4.3.3 Palaeogeographical setting

Today, the northernmost part of the Arctic Slope is at a latitude of 71° 16´ N and before the concept of plate tectonics and plate movement the fossil floras of the region posed a dilemma. The abundance of leaf fossils and, in particular, those representing warm conditions (thermophilic taxa), suggested that the climate of the region was much warmer than that of the present day. Rather than suggesting Alaska was further south, this was taken as evidence that the polar regions, and therefore global climate, was considerably warmer in the past. Now that we know crustal plates can move, we need to establish the palaeoposition of the Arctic Slope before we can interpret the global significance of its palaeoclimatic signal.

Early palaeomagnetic work positioned the Arctic Slope during the period of time when the Nanushuk Formation was deposited (Albian–Cenomanian) at between 80–85° N. Subsequently, however, direct measurement of the palaeomagnetism in Nanushuk Formation rocks indicated a lower latitude of 74.5 ± 7.5°. Note however that this is still some 5° poleward of its present position. As more data have been accumulated, the palaeogeographical position has become more secure and a palaeolatitude of approximately 75° N in the early Cenomanian now seems robust. However, during the rest of the Cretaceous the Arctic Slope appears to have moved closer to the palaeomagnetic North Pole, and by late Maastrichtian times northernmost Alaska was at approximately 85° N.

Palaeomagnetic studies can only provide positions relative to the magnetic pole that may, or may not, be the same as the rotational pole. For living organisms and the ocean/climate system, the position of the magnetic pole has only minor significance; it is the rotational pole that is important. Although theories about the Earth's interior and the generation of the Earth's magnetic field make a link between the rotational and magnetic poles, the difference in them can be quite considerable and constantly changes. For example, in 1994 the magnetic North Pole was measured by the Geological Survey of Canada to be offset from the rotational pole by 12.7° latitude at 78.3° N and 104.0° W. Moreover, this was 150 km north-west of the position where it had been located a decade earlier. To test the congruence, or otherwise, of the average rotational and magnetic poles during the Cretaceous, Ann Lottes of the University of Chicago examined the distribution of Cretaceous climatically sensitive sediments such as coals and evaporites. She found that the best fit for the distributions, indicative of the position of the rotational pole, was within 4° of the magnetic pole in the Maastrichtian. This separation is less than the errors of most palaeomagnetic studies, so for most purposes we can regard the two poles as being essentially congruent. There is certainly no evidence for a sustained separation and so the fossil biota of northern Alaska therefore represents a truly polar ecosystem.

4.3.4 The Cretaceous flora of the Arctic Slope

The Arctic Slope Nanushuk, Tuluvak, and Prince Creek formations yield an abundance of plant fossils ranging in age from Albian to Maastrichtian. Large-scale plant remains (the *megaflora* — leaves, wood, etc.) are restricted to non-marine lake-bed shales, fluvial sandstones, and ironstone nodules and sheets within bentonitic clays. All these sediments represent the uppermost alluvial floodplain deposits associated with the Cretaceous Corwin and Umiat Deltas. Pollen and spores are abundant in almost all sediments, the exceptions being the coarser-grained sandstones and the bentonites. Taken together, these plant remains and their association with different sedimentary environments help us to build up a picture of the composition, structure, and ecological development of the Cretaceous polar forests. Inevitably, the kinds of plants that made up these forests are less familiar to us than the plants that live today. All of the Cretaceous species are now extinct, as are most, but not all, of the genera (plural of *genus*). However, with the exception of the seed ferns and the bennettitales, all the major groups that exist today were present in the Cretaceous. Box 4.1 provides an overview of the evolution of the major plant groups.

Box 4.1 The evolution of major plant groups

In Figure 4.11, you will see a simple 'balloon' diagram that shows the major past and present plant groups. The point at which each balloon starts marks the first fossil evidence of the group and the end of the balloon indicates its apparent extinction. The width of the balloon represents how 'important' the group was at any given time, where importance is a combination of species diversity and abundance as measured by the number of individuals and their biomass. This, of course, is a very imprecise measure but in qualitative terms it provides us with an insight to past plant life.

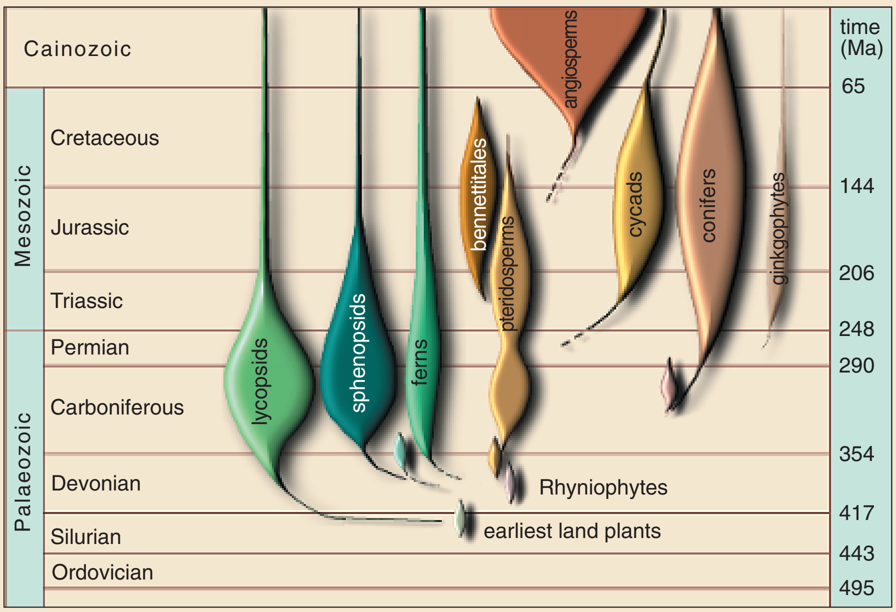
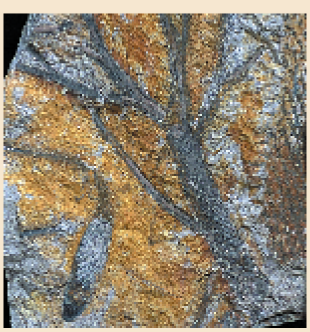


Figure 4.11 Balloon diagram of major plant group evolution.



The lycopsids

This group of plants reproduced by means of spores that were produced in kidney-shaped sporangia attached to the 'upper' side of the microphylls. The helically arranged microphylls and kidney-shaped sporangia borne on the upper side of the microphylls along the sides of the stem are features that characterize all the lycophytes or lycopsids. Today, these plants are represented by the clubmosses *Lycopodium* and *Selaginella*. Figure 4.11 shows that the lycopsids began to diversify in the Late Devonian and by the Late Carboniferous they dominated much of the world's vegetation. By the Cretaceous, however, they were smaller plants, fewer in number and less diverse. However, lycopsid spores are quite commonly preserved in Alaskan Cretaceous rocks and although their stems and leaves are hardly ever preserved they must have been present in the polar forests.

The sphenopsids

Another group that played a major role in the Carboniferous is the sphenopsids. The modern representatives of this group are the 'horsetails' or 'scouring rushes' which have the Latin generic name *Equisetum*. Today, these plants are rarely more than a few metres tall and this seems to have also been the case in the Cretaceous Arctic forests. *Equisetites* (the fossil form of *Equisetum*-like sphenopsids) is extremely abundant in most Cretaceous sediments on the Arctic Slope. Sphenopsids were apparently some of the first plants to colonize river banks and any disturbed ground and before the appearance of grasses in the mid–Late Cretaceous formed much of the ground cover together with ferns. Like ferns, all of the sphenopsids, past and present, reproduce by means of spores.

The ferns

The ferns have a long evolutionary history stretching back into the Late Devonian. Their spores are usually (but not always) borne in sporangia situated on the underside of fronds. Ferns come in a variety of shapes and sizes; some have a small stem or rhizome that sits on or under the soil surface, while some so-called tree ferns produce a trunk made up of intertwined roots and stems. Some have extremely elongated fronds that scramble over and climb up other plants, while some are aquatic and float on the surface of ponds and lakes. The tree habit dates back to the Late Devonian but has evolved many times over in different lineages of ferns.

The seed fern or pteridosperms

Sometimes it is very difficult to distinguish true ferns from the seed ferns just from the foliage. The difference, as the name suggests, is that seed ferns, otherwise known as pteridosperms, reproduced by seeds and not spores. Seed ferns were particularly abundant in the Late Carboniferous, Triassic and Jurassic, but during the Cretaceous they succumbed to competition from the flowering plants (angiosperms) and eventually became extinct in the Late Cretaceous.

The cycads

The cycads are a group that has survived at least from Permian times and probably had their origins in the Carboniferous. They reproduce by means of seeds, mostly borne on modified fronds grouped together to form cones. The only living exception is the most primitive living example, *Cycas*, where modified fronds bearing seeds are separate from one another and do not form a cone. Plants are either female or male; the male plants always producing pollen from cones. Modern cycads typically have a squat trunk bearing whorls of leathery evergreen fronds. Today, they are found only in regions where frosts are non-existent or not severe, and each genus occurs on several different continents. This fragmented distribution indicates that the modern plants are the remnants of a previously more widespread distribution; i.e. they are relictual. This is confirmed by fossil evidence that shows that the group was distributed worldwide in the Mesozoic, and even made up a significant component of polar vegetation. However, unlike their modern counterpart these polar cycads were deciduous and had vine-like stems.

The bennetitales

This group of cycad-like plants were restricted to the Mesozoic. They produced seeds in cone-like structures sometimes surrounded by protective scales or bracts. As with the cycads, male and female plants were sometimes separate but they could also be bisexual and the reproductive structures sometimes even had both male and female parts arranged in a similar way to that of flowering plants. The fossil foliage of cycads and bennetitales are often very difficult to distinguish between and distinctions are usually made on the basis of microscopic details of the epidermal cell walls.

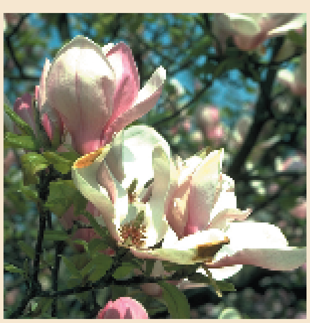
The ginkgophytes

This group of plants is only represented by one species today, *Ginkgo biloba* or Maidenhair tree. In the Mesozoic, this tree was global in distribution but was particularly abundant in polar forests. Today, it only has a presumed natural occurrence in China. The tree is often planted in gardens or as a street tree but usually only the male is used in this way because the female tree produces fleshy fruits that have the odour of rancid butter when ripe.

The conifers

The conifers originated in the Late Carboniferous and rose to dominate many plant communities in the Mesozoic. They are, of course, still a highly successful group and thrive in the forests across North America and Eurasia. Most conifers are woody trees although at least one species is a small parasite living in the branches of other trees. Most conifers reproduce by means of seeds borne in cones, but some cones have been modified to be fleshy, berry-like structures attractive to animals as food. Juniper is one such plant. A typical conifer female cone has seeds borne on a woody scale associated with a tongue-like bract. These bracts can be seen in the picture of a Douglas Fir cone (inset). Pollen is produced in a male cone that is not as massive as the female cone.

Most modern families of conifers arose in the Mesozoic but one abundant conifer family that disappeared at the end of the Cretaceous was the Cheirolepidiaceae. These dominated the vegetation at low latitudes (<40°) and were adapted to seasonal drought. They had very thick cuticles, small leaves, and were deciduous, dropping their photosynthetic shoots when conditions became too dry. You can find abundant fossil cheirolepidiaceous conifers in the Lower Cretaceous Wealden Beds of Southern England.



The angiosperms

Angiosperms are flowering plants. It is perhaps easier to provide examples of angiosperms than it is to define them. They may be herbaceous like buttercups or tulips, or woody like alders, willows or oaks. Palm trees are also angiosperms which, like tulips and grasses, only produce one seed leaf or cotyledon when they germinate. They are therefore called 'monocots' as distinct from buttercups and willows which are called 'dicots'. Some biochemical components of angiosperms originated in the Carboniferous but morphological features typical of angiosperms began appearing in the Triassic. However, it is not until the Cretaceous that we see these features coming together and conferring significant evolutionary advantage.

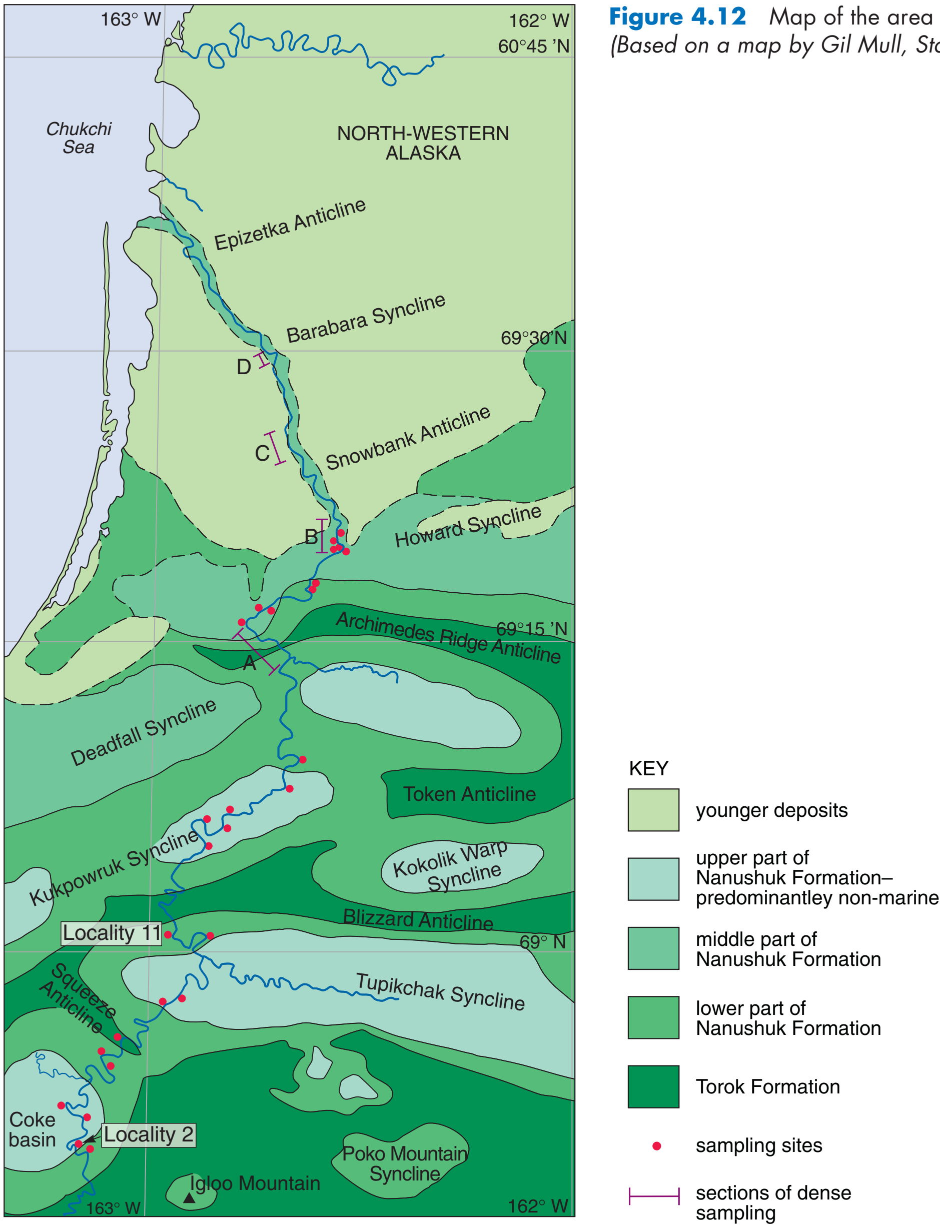


Figure 4.12 Map of the area around the Kukpowruk River. *(Based on a map by Gil Mull, State of Alaska Geological Survey.)*

It is not possible here to examine all the fossil localities across the Arctic Slope. Instead, we will look in detail at several plant-yielding sections which represent a range of ancient depositional environments and communities. We will begin with those exposed along the banks of the Kukpowruk River at the western end of the Arctic Slope.

The Kukpowruk River transects a series of intertonguing marine and non-marine sediments of the Torok (marine), and Nanushuk (both marine and non-marine) formations (Figure 4.12). The minor folding of the region leads to repeated exposure of the various formations present, affording the opportunity to examine repeated associations of plant assemblages and sedimentary facies. The shallow marine shales and sandstones of the Nanushuk Formation overlie, but also intertongue with, the Torok Formation. Dominant rock types are shale, siltstone, sandstone and claystone forming a package that is 1500 m thick in the south-west to 600 m thick in the north-east.

Taken together, the Torok–Nanushuk Formations comprise a package of sediments representing an overall shallowing and transformation from shallow marine to fully non-marine environments as the Corwin Delta complex prograded.

A typical section of the upper part of the Nanushuk Formation along the Kukpowruk River is shown in Figure 4.13. For now, do not worry about what kinds of plants the different names in the units listed below represent — we will deal with that later. Figure 4.14 is a graphic log of this section; on the left-hand side of the sedimentary log are numbers that refer to beds grouped together into informal units that can be described as follows:

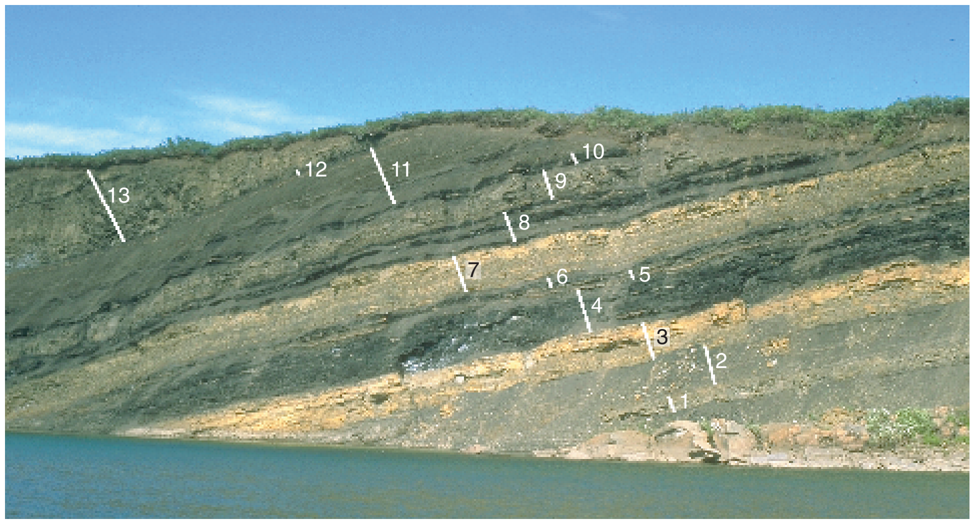


Figure 4.13 Typical section through the upper part of the Nanushuk Formation along the Kukpowruk River. Numbered bars refer to the units shown in Figure 4.14. The cliff is just over 20 m high. *(Bob Spicer, Open University.)*

Locality 2: 68° 49′ 11″ N, 162° 10′ 38″ W

Unit 1. The base of the documented section; this consists of an olive-grey indurated siltstone, 11m thick, within a carbonaceous mudstone.

Unit 2. Carbonaceous mudstone, rich in small *Podozamites* leaves and rare *Pityophyllum* leaves.

Unit 3. A series of yellow-weathering grey siltstones and fine-grained sandstones with a crumbly texture containing abundant *Equisetites* rhizomes, *Podozamites* fragments, wood pieces representing small branches and small compressed logs preserved parallel to bedding. Occasional small tree stumps, a few decimetres in diameter, occur normal to bedding and are rooted in the underlying mudstone.

Unit 4. A poor quality coal, containing numerous ironstone nodules and thin sandy layers, abundant logs, branchwood and *Podozamites* leaves. *Pityophyllum* is also present but less abundant.

Unit 5. An olive-grey siltstone, containing numerous nodular and sheet form ironstone concretions.

Unit 6. Another thin coal within which is rooted a small (approximately 20 cm diameter) upright tree trunk.

Unit 7. The tree trunk (shown in Figure 4.14) rooted in Unit 6 protruded approximately 1 m into this coarsening-upward, yellow/orange weathering grey siltstone rich in *Podozamites* fragments.

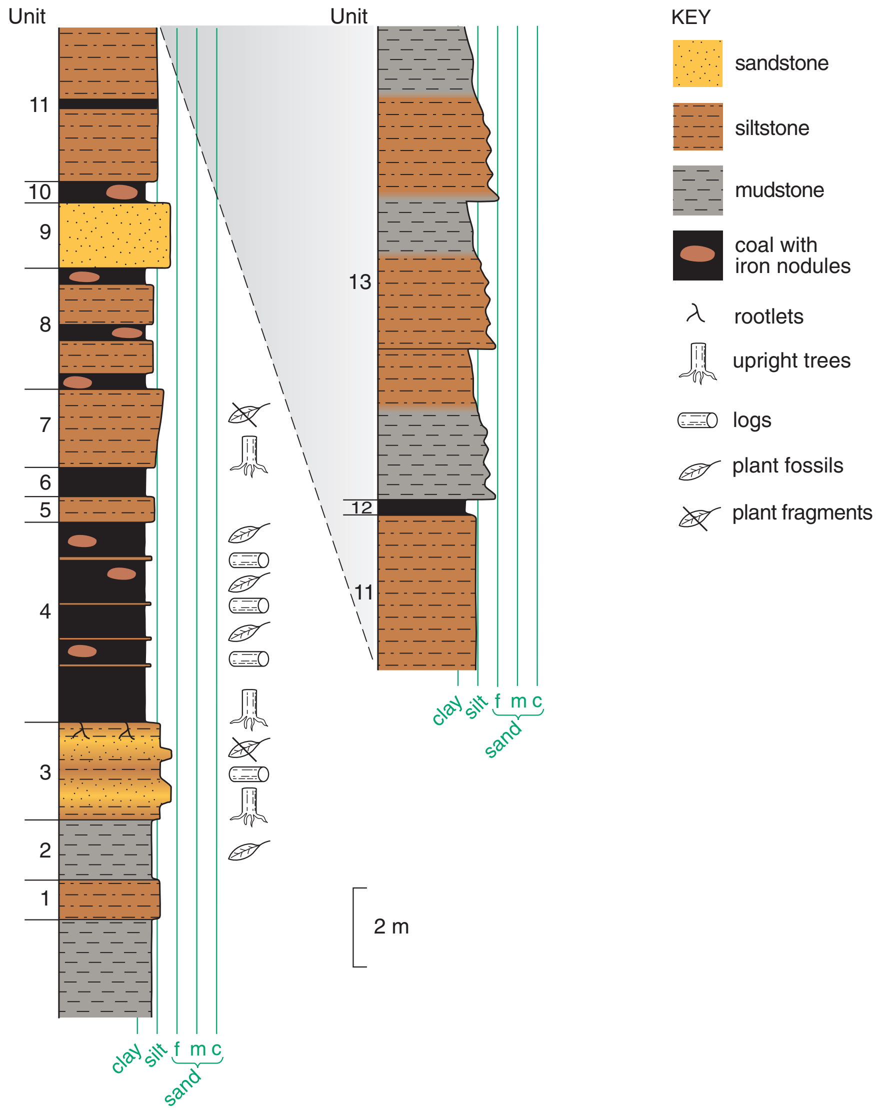


Figure 4.14 Sedimentary log of the Kukpowruk River Corwin Formation. *(Spicer and Herman, 2001.)*

Unit 8. A sequence of three thin (<0.51m) poor quality coals, containing some ironstone concretions, separated by olive-grey siltstones.

Unit 9. A grey, weathering to olive-grey/yellow, fine-grained sandstone.

Unit 10. A poor quality coal containing ironstone nodules.

Unit 11. An olive-grey to brown siltstone with a thin, poorly developed coal in the lower third, above which there are occasional (up to four) white laterally discontinuous, indurated bands.

Unit 12. A thin very poor quality siliciclastic-rich coal.

Unit 13. A yellow-weathering grey well-bedded series of siltstones and fine-grained sandstones forming a set of three fining-upward cycles (estimated to be up to 121m thick).

At the bend in the river, a high angle normal fault, of unknown throw, brings down blocky, cross-bedded, olive-grey siltstones and sandstones rich in *Podozamites*, *Ginkgo*, rare *Birisia*, *Equisetites*, *Pityophyllum*, and compressed logs. *Ginkgo* predominates in the sandier beds, while *Podozamites* is most common in the siltstones. These beds are moderately contorted and overlie, apparently with an erosional contact, yellow/grey sandstones and siltstones that dip at approximately 45° to the west.

The section is interpreted to represent a well-vegetated floodplain between, but close to, small rivers. Several environments are represented here. The most obvious feature is the abundance of coal beds that represent *mires*. The word 'mire' is a general term to describe any wet non-marine environment in which plant material accumulates to an extent that the amount of organic matter far exceeds that of siliciclastics. This can occur in a low-lying depression that fills with water and is colonized by plants (in which case we refer to it as a *swamp*), or it may be a *raised bog* that is maintained in a water-saturated state by rainfall alone. A swamp may develop into a raised mire over time if organic accumulation is facilitated by a climate conducive to growth and sufficient rainfall distributed all year round to prevent the bog drying out. As the organic matter accumulates, the surface of the mire rises above the local water table and eventually even above the raised water levels associated with occasional flooding. At this point, no siliciclastic material will enter the mire by water transport and the coal becomes relatively ash free (and therefore desirable from an economic point of view). The only sources of inorganic material are those derived from the plant material itself and airfall material associated with wind-blown dust or volcanic eruptions.

- ❍ Based on the description of mire type and development just given, which type of mire do you think the coals in the Kukpowruk section (Figure 4.13) represent?
- ● In this case, the coals are of poor quality with a high inorganic content which suggests low-lying swamps rather than raised bogs.

In addition to the swamps represented by the coals, floodplain pond and crevasse splay depositional environments are also represented. The carbonaceous shales (Units 1 and 2) represent low-energy situations but with a high inorganic input relative to the accumulation of organic material. Some plant remains were being preserved, therefore wholesale decay is not an explanation for the lack of organic matter. Instead, the rate of influx of mud was high relative to that of plant material. A floodplain pond depression that was subject to continuous or frequent inundation by silt-laden water is indicated. Individual plant remains show little or no sign of mechanical fragmentation so they are unlikely to have travelled far before being deposited. That the environment was vegetated, and supported tree growth and not just aquatic plants, is shown by the *in situ* tree trunks projecting into Unit 3 (Figure 4.14). Unit 3 is made up of altogether coarser-grained sediments suggesting higher-energy deposition and one in which the energy fluctuated. This variation is indicated by the fluctuating grain size occurring in discrete layers. The sediment must have been deposited rapidly as it entombed and preserved an upright tree trunk, but also washed in fallen trees from elsewhere as evidenced by the trunk lying parallel to bedding. In the upper parts of Unit 3, fragmented plant remains were deposited as current strengths lessened. Subsequently, the surface of this newly deposited sediment was colonized by other plants whose roots penetrated the upper parts of the Unit. Such a sequence of events is typical of parts of a crevasse splay event where a nearby river broke its banks and deposited sediment on the interfluve floodplain surface.

- ❍ In Figure 4.14 and the description above, there is very little reference to sedimentary structures. Why do you think these were not obvious in this succession of rocks?

- The abundance of preserved roots throughout the succession indicates a high degree of bioturbation due to root penetration. Preserved roots are those that were growing when the next layer of sediment was deposited, and effectively smothered and sealed the root-bearing layer. Roots of previous generations of plants occupying that layer are likely to have decayed, but in the growing process they would have destroyed all original sedimentary structures. This is common in non-marine sediments.

Figure 4.15 *Podozamites* leaves. *(Bob Spicer, Open University.)*

Figure 4.16 Shoots and leaves of *Podocarpus*. *(Bob Spicer, Open University.)*

The shoot form of *Podozamites* (Figure 4.15) is common in the coal-forming mires and associated sediments. We do not really know what the *Podozamites* plant looked like, but circumstantial evidence of frequent association of *Podozamites* leaves with upright trunks suggests that it was a tree. The trunks appear to be relatively straight, rather like that of a modern plantation-grown conifer. Given the similarity of leaf form, a good modern analogue for *Podozamites* is probably the Southern Hemisphere conifer *Podocarpus* (Figure 4.16).

Pityophyllum (Figure 4.17) was also evidently a conifer but whether it was a tree or bush is unclear. Both *Podozamites* and *Pityophyllum* are common in the coals, and because coals form in stagnant conditions, it is likely that the leaves were not washed in, but grew on plants that were components of the mire community itself. However, these plants were not restricted to the swamps, and as leaf forms they are ubiquitous in almost all the sediments. When the Nanushuk Formation was being deposited, the *Podozamites* tree and, to a lesser extent, *Pityophyllum* plant were widespread and abundant across the Corwin Delta floodplain.

Figure 4.17 *Pityophyllum* leaves forming a leaf mat in Nanushuk Formation sedimentary deposits. *(Bob Spicer, Open University.)*

One plant that had a more restricted distribution is *Ginkgo*. In the field description above, a fault brings into juxtaposition with the logged section a series of cross-bedded sands that contain abundant *Ginkgo* leaves (Figure 4.18) in addition to *Podozamites*. Such large-scale channel sandstones are absent from the logged section in Figure 4.14 as is *Ginkgo*.

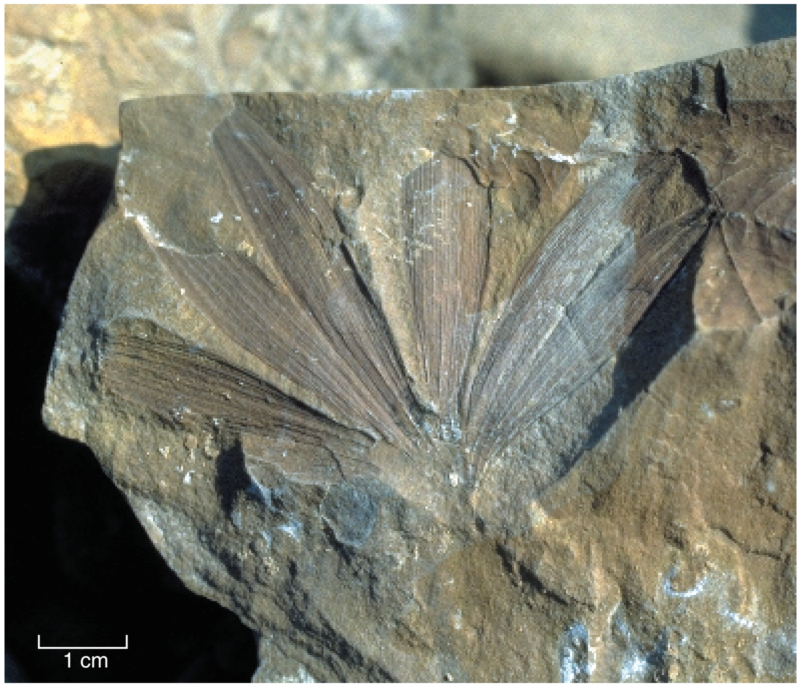


Figure 4.18 A *Ginkgo* leaf from Nanushuk Formation sediments. *(Bob Spicer, Open University.)*

- ❍ What might this suggest regarding the temporal and/or spatial distribution of *Ginkgo*?
- ● The throw on the fault is unknown so potentially it is possible that *Ginkgo* may have a different stratigraphical distribution to *Podozamites*, although clearly, at the time interval represented by the *Ginkgo*-bearing blocks, both *Ginkgo* and *Podozamites* co-occurred. Another possibility is that *Ginkgo* had a more restricted ecological distribution and its close association with channel sandstones suggests it might have been a stream margin plant.

In fact, this association of *Ginkgo* with channel-fill sandstones and crevasse splay sediments is repeated many times in the Arctic Slope successions which suggests that *Ginkgo* was indeed a plant of river margins. We never find *Ginkgo* in coal beds and only rarely do they occur in carbonaceous shales and siltstones.

The single living species of *Ginkgo*, *Ginkgo biloba*, is a native of a small area of China and given that it has been prized as an ornamental tree for a long time its natural ecological distribution is uncertain. The modern form is a tree and there is every reason to suppose that this is a good analogue for the ancient forms. However, the Cretaceous of the Arctic Slope saw not just one species of *Ginkgo*, but a whole diversity of related plants all belonging to the ginkgophytes. These leaf forms have a common similarity in that they look like highly dissected *Ginkgo* leaves and the most common are assigned to the genus *Sphenobaiera* (Figure 4.19).

Figure 4.19 *Sphenobaiera. (Bob Spicer, Open University.)*

If *Podozamites*, *Pityophyllum* and *Ginkgo* were the main forest trees represented in the Kukpowruk section, what was growing beneath them? In Unit 3 (Figure 4.14), there are abundant rhizomes of *Equisetites*. Rhizomes are horizontal stems and in the case of *Equisetites* these grew underground and at intervals produced upright stems, often with cone-like reproductive structures that produced spores. The rhizomes are quite easy to identify because, like all members of this plant group (the sphenophytes), they have striations running along the stems and at intervals there are breaks in these striations at nodes (Figure 4.20). Often at these nodes other rhizomes, upright stems or roots are produced and in many instances there are whorls of sub-spherical nodules. These are characteristic of *Equisetites*: such nodules are also produced by the modern relative *Equisetum* (scouring rush or horsetail, Figure 4.21) and are the site of concentrations of nitrogen-fixing bacteria. This association with nitrogen fixers is common in plants growing in nutrient-poor conditions, particularly vigorous-growing early colonizers of river banks and point bars. Not surprisingly, *Equisetites* rhizomes are one of the most commonly identifiable plant fossils in many Cretaceous floodplain sediments. Before grasses evolved and became ecologically important, *Equisetum* 'meadows' formed the dominant ground cover in disturbed environments.

Other ground cover plants were ferns. In the siltstones and sandstones of the downthrown side of the fault, remains of *Birisia* were found (Figure 4.22). This is a common Cretaceous Arctic fern and its frequent association with *Equisetites* in the absence of other plants suggests that, like *Equisetites*, it was an early colonizer. In some settings, even marginal marine siltstones and sandstones, *Birisia* leaves are the only fossils found and they occur as large, minimally broken fronds in some abundance. This suggests a community local to the environment of deposition composed solely of *Birisia* ferns. Other ferns have a more scattered distribution, are always mixed with other types of plants, and not limited to any particular sedimentary facies. Consequently, these are most likely to have been present in mixed communities and are likely to have formed ground cover in more mature communities.

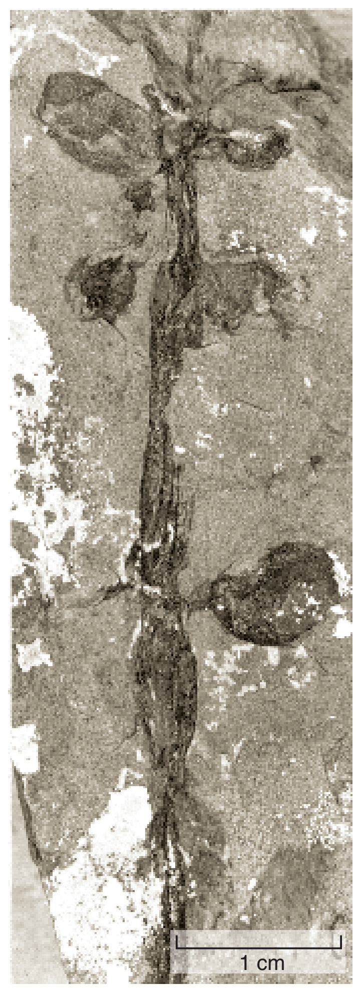


Figure 4.20 *Equisetites* rhizome with nodules. *(Bob Spicer, Open University.)*