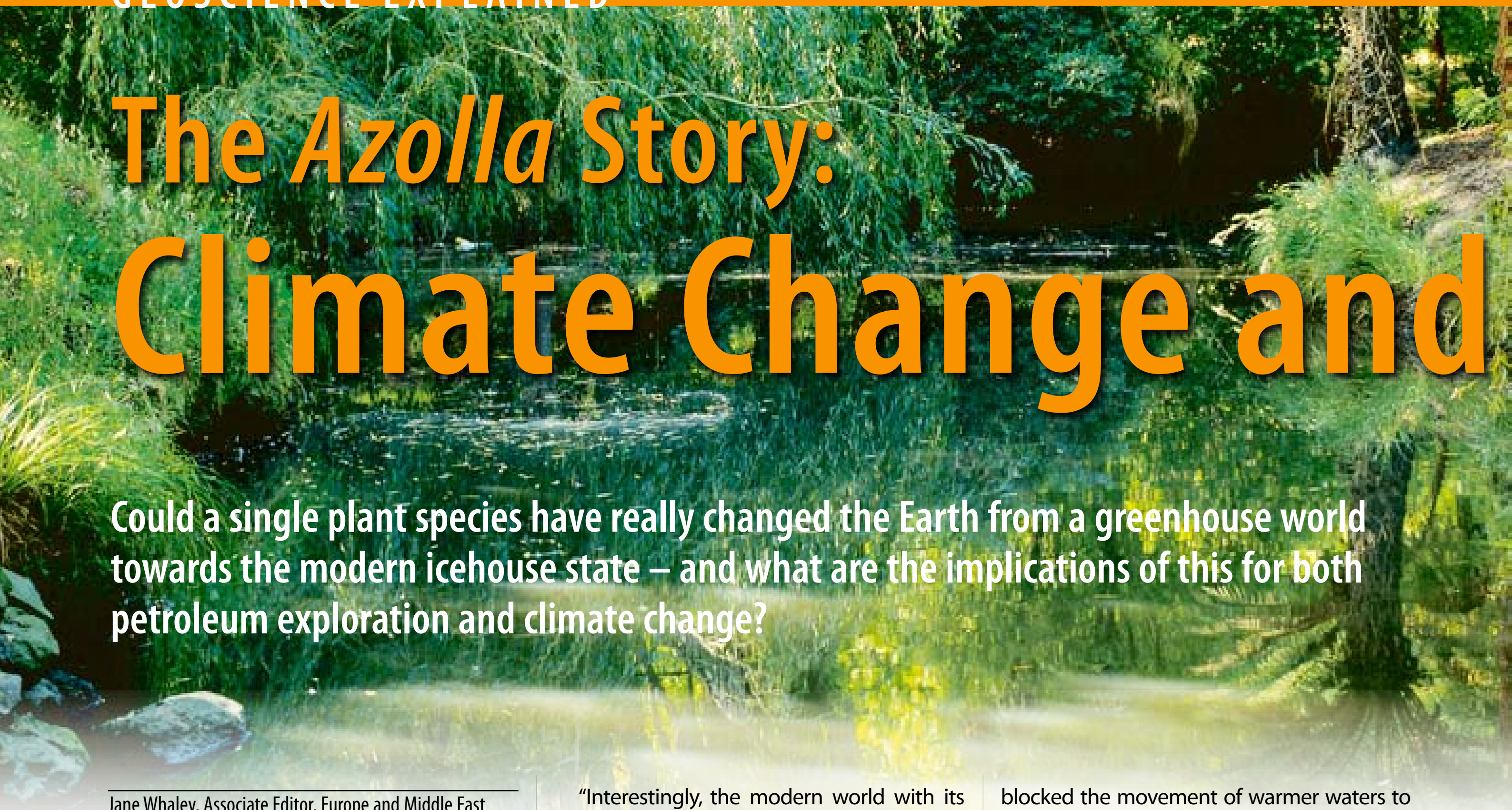


Photo: Stanislaw Mazur

The *Azolla* Story: Climate Change and

Could a single plant species have really changed the Earth from a greenhouse world towards the modern icehouse state – and what are the implications of this for both petroleum exploration and climate change?

Jane Whaley, Associate Editor, Europe and Middle East

Reading the popular press, one could be forgiven for thinking that the 'greenhouse effect' is an exclusively modern phenomenon. As geoscientists know, however, major changes in temperature have occurred throughout the geological record and particularly in the Cenozoic, where they are now the subject of intense research.

Dr. Jonathan Bujak is a renowned palynologist who has been studying these changes for many years. "At the moment we are in the grip of a series of cycles averaging 100,000 years, typically comprising longer glacial phases and warmer shorter interglacial phases," he explains. We are now about ten to twelve thousand years into our present interglacial phase."

Unique bipolar glacial world

"To aid our discussions on present-day climate change, it is vital that we gain a better understanding of the reasons behind the present glacial-interglacial cycles as well as the mechanisms which drove past shifts from greenhouse to icehouse world," he continues. "Glacial-interglacial cycles correlate closely with rhythmic variations in the earth's orbital geometry, but climate models indicate that the high levels of anthropogenic CO_2 now being injected into the atmosphere by the burning of fossil fuels could interrupt this cyclicity, particularly if they also trigger the release of methane hydrate deposits."

"Interestingly, the modern world with its bipolar glaciation may be unique in the history of the earth, as no previous bipolar state is known from the geological record. Our icehouse world is characterised by a high latitudinal geothermal gradient, with a wide temperature difference between the equator and poles. What unique conditions in the early Tertiary led to our bipolar world? "The key to this is a succession of changes involving both plate tectonics and greenhouse gases," Jonathan explains. "During the 1970's the theory arose that both the Arctic and the Antarctic became isolated from warm marine currents as a result of changes in the land-sea configuration and the opening and closing of marine gateways. The separation of Antarctica from Australia and South America during the Eocene to early Miocene initiated the Antarctic Circumpolar Current (ACC) which blocked the movement of warmer waters to Antarctica, resulting in a thermally isolated landmass at the South Pole."

"According to this theory, we have the opposite situation at the North Pole – an ocean that is thermally isolated by landmasses. The Arctic Ocean had been previously warmed by Pacific currents flowing through a wide oceanic connection, but this was largely closed by the end of the Cretaceous due to plate tectonic movements. The main Arctic marine connection today is via the Norwegian-Greenland Sea, but the net flow is southwards due to the large number of rivers emptying into the Arctic."

"The interesting fact about enclosure of the Arctic Ocean, however, is that despite the restrictions to warm water ingress, temperatures remained relatively high until the Eocene. Why was this?" Jonathan asks.

Photo: Ian Miller

Azolla fossil from the Eocene Green River Fm in Utah.

Arctic Hydrocarbons

Dr. Jonathan Bujak, seen here with modern samples of Azolla, is a palynologist and palaeoclimatologist with more than 30 years experience. After working for Robertson Research, Mobil Oil and PetroCanada he joined the Geological Survey of Canada, where he worked with geologists and oceanographers at the Bedford Institute of Oceanography reconstructing the Triassic to Recent history of the Atlantic. Since 1982 he has been Senior Partner with Bujak Research Limited, based in Canada and the UK, providing consulting services to government and industry. He has published more than 100 articles and has been a designated biostratigraphic expert in various North Sea and Faroe-Shetland equity disputes. His current research is focused on the oceanographic and climatic history of the Arctic.

CO_2 – cause or effect?

"To answer this we must look at that unique aspect of our planet, our atmosphere, currently the focus of intense research. As well as shifts in temperature, we now know that there have been major changes in the composition of the atmosphere including greenhouse gases such as CO_2."

Discussions on climate change are frequently accompanied by the well known 'hockey stick' graph, showing atmospheric CO_2 (pCO_2) over the past millennium. Values remained relatively static at about 280 ppm (parts per million) until the dawn of the industrial revolution in the Western World in the eighteenth century, after which levels rose dramatically to our present level of about 380 ppm. "These figures are alarming," says Jonathan, "so we need to put them into a geological context and try to extend the graph back through geological time. How much of this increase is man-made and how much could be due to natural cyclicity?"

"By measuring the levels of pCO_2 in air bubbles taken from ice cores from Greenland and the Antarctic, we can extend the graph back to the middle of the Pleistocene, 400,000 years ago, when the earliest *homo sapiens* was already wandering the earth. From this we can identify clear cyclicity in pCO_2 in the past, with, for example, cores from the eastern Antarctic showing glacial lows of 180 to 190 ppm and interglacial peaks of 280 to 300 ppm, all significantly below our present level of 380 ppm. As the graphs show, each peak was followed by a very sharp reversal but, as Colin Summerhayes of the Scott Polar Research Institute has recently pointed out (Geoscientist, Vol 17, No 7), during previous glacial-interglacial cycles pCO_2 levels were *following* temperature changes, whereas we are now in a situation where pCO_2 levels are *preceding* changes in temperature."

"Worldwide pCO_2 measurements taken by scientists at the Scripps Institution of Oceanography over the past 45 years show an average rise of over 2 ppm per year, from 280 ppm to almost 400 ppm," says Jonathan. "Increased use of coal in some countries could push this trend much higher, with a major impact on Arctic and Antarctic deglaciation as values increase from 400 to 800 ppm. Climate models indicate that, due to carbon emission from fossil fuels, we may now be crossing a threshold of pCO_2 levels that will break the present glacial-interglacial cyclicity, especially if this also triggers the additional release of methane hydrate deposits. It is clear though that we are already shifting into a climatic system previously unknown to us and increased energy in this system will certainly result in more unpredictable and violent weather."

"We would be moving into a world more like the Miocene and perhaps even the early Paleogene and Cretaceous, when there was no permanent glaciation at either pole," Jonathan points out. "We therefore need to understand what caused earlier variations in pCO_2, because changes of similar magnitude could now occur in a matter of decades."

CO_2 levels of 3,500 ppm

When we can no longer use the CO_2 bubbles locked into the ice, the graph can be extended further back in time by using 'proxies' such as alkenoid carbon isotopes and boron isotopes. Although results from these proxies may differ in detail, they generally agree with those achieved through estimates of palaeotemperatures and climate modelling.

"What is fascinating is that all of these techniques indicate that pCO_2 levels were even higher in the past," Jonathan explains. "Between the Oligocene and mid-Miocene, 11 to 35 million years ago, values averaged 600 ppm, get if we extend into the Late Eocene, we see levels possibly up to 2,000 ppm. This reflects a major decrease starting in the Eocene and coinciding with the development of widespread Antarctic glaciation in the earliest Oligocene. An Eocene-Oligocene boundary fall in pCO_2 is supported by climate models, which indicate that large-scale Antarctic glaciation cannot occur with pCO_2 values above ~850 ppm. Perhaps we can use this to predict the effect of future increases in pCO_2 on Antarctic deglaciation?"

The story told by estimated pCO_2 levels becomes even more interesting as we go further back in time to the end of the Paleocene, about 55 million years ago. "At this stage, levels of pCO_2 in the atmosphere may have been as high as 3,500 ppm – that's almost 10 times present day levels," says Jonathan. "Even the more conservative researchers, such as Mark Pagani at Yale, indicate that early Eocene pCO_2 values would have been in the region of 2,000 ppm. This was a true greenhouse world, which was inherited from the Mesozoic, continuing into the Paleocene. Then near the beginning of the middle Eocene, about 50 million years ago, pCO_2 levels unexpectedly and dramatically fell as low as 600 ppm. At the same time, palaeotemperature proxies indicate decreased temperatures, especially at higher latitudes, reflecting the initial shift from the Mesozoic-Early Eocene greenhouse world towards the modern icehouse climate. Why? We need to find out what happened to cause this dramatic fall in pCO_2."

Greenhouse to icehouse transition

"Extrapolating from our present world, we can see that conditions were very different in the Paleocene greenhouse world, with some environments totally unknown today. Increased pCO_2 resulted in higher temperatures, especially at the poles, but these regions still had seasonality, as today, with 24 hour summer light and 24 hour winter darkness, yet with much higher temperatures than those of today. Arctic biotas included crocodiles, turtles and palm trees as well as the early representatives of many of today's deciduous trees."

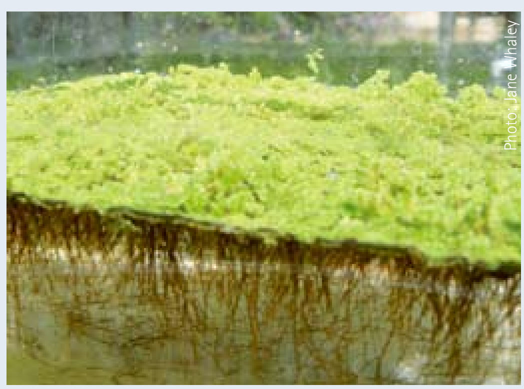
Palaeotemperatures are estimated using various marine and terrestrial markers as well as oxygen isotopes, backed up by climate models. Oxygen isotopes clearly show that temperatures rose in the early Tertiary to a peak about 55 million years ago near the Paleocene-Eocene boundary, an event known as the PETM (Paleocene-Eocene Thermal Maximum). "This move from greenhouse to 'super-greenhouse' state was probably triggered by a major increase in both carbon dioxide and methane greenhouse gasses," Jonathan says. "These may have partly resulted from extensive volcanism, which in turn caused the release of submarine methane hydrates. The Greenland Mantle Plume, a major volcanic province, reached peak activity at this time, with associated doming of the plume resulting in increased enclosure of the Arctic Ocean. This combination of events increased global warmth and may have pushed average Arctic temperatures close to 15˚C."

Azolla: a Potential Source Rock?

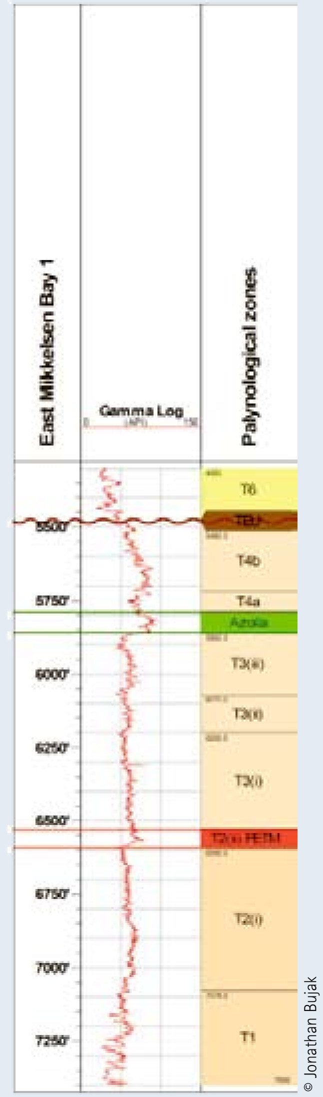
The widespread occurrence of fossil *Azolla* suggests that it has been involved in a massive drawdown of atmospheric carbon from the atmosphere. These large accumulations of carbon absorbed in a relatively short space of time had to go somewhere – so could the *Azolla*-filled strata be an important new source rock?

"The ACEX cores and Arctic exploration wells give clues to this," Jonathan says, "providing evidence for the stratigraphy and geochemistry of the interval in a variety of paleo-environments. The Azolla interval has Total Organic Carbon (TOC) values of over 5% at the ACEX site, but here the section is thermally immature due to lack of overburden. However, more mature sections occur in several wells, indicating the maturation levels at which the *Azolla* interval begins to source hydrocarbons and the character of the petroleum products. These data can then be extrapolated into other Arctic regions in order to predict the occurrence and character of the potential source rock in a variety of paleo-environments, including various deltaic facies plus near and offshore locations away from the deltas.

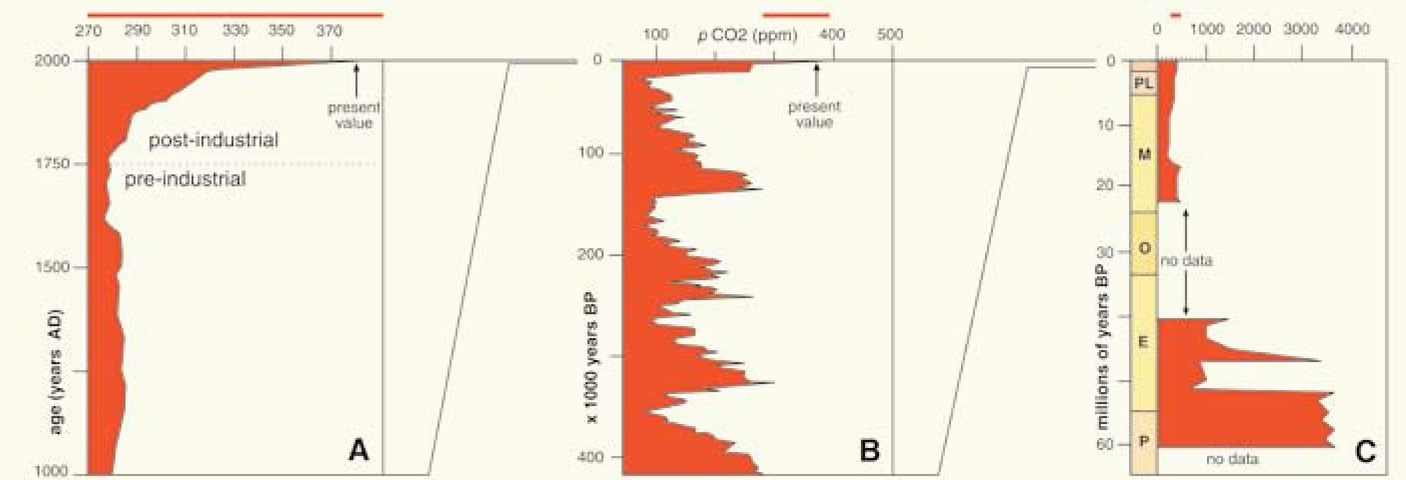
The indications are that the *Azolla* interval could indeed be an Arctic-wide source rock.



Fossil and modern Azolla are morphologically identical. The floating freshwater fern grows at a very fast rate, rapidly clogging domestic ponds, and absorbs large quantities of carbon and nitrogen.



The Azolla and PETM events are often characterised by distinctive high-gamma curves in northern Alaskan wells, as in Humble Oil East Mikkelsen Bay State 1. The right column shows palynological zones, and the Terminal Eocene Unconformity (TEU) that is often developed in the region.



Atmospheric CO_2 values through time. A: The 1000 year 'hockey stick diagram' based on Antarctic Law Dome ice cores (Etheridge et al., CSIRC) and measured air values between 1969-2004 (Keeling & Whorf, cdiac@ornl.gov). B: The 400,000 year record of Petit et al. (1997) from the Vostok ice core, $p\,CO_2$ peaks correlate closely with interglacials. C: The 60 million year record of Pearson & Palmer (2000) based on boron isotopes. Horizontal red bars show the equivalent $p\,CO_2$ scale.

"Then suddenly, near the beginning of the Middle Eocene, there was an abrupt decrease in temperatures as the super-greenhouse world began to cool towards the present ice-house regime. We see evidence of this at both poles, with the earliest ice-rafted material being recognised in the Antarctic and warm marine plankton species dying out in the Arctic. This cooling appears to have occurred at about the same time as the major pCO_2 decrease we have already noted, and we are now trying to confirm the precise correlation between these events."

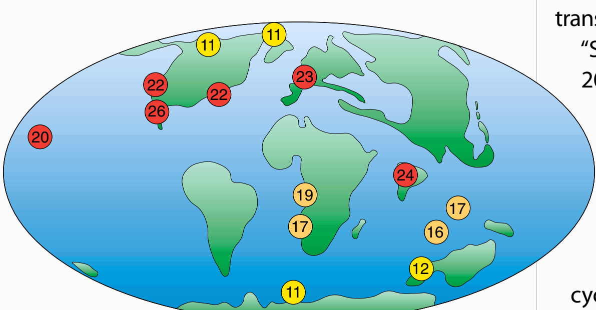
"Could the sudden decease in atmospheric gasses have triggered the reduction in temperature? And what caused this drop in pCO_2?"

The 'Azolla interval'

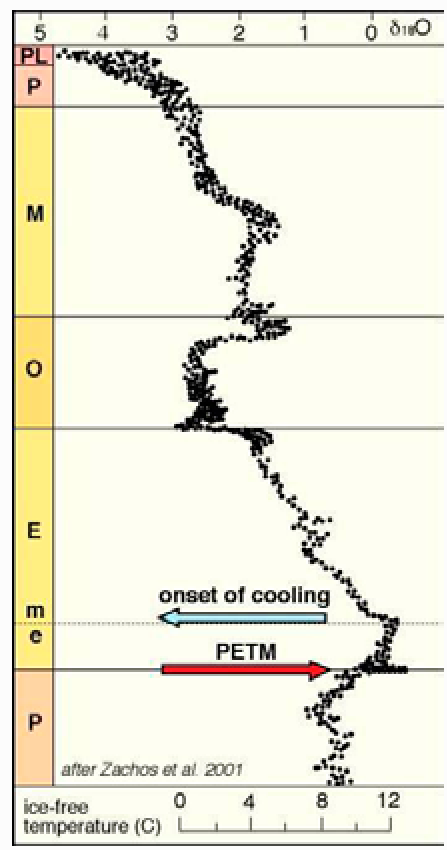
Jonathan has studied many petroleum exploration wells from the Arctic region, and has also worked with experts like Dr. Henk Brinkhuis, a geologist from Utrecht University, on the 2004 ACEX (Arctic Coring Expedition) cores from the central Arctic Lomonosov Ridge. Previous geological data were mainly confined to shallow cores recovered by the Lomonosov Ridge Expedition (LOREX), in which Jonathan participated in the early 1980's.

"ACEX was the first Integrated Ocean Drilling Project (IODP 302) expedition into the Arctic and recovered over 400m (1,400ft) of cores, including 200m (700ft) of Paleocene and Eocene deposits," explains Jonathan. "In the section corresponding to the earliest Middle Eocene - near the point in time when we start to see a sudden shift in CO_2 levels - we found more than eight metres of core composed almost completely of a plant known as *Azolla*, a floating fern sometime found in suburban ponds. But *Azolla* is a freshwater plant, so what is it doing in the middle of the Arctic Ocean? Did it grow there or was it transported to the depositional site?"

"Since the ACEX cores were drilled in 2004, I have been able to confirm the *Azolla* interval in more than 50 Arctic wells from northern Alaska, the Canadian Beaufort and the Chukchi Sea." Jonathan continues, "As in the ACEX cores, *Azolla* usually occurs as laminations, reflecting seasonal or longer cycles. This indicates that the plant grew *in situ* and was not transported to these areas. The '*Azolla* interval', as it is termed, occurs within the same biostratigraphic zone in both the ACEX cores and the exploration wells. It is also represented in coeval well and IODP sections to the south, where it probably represents transported material. These provide confirmation that the event lasted about 800,000 years."



The stable greenhouse world of the early Tertiary was characterised by a low latitudinal thermal gradient, with mean annual temperatures estimated to have reached 11° at the poles – and yet the Arctic was, as now, largely enclosed. The illustrated late Paleocene values are surface temperatures illustrated by Tripati et al. (2001). Note the 11˚C values close to 80˚ north. Unpublished work by Dr. Bujak indicates Arctic PETM values may have temporarily reached 15˚C.



Global deep-sea oxygen isotope records based on data from more than 40 DSDP and ODP sites by Zachos et al. (2001). The temperature scale was computed for an ice-free ocean and thus applies to the time preceding the onset of large-scale glaciation of Antarctica (about 35 Ma)

"As we have discussed, the Early Eocene Arctic Ocean Basin was largely enclosed, with elevated temperatures, evaporation and precipitation leading to increased run-off and the development of extensive surface freshwater layers," Jonathan explains. "Our model suggests that *Azolla* was an

GEO ExPro schedule fall 2007

GEO ExPro 05-2007
Publication date: October 22nd
Ad material deadline: October 5th
Main events where GEO ExPro will be present:
SPE Annual Technical Conference, Anaheim , California November 11-14
AAPG International, Athens, Greece, November 18-21

GEO ExPro 06-2007
Publication date: November 12th
Ad material deadline: October 26th.
Main event where GEO ExPro will be present:
IPTC, International Petroleum Technology Conference - AAPG, EAGE, SEG and SPE
Dubai.UAE, December 4-6

opportunistic plant, able to repeatedly colonize the freshwater layers which periodically spread across large areas of the Arctic Ocean. As fossil *Azolla* is identical in morphology to the modern plant, we can learn a great deal about the environment in which it was growing from its modern habitats."

Henk Brinkhuis and his colleagues therefore initiated the 'Darwin *Azolla* project', comprising an international team of experts on modern and fossil *Azolla*, as well as other geological disciplines such as isotopes and climate modeling, in order to determine the precise conditions associated with the event and its implications for climate change.

Modern Azolla has been used as a natural fertilizer in rice fields for more than 1,000 years. Dr Francisco Carrapico, an expert on modern Azolla at Lisbon University, has documented the Azolla blooms around the world.

Massive CO_2 drawdown?

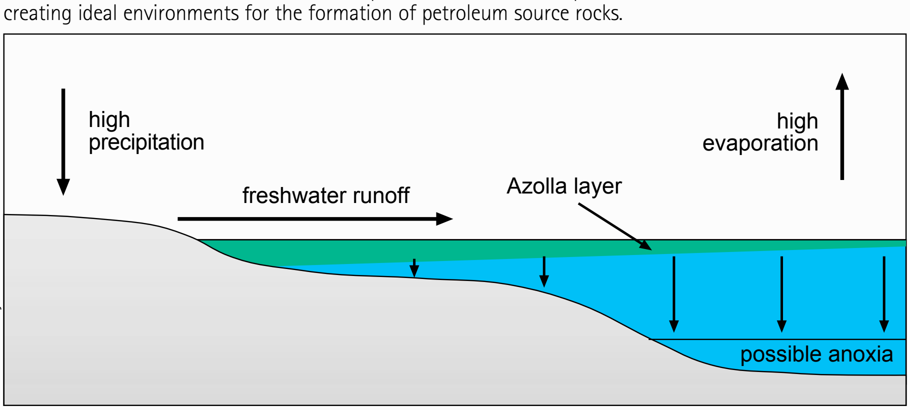
We now know that *Azolla* is an aquatic freshwater fern which prefers warm and calm waters and plenty of light, achieving optimum growth with about 20 hours of daylight. It is one of the fastest growing plants on the planet, and can double its biomass in 2 to 3 days. *Azolla* has also been used for over a thousand years as natural fertilizer, particularly in the Far East and parts of southern Europe, where it is planted in rice fields alongside the young rice plants. This is because *Azolla's* algal symbiont, a nitrogen-fixing cyanobacterium inside the leaf cavities, draws down atmospheric nitrogen which provides nutrients for the rice.

Azolla also absorbs atmospheric CO_2 at a fast rate, leading us to ask an important question; could the flourishing of this carbon and nitrogen absorbing plant in the Arctic have been responsible for an abrupt reduction in atmospheric CO_2?

"We have preliminary estimates from modern *Azolla* suggesting that it may be able to absorb up to 1,000kg of nitrogen and 6,000kg of carbon per acre each year, "Jonathan explains. "As the *Azolla* event lasted for 800,000 years and may have covered an area of up to four million square kilometres, or nearly a billion acres, it can be seen that widespread floating mats of *Azolla* in the Arctic Ocean during the Middle Eocene could have absorbed sufficient carbon to strongly reduce the levels of atmospheric CO_2."

"It must be remembered that this is still just a working model, but it does let us frame our questions and research in order to test its validity".

Schematic diagram of Azolla growth in episodic Arctic freshwater layers. Freshwater runoff into the largely enclosed early Middle Eocene Arctic Basin resulted in variable water stratification and bottom water anoxia. Warm conditions, high nutrients and periodic surface freshwater layers encouraged the growth of Azolla, which drew down carbon from the atmosphere and was then deposited into the anoxic bottom water, creating ideal environments for the formation of petroleum source rocks.



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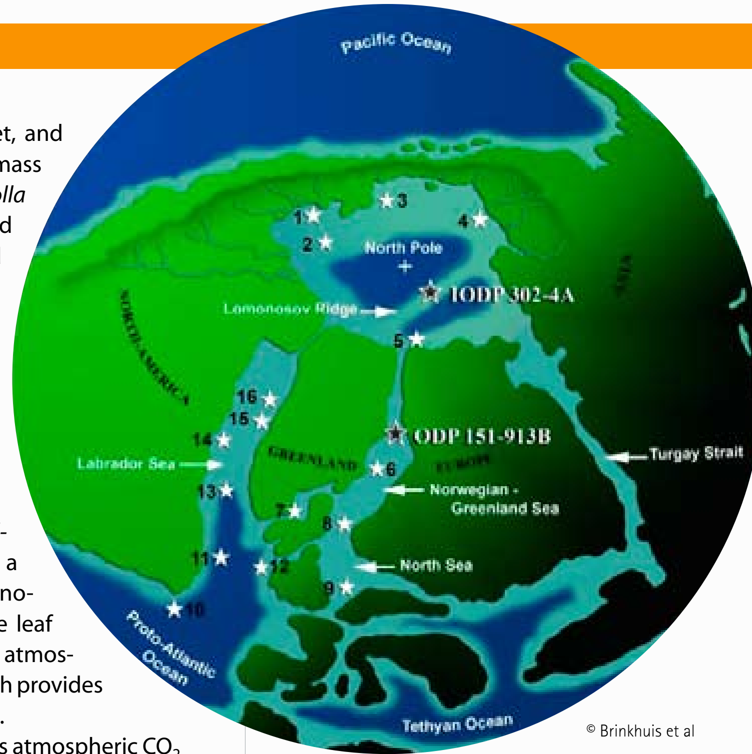

© Brinkhuis et al

The early Eocene Arctic basin, showing IODP/ODP site locations and geographic distribution of Azolla, including probable transported occurrences in the Nordic seas (from Brinkhuis et al., Nature, Vol. 441, No. 1, 1 June 2006).

Implications of the *Azolla* event

As Jonathan points out, "The Arctic *Azolla* Model has a variety of implications. Did the large quantities of atmospheric carbon that were absorbed by *Azolla* result in an important new source rock of possible Arctic-wide distribution? We already have data suggesting that this may be the case." (see box)

Could *Azolla* really have triggered the initial shift from the Mesozoic greenhouse world towards our present icehouse state? Almost all major changes in the nature of the Earth and its climate are now attributed to cataclysmic geological events, so is it possible that the flourishing of a weed could have also altered the planet in such a dramatic way? Various teams are now testing the model by integrating biological and geological data, but as Jonathan says: "Whatever the outcome, it will move our knowledge closer to understanding past and present causes and results of climate change – certainly of the utmost significance to us all. So the next time you see Azolla growing in a pond or lake, think about how this tiny plant may have dramatically altered our world."

Is the famous geologist's maxim 'the present is the key to the past' being challenged? Perhaps, in fact, the past holds the key to our future.