



The Eocene Arctic *Azolla* phenomenon: species composition, temporal range and geographic extent.

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Azolla is a free-floating freshwater fern that is renowned for its rapid vegetative spread and invasive biology, being one of the world's fastest growing aquatic macrophytes. Two species of this plant have been shown to have bloomed and reproduced in enormous numbers in the latest Early to earliest Middle Eocene of the Arctic Ocean and North Sea based on samples from IODP cores from the Lomonosov Ridge (Arctic) and from outcrops in Denmark (Collinson et al 2009 a,b Review of Palaeobotany and Palynology 155,1-14; and doi:10.1016/j.revpalbo.2009.12.001). To determine the geographic and temporal extent of this *Azolla* phenomenon, and the spatial distribution of the different species, we have examined samples from 15 additional sites using material from ODP cores and commercial exploration wells. The sites range from the Sub-Arctic (Northern Alaska and Canadian Beaufort Mackenzie Basin) to the Nordic Seas (Norwegian-Greenland Sea and North Sea Basin).

Our data show that the *Azolla* phenomenon involved at least three species. These are distinguished by characters of the megaspore apparatus (e.g. megaspore wall, floats, filosum) and the microspore massulae (e.g. glochidia fluke tips). The Lomonosov Ridge (Arctic) and Danish occurrences are monotypic but in other sites more than one species co-existed. The attachment to one another and the co-occurrence of megaspore apparatus and microspore massulae, combined with evidence that these spores were shed at the fully mature stage of their life cycle, shows that the *Azolla* remains were not transported over long distances, a fact which could not be assumed from isolated massula fragments alone. Our evidence, therefore, shows that *Azolla* plants grew on the ocean surfaces for approximately 1.2 million years (from 49.3 to 48.1 Ma) and that the *Azolla* phenomenon covered the area from Denmark northwards across the North Sea Basin and the whole of the Arctic and Nordic seas. Apparently, early Middle Eocene Northern Hemisphere middle and high latitude environmental conditions were suitable for simultaneous widespread proliferation of several *Azolla* species. This episode coincides with the termination of a period known as the 'Early Eocene Climatic Optimum' (EECO). Both field data and general circulation/climate model experiments invoke high precipitation conditions for the EECO and these might have aided in the onset of massive *Azolla* proliferation in the Northern Hemisphere.