Feature

Going underground: in search of Carboniferous coal forests

The development of coal forests during the Carboniferous is one of the best-known episodes in the history of life. Although often reconstructed as steamy tropical rainforests, these ancient ecosystems were a far cry from anything we might encounter in the Amazon today. Bizarre giant club-mosses, horsetails and tree ferns were the dominant plants, not flowering trees as in modern rainforests. At their height, coal forests stretched all the way from Kansas to the Kazakhstan, spanning the entire breadth of tropical Pangaea. Most of what we know of their biodiversity and ecology has been quite literally mined out of the ground through two centuries of hard labour. Without coal mining, our knowledge would be greatly impoverished. Over the past few years, we've been exploring underground coal mines in the United States, where entire forested landscapes have been preserved intact over huge areas. Never before have geologists had to opportunity to walk out through mile upon mile of fossilized forest. In this feature article, we describe some of our recent explorations and attempt to shed new light on these old fossils.

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Carboniferous coal deposits, and the amazing plant fossils they contain, have always held a fascination for scientists. In the late seventeenth century, long before the age of Carl Linneaus, Carboniferous plants were being described, illustrated and assigned binomial names. By the time Charles Lyell was laying the foundations of geology, 150 years later, Carboniferous fossil plants were often at the forefront of his mind. Whilst wrestling with the origin of coal, it was his exploration of fossil forests in North America that finally convinced Lyell that coal was the compacted remains of ancient peaty soils. (Formerly, he had wondered whether coal was the result of transported plant debris, as might accumulate in a log-jam on a river.) In the mid-nineteenth century, understanding of the origin of coal took another great leap forward. Joseph Hooker (later Director of the Royal Botanic Gardens, Kew) found limestone nodules embedded within coal seams in Lancashire, UK, which contained remains of plants preserved at cellular level. This paved the way for the painstaking reconstruction of many of the coal-plants that we now know so well—plants like the giant horsetail, *Calamites*, or the tree-sized club-moss, *Lepidodendron*.

Going underground

Exploration of underground coal mines, sometimes under perilous conditions, has always been an important part of the life of a Carboniferous palaeobotanist. One twentieth-century figure who knew this well was Marie Stopes. Before turning her hand to the controversial fields of birth control and eugenics, she forged a successful career as a coal geologist, crawling down deep coal mines to collect fossils (see *Geology Today* v.24, pp.136–141). In recent years, we have been following in the footsteps of Dr Stopes, exploring coal mines in Illinois, Indiana and Kentucky, USA. It is a fantastic experience going underground in search of fossil plants. Deep mines in the United States mostly use a 'room and pillar' method of extraction, where only part of the coal seam is removed, the remainder

Fig. 1. Walking along mile upon mile at stoop in the Millennium Mine. You need to be really passionate about fossil plants to search for them underground!

left as pillars to hold up the roof. Passages are usually only the height of the thickness of the coal seam (1.5–2 metres) and, as you can imagine, there's a lot of stooping and banging of heads involved! (Fig. 1). The other thing to remember is that it is pitch black, so we search for fossils using spotlights secured to our helmets.

In many of the mines we visit, the roof of the passageways is covered with spectacular fossil plant assemblages. These fossils represent remains of the last generation of rainforest trees that grew before coal formation ended. The fossils are really quite amazing with fallen trees lying flat on the top of the coal amid piles of leaf litter (Fig. 2). Here and there you can find tree-trunks several tens of metres long, sometimes terminating in a crown of branches and leaves. It is quite unusual to find nearly complete fossil trees like this. At two of our sites we find clues as to why whole trees got preserved in this way. At Riola and Vermillion Grove mines, the roof rock is made up of tidally laminated mudstones that show that the fossil forest was buried in place when the sea suddenly rushed in. But what caused this abrupt marine transgression? In places the coal is fractured by claystone dykes, which record the occurrence of a major palaeo-earthquake. In this case, a seismic event seems to have caused a massive swathe of coastal Coal Forest to subside below sea level preserving it intact, forever. In other examples, fossil fossils were overwhelmed by sea level rise due to climate change, as discussed later.

Fig. 2. A lycopsid trunks, several tens of metres long, lying horizontal in the roof rock.

Space, the final frontier

The discovery of an entire forested landscape preserved along mile after mile of underground passageways presents an amazing opportunity for anyone interested in fossil plants. In much the same way as an ecologist might map the spatial distribution of tree species in the present-day Amazon rainforest, so we are able to do the same for these Carboniferous coal forests. Admittedly it is a weird perspective. As we walk along underground and look at the fossils in the roof we are looking up at the leaf litter layer from the perspective of the peaty soil beneath. Sometimes we see the base of tree stumps still in an upright position, the broken ends of their roots snaking down towards us. These upright tree stumps (called 'kettle-bottoms' by miners) can be dangerous. They can fall out of the roof without warning crushing anything beneath and great care is always taken to secure them with roof bolts or roof supports (Fig. 3).

When most palaeobotanists examine the fossil remains of coal forests, they do so in sea cliffs or opencast mines where bedding plane exposures are limited. Unique to our discoveries is the possibility of observing the same bedding plane over tens of thousands of hectares. For us, space really is the final frontier! Working in exactly the same way that a modern ecologist operates, we mark out quadrats in the roof and study the kinds of species present from one place to another to build a picture of the mosaic of plants scattered across the land surface (Fig. 4). Sometimes we find sedimentological evidence of large river channels, many kilometres wide, draining through the Coal Forests in the same way that the Rio Negro meanders through the Amazon rainforest today. In these cases, we can observe changes in the pattern of species from the channel levees to the low-lying floodbasins. This is really exciting because never before has it been possible to describe the spatial structure of a 300-million-year-old rainforest!

Fig. 3. Does this tree stump measure up? John Nelson examines a giant stump ('kettle bottom') supported by a prop and a roof bolt.

Fig. 4. A fossil pteridosperm pinnae, preserved in beautiful detail.

Megamires

One of the truly amazing facts about the coal basins of Illinois, Indiana and Kentucky is that you can trace a coal seam from one side of the basin to another. Even more extraordinary, within the limits of geological time resolution, you can correlate some of these coal seams with those found in the Appalachians further to the east. This means that some of the peat mires that formed the coal must have been absolutely huge: megamires covering hundreds of thousands of square kilometres. In fact these were the largest mires to develop in the entire history of our planet. The scale of these peat mires has baffled geologists for centuries. Charles Darwin once commented to his friend Joseph Hooker that he supposed, 'coal had been rained down to puzzle mortals'. To some degree, Darwin's puzzle still remains. We still only understand, in part, how these megamires established over such vast areas.

One recent insight that sheds light on the origin of coal comes from the field of sequence stratigraphy. Detailed studies of cyclothem successions show that the Carboniferous was a time interval subject to rapidly fluctuating climate. As the polar ice cap on Gondwana waxed and waned in size in response to Milankovitch orbital cycles, so sea level and climate changed in synchrony. Coal seams developed in the Carboniferous tropics during deglaciation events as sea level rose and climate became warm and wet. This triggered the development of peat mires across the low-lying regions of equatorial Pangaea. However, many pressing questions remain. How did peat mires manage to keep pace with rapidly rising sea level? If sea level rise occurred at a similar rate to that seen at the end of the last Ice Age, then peak rates would have been several metres per century. Under these conditions, how did rainforests keep out the rising seas? One possibility is that Carboniferous coastlines were fringed with mangroves. In modern tropical systems, mangroves place a huge role in limiting saltwater penetration inland (Fig. 5). Another possible factor was that sea level rise was initially slow and for a time peat accumulation was able to keep pace.

Rainforests got rhythm

Studying the Carboniferous Coal Forests in the context of cyclothems and ice age cycles throws up some surprising insights. Although we tend to think of the Carboniferous tropics as being more or less permanently covered by rainforests, this was not the case at all. As already noted, economic coal seams mostly formed during deglaciation events as the sea level rose and the climate became warm and wet. During intervening glacial phases, the tropics were cool and dry by comparison. As we have discovered in recent investigations of coal mines in Illinois, the vegetation that dominated the tropics during these glacial episodes was very different from that of the Coal Forests, consisting of arid-adapted conifers and other seed-bearing plants. Presumably during these cool/dry episodes the Coal Forest contracted into isolated 'refuges' before bouncing back when the climate warmed again. If this were the case, why then do museum dioramas always depict the Carboniferous tropics covered with luxuriant rainforest?

The answer to that question is the hugely biased nature of the fossil record. Fossil plants are best preserved in waterlogged boggy sediments. In contrast, they are swiftly oxidized to oblivion in dry soils. Consequently, although arid-adapted vegetation may have dominated the Carboniferous tropics, almost no record has been left behind. Only a few scraps of plant

Fig. 5. Modern mangroves of *Rhizophora mangle* at Fakahatchee Bay in the Florida Everglades. Did mangroves stabilize Carboniferous coastlines? (courtesy of Jiri Kvacek, National Museum, Prague)

material have escaped destruction, buried in incised valleys that drained the arid land surface during glacial episodes (Fig. 6). Not only have wetland plants been preferentially preserved, but also their close proximity to economic coal seams means that palaeobotanists have always had ready access to these plant fossils. In contrast, the arid-adapted plants occur in sediments that are rarely uncovered by mining. This double bias means that our understanding of the Carboniferous tropics may be completely flawed. In fact, perhaps the whole iconography of this episode of the history of life needs to be redrawn? Were the Coal Forests just wet blips in an interval dominated by drylands?

End of an era

Nevertheless, despite being repeatedly buffeted by climate change, the coal forests survived for 15–20 million years in tropical Pangaea before collapsing at the end of the Carboniferous. This was not quite the end for the coal forests, because a small enclave survived in China until the Late Permian. What caused the demise of the coal forests is the source of huge debate at the moment. Some scientists argue that severe global warming caused the tropics to dry out completely and the wetland-adapted plants couldn't survive. Others think that the uplift of the Variscan Mountains across central Pangaea wiped out the coal forests, breaking up the habitat and drying out soils by lowering the water table. Whatever the cause, the majestic coal forests—which had been a recurrent feature of the tropical zone—disappeared in the United States at the end of the Carboniferous. One of the last economic coal seams formed in our study area in Illinois is the Calhoun Coal. Not far above this mostly red beds prevail.

We are all familiar with the threefold division of the Phanerozoic into the Palaeozoic, Mesozoic and Cenozoic eras. The boundaries between these eras are fixed by mass extinctions in the animal kingdom, in particular the Permian–Triassic (P/T) and Cretaceous–Tertiary (K/T) events. In contrast there are no major changes in the make-up of the plant kingdom. In fact, in the past, palaeobotanists talked of a 'Palaeophytic Era' terminated by the collapse of the Coal Forests at the end of the Carboniferous. The 'Mesophytic Era' that commenced after their demise was defined by a rise in the dominance of arid-adapted conifers. However, most geologists now recognize that the Palaeophytic–Mesophytic transition is a messy boundary, which is worse than misleading. It has been rightly spurned by stratigraphers. As we have already seen, arid-adapted conifers competed for dominance with the Coal Forests throughout the Carboniferous ice age cycles. The start of the 'Mesophytic' in the Permian merely represents their final victory.

Fig. 6. Fragment of a walchian conifer. A rare scrap of plant material surviving from one of the glacial episodes, which occurred between times of coal

Final thoughts

In this feature article, we have taken a new look at the Carboniferous coal forests. These fossil ecosystems are so familiar to most geologists that we've taken them for granted and assumed we know more or less everything there is to know about them. That couldn't be further from the truth. Exciting and fundamental questions remain about the rise and fall of these first rainforests and the origin of coal seams they produced. Coal may not have been rained down to puzzle mortals, as Darwin joked. However, understanding coal-bearing strata and the fossils they contain remains a field of active research constantly propelled by a stream of exciting new discoveries.

Suggestions for further reading

Dimichele, W.A., Falcon-Lang, H.J., Nelson, J., Elrick, S. & Ames, P. 2007. Ecological gradients within a Pennsylvanian mire forest. *Geology* v.35, pp.415–418.

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