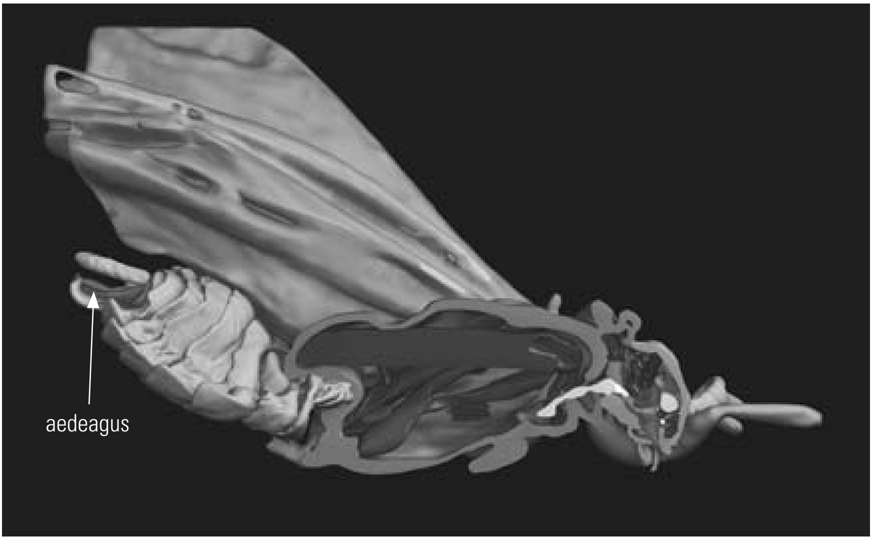


Male (left) and female (above) fossilized harvestman organs 410 million years old from the Rhynie Chert in Scotland. (Courtesy Dr Jason Dunlop)

(Top left) Two blue-back bedbugs having traumatic sex in which the male violently inserts his penis into the body of the female.

(Above) A female praying mantis mating with and eating her mate. The act of being eaten apparently causes the male to eject more sperm during his last moments.

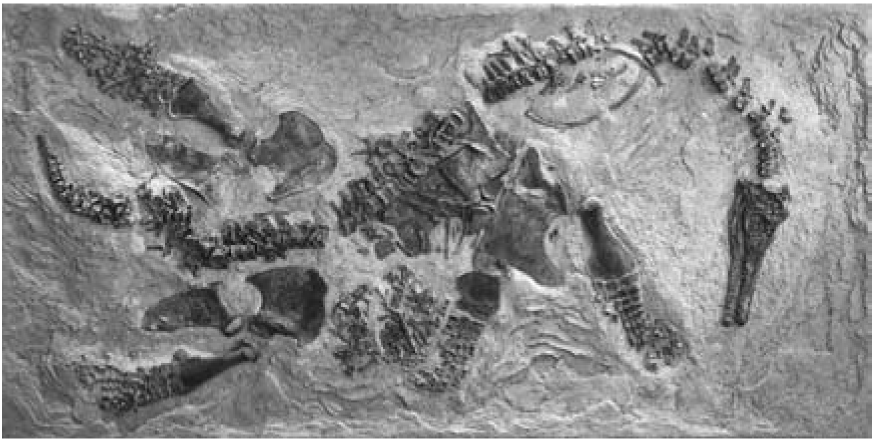
(Left) Dragonflies were one of the first animals studied to show that males can remove the sperm of previous matings while inseminating a female.



A 42-million-year-old stresipteran insect, *Mengea tertiaria*, preserved in amber, showing the insect's penis (aedeagus). (Courtsey Professor Hans Pohl, Germany)

Necrophiliac snakes. Four male garter snakes in Manitoba, Canada, courting (chin-rubbing) a female who is so long dead that she's turned blue. (Courtesy Professor Rick Shine)

Captive Galápagos turtles in the act of mating. It takes a few hours and a long penis for the male to reach the female's cloaca with large shells in the way.



A 70-million-year-old plesiosaur, *Polycotylus,* from Kansas, with embryo, the first evidence these animals reproduced by copulation. (© Natural History Museum of Los Angeles County, with permission)

Fossil dire wolf skeleton, *Canis dirus*, from La Brea site in Los Angeles. This example is a male clearly showing the penis bone (baculum). (John Long, with permission Page Museum, LA)

This fossil penis bone (baculum) of a 12,000-year-old walrus from Siberia measures 4.5 feet (140 centimeters) – the world's largest fossil sexual organ. (©2011 Ripley Entertainment Inc)

Spotted hyena mother, *Crocuta crocuta*, with her young pups. Female hyenas bear a penis-like clitoris and give birth painfully through it.

Bonobos, *Pan paniscus*, are our closest animal relatives, and like us they show a diverse range of sexual behaviors, used for social as well as reproductive needs. (Courtesy Vanessa Woods/ Bonobo Handshake)

Image of a mouse embryo with Hoxd13 gene expression illuminated, showing the link between the genital area and limbs. (Courtesy Professor Martin Cohn, Florida) and have the same personality traits. Imagine a world of just one person, multiplied a billion or more times. True it would make life easier for shoe and clothing manufacturers, but the first new disease through mutation to come along could potentially wipe the whole population out.

Aside from the social benefits, sexual populations have two main evolutionary advantages over asexual ones. Firstly, they can adapt more readily to changes in environment, and secondly, they are less prone to accumulation of deleterious mutations in their genes. British scientists Peter Keightley and Adam Eyre-Walker undertook some experiments that estimated genetic mutation rates in a range of animal species, but in particular focusing on fruit flies (*Drosophila*). They concluded that sex is maintained not just to purge the genome (the complete genetic material) of seriously harmful mutations, it is also principally driven by adaptive evolution, perhaps in combination with other mechanisms. In simple terms, sexual reproduction, and sharing different DNA, gives us a better ability to cope with the unexpected challenges in our environment that would otherwise wipe us out.

Sarah Otto from the University of British Columbia has written extensively about the evolutionary implications of sexual reproduction and rightly points out that, while enabling diversity, it is a costly exercise to reproduce sexually. The animal or plant has to find or stumble upon a suitable partner, risk sharing diseases, and becomes an easy target for predators during mating, sometimes even a target for the mate itself, as with praying mantises and some other invertebrate species. Sex is not an efficient way of sharing genes. When we mate sexually we share only 50 per cent of our genetic material with our partner, whereas asexually budding organisms have 100 per cent of their genetic material carried into the next generation. And Otto highlights what biologists call the 'cost' of sex, in that sexually reproducing organisms need to produce twice as many offspring as asexual organisms or they lose out in the population race.

Despite these drawbacks, evolution has shaped the living world in such a way that few large creatures today actually reproduce asexually (only about 0.1 per cent of all living organisms, excluding bacteria of course). Sex generates variation, and that is certainly a good thing when dealing with the constant and unpredictable changes in our environment: continents are slowly moving to new latitudes, ocean currents change, the climate shifts, or sudden traumatic events occur with volcanic eruptions or sudden (in geological terms) sea-level changes. Populations with genetic variability can adapt more readily to such pressures than those without much variation. The great German biologist August Weissman first said this back in 1889 and, despite much new work analyzing the pros and cons of sexuality, it still holds true today.

Once single-celled organisms began building more complex bodies (metazoans), sexual reproduction became the dominant method of reproduction. The explosion of life at the start of the Cambrian period, 540 million years ago, heralded the coming of many different kinds of animal body plans, most of which are still with us today. These include the first worms, mollusks (eg clams, snails) and joint-legged animals (arthropods, like insects, crabs and spiders). And this last group, as it turns out, enjoys some of the weirdest and most perverse sexual behavior of any creatures.