GSA Data Repository 2015350

Supplemental Information for:

Lycopsid forests in the early Late Devonian paleoequatorial zone of Svalbard

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DR1. Palynology

Methods
Standard palynological preparation methods were used. For routine samples 5g of rock was rough crushed and then treated with 30% HCl to remove carbonates. After decant washing the sample was demineralized with 60% HF. The sample was then decant washed to neutral and sieved at 15 µm. The sample was then transferred to a glass beaker and briefly boiled in 30% HCl to dissolve neoformed fluorides. The sample was then diluted in water and resieved at 15 µm, the fluorides remaining in solution and separating with the waste water. The sample was then vialed and a strew slide mounted in Elvacite 2044. Some samples contained amorphous organic matter which was fragmented using a 15 second treatment in a Sonics and Materials ultrasonic probe followed by resieving. No oxidative methods were employed as the spores were generally yellow to orange in color. Selected sample were picked for megaspores and sporangial fragments using a finely drawn pipette connected to a mouth tube. Selected samples were reprocessed for the megaspore and mesofossil fraction. These samples ranged up to several 100 g in weight and a plastic tank connected to laboratory tap was used for effective and safe neutralization. The megaspore fraction was top sieved out at 150 µm and the spores counted in wet strew using a stereoscopic microscope.

Palynological Zonation
There are two standard palynological zonations (e.g., Richard and McGregor (1986) and Streel et al., 1987). That of Streel et al., (1987) is based on sections in Western Europe and contains different palynological assemblages to those of Svalbard which is palynologically most similar to Northern and Eastern Europe. There are some common elements in the zonation of Richardson and McGregor (1986) but these are from Arctic Canada and generally lack any independent time correlation using conodonts. This contribution uses more more recent zonations (e.g., Avkhimovitch et al., 1993) that are both from Northern and Eastern Europe and hence from the same palynological province, Importantly there are partial revisions/additions to these zonations (e.g., Tel'nova, 2008; Turnau and Racki, 1999; Turnau and Narkiewicz, 2011; Stempień-Sałek, 2002) that are calibrated using conodonts to the standard Devonian time scale. Importantly these new zonations attempt a higher resolution refinement of the zones in the late Givetian to early Frasnian interval.

Detailed argument for the age of the lower part of the Mimerdalen Subgroup.
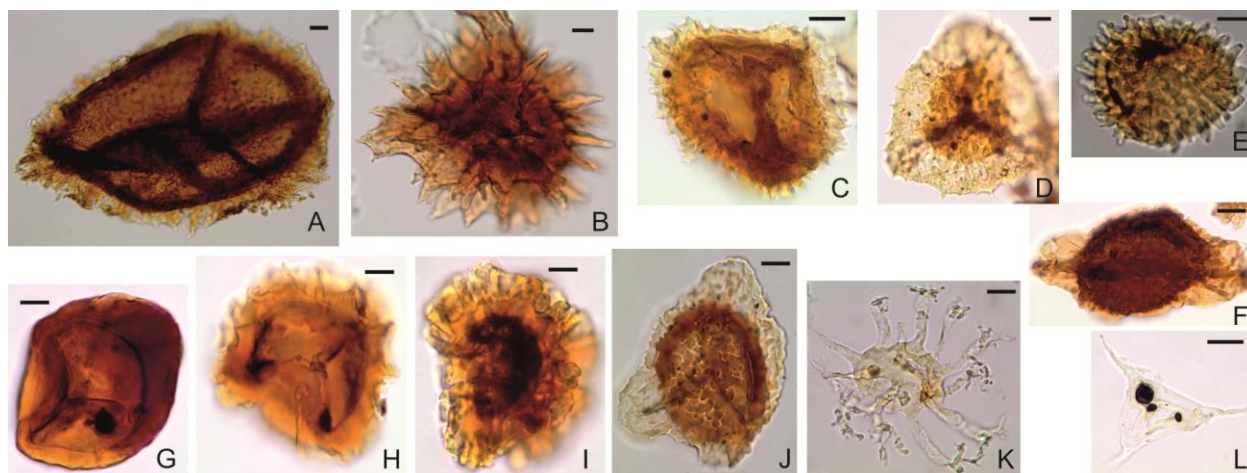
DR1-1. Palynomorphs from the forest localities and Mimerdalen succession, supplemental to Figure 4 in main text. All scale bars are 10 µm unless indicated. Samples, slide numbers, coordinates, taxonomic citations and supporting references are provided in DR2.
A: *Triangulatisporites rootsii*, scale bar is 20 µm. B: *Ancyrospora incisa*. C: *Kraeuselisporites pomeranius*. D: *Spelaeotriletes krestovnikovii*. E: *Raistrickia bucera*. F: *Archaeoperisaccus verrucosus*. G: *Archaeozonotriletes variabilis.* H: *Chelinospora concinna.* I: *Archaeozonotriletes timanicus.* J: *Cristatisporites triangulatus.* K: *Multiplicisphaeridium ramusculosum.* L: *Veryhachium trispinosum.*

Fiskekløfta Black Shale III (*6* in Figure 1c, 2)

The assemblages are dominated by *Geminospora lemurata* together with *Contagisporites optivus* which are the microspores and megaspore of the archaeopteridalean progymnosperms. Also present is the plexus of patinate variably sculptured spores including *Archaeozonotriletes variabilis*, *A. timanicus* and *Chelinospora concinna*. *Cristatisporites triangulatus* can be quite common and there are rare specimens of *Ancyrospora incisa*. This assemblage can be placed in the IM spore subzone (Turnau & Racki, 1999; Obukhovskaya, 2000; Avkhimovitch et al., 1993) of late Givetian age. The Fiskeløfta Shale in both the Estheriahaugen and Fiskekløfta localities, within Mimerdalen to the south of the current localities, contains rare acritarchs (*Multiplicisphaeridium ramusculosum* and *Veryhachium trispinosum*) and represents a transgressive flooding with a marine influence. Given its late Givetian age this can be correlated with the Geneseo Taghanic Onlap (Marshall et al., 2011; Turnau, 2014).

The Fiskekløfta Shale also contains a significant fish assemblage (Nilsson, 1941) including *Asterolepis scabrata* (close to *A. ornata*) and *Psammosteus arenata* (probably synonymous with *P. paradoxa*). *A. ornata* and *P. paradoxa* are both found in the Gauja Formation in Latvia (Mark-Kurik, 2000) where an IM spore assemblage is also known (Mark-Kurik et al., 1999).

The 8b shale above the Lower Svalbardia Sandstone (8b in Figure 1c, 2)
In addition to the common species from the Fiskekløfta Black Shale this more diverse assemblage contains *Spelaeotriletes krestovnikovii*, *Kraeselisporites pomeranius* and abundant *Cymbosporites magnificus* with *Verrucisporites submamillarius*. A rare, but persistent, spore is *Archaeoperisaccus verrucosus* which occurs together with *Raistrickia bucera.* These place it in the BI subzone of Avkhimovitch et al., (1993) and within the Givetian-Frasnian boundary interval (Obukhovskaya, 2000). Tel'nova (2008) recognized some six palynological assemblages in the late Givetian to early Frasnian interval from the Timan, Russia. Both *A. verrucosus* and *K. pomeranius* (as *Perotriletes* (sic) *vermiculatus*) have first occurrences in PA-3 (*vermiculatus-domanicus*). Limited conodont evidence for the Timan (Ovnatanova and Kononova, 2008) confirms a latest Givetian age for this assemblage.

DR2 Sample, slide numbers (e.g. Mimer-94) and England Finder co-ordinates (e.g. Q37/3) for palynomorphs illustrated on Figure 4 and in DR-1 together with taxonomic citations and supporting references. All figured specimens are curated in Ocean and Earth Science, University of Southampton.

Spores
Ancyrospora incisa (Naumova) Obukhovskaya in Avkhimovitch et al., 1993, Mimer-110B pick, J22/4
Ancyrospora spp, multifurcate tips, Mimer-71 <150, H21/1
Archaeoperisaccus verrucosus Pashkevitch 1964, Mimer-94, W25/2
Archaeozonotriletes timanicus Naumova 1953, Mimer-94, T44/2
Archaeozonotriletes variabilis (Naumova) Allen 1965, Mimer-94, P48/4
Chelinospora concinna Allen 1965, Mimer-94, U28/1-2
Contagisporites optivus (Chibrikova) Owens 1971, Mimer-71/2, O37/2
Cristatisporites triangulatus (Allen) McGregor and Camfield 1982, Mimer-36, W28/1
Cymbosporites magnificus (McGregor) McGregor and Camfield 1982, Mimer-77/1, Y25/1
Geminospora lemurata (Balme) Playford 1983, Mimer-95, M35/2
Kraeuselisporites pomeranius (Stempień-Sałek) Turnau 2011, Mimer-94, K44/4
Nikitinsporites spitsbergensis Allen 1965, Mimer-77 mega, Q37/3
Raistrickia bucera (Chibrikova) Obukhovskaya 2005, Mimer-94, S44/3
Spelaeotriletes krestovnikovii (Naumova) Obukovskaya in Avkhimovitch et al., 1993, Mimer-117, N33/4
Tholisporites densus McGregor 1960, Mimer-77/1, K39/2
Triangulatisporites rootsii Chaloner 1959, Mimer-71 Tri pick, F17/4
Verrucisporites submamillarius (McGregor) Chi and Hills 1976, Mimer-77, 610g/1, J16/4

Acritarchs
Multiplicisphaeridium ramusculosum (Deflandre) Lister 1970, Mimer-43, P36/1
Veryhachium trispinosum (Eisenack) Stockmans and Willière 1962, Mimer-45, T30/4

Allen, K.C., 1965, Lower and Middle Devonian spores of North and Central
    Vestspitsbergen: Palaeontology v. 8, p. 687-748.
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    Russian Platform: Paleontological Journal v. 42, p. 997-1166.
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    Paper, v. 70-38, 1-157.
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DR3: Critique of the late Famennian age formerly attributed to the Plantekløfta Formation

The Plantkløfta Formation has been attributed very different and younger ages by a number of authors following the original palynological studies of Vigran (1964) and Allen (1965, 1967). Dibner (in Pčelina et al., 1986) studied the palynomorphs from a number of exploratory drill cores and dated it as Famennian. This was based largely on the presence of *Archaeozonotriletes famenensis*, now *Grandispora famenensis*. We have found no specimens of this rather distinctive spore in our samples. But in 1965 Allen suggested that *A. famenensis*, as described by Russian palynologists, might be comparable to *Cymbosporites magnificus*. It would appear that Dibner has accepted this comparison with *A. famenensis* as the senior synonym and, in consequence, changed the age to Famennian.

Piepjohn et al., (2000) have dated the Plantekløfta Formation on samples from Munindalen as late Famennian (latest Devonian) based on the rare occurrence of *Retispora lepidophyta*. The older spores present in the same samples all being regarded as reworked. A single specimen of *Retispora lepidophyta*, as determined by Grewing (Piepjohn et al., 2000), was illustrated by Schweitzer (1999, plate 6, fig. 10 and plate 7, fig. 1). This is regarded as a misidentification for several reasons. Firstly, it is far too large in size, the individual scale bar showing it to be over 250 µm in diameter whereas all the detailed morphological descriptive studies show *R. lepidophyta* to be consistently smaller in size (e.g. Playford, 1976; 27-112 µm, mean 68 µm, 90 specimens). This is confirmed by detailed biometric studies by Maziane et al., (2002) through its total range (28-108 µm, mean 54 µm, 3752 specimens). The defining characteristic of *Retispora lepidophyta* is the presence of regularly distributed circular holes (fovea) in the exoexine of the spore. However, examination of the illustrations in Schweitzer (1999) show that the fovea are concentrated in certain areas on the exoexine and have obvious 90° corner angles that define equal sided squares, i.e., they are negative pseudomorphs of pyrite cubes. This is commonly found as a diagenetic mineral in palynomorph walls. In addition, the illustrations of Schweitzer (1999) show a spore with short distal spines on the exoexine and a concentration of longer spines, at both the intexine/exoexine contact, and on the central distal area. *Retispora lepidophyta* does not have this type of sculpture and the spore can be reassigned to *Grandispora*. Piepjohn et al., (2000) compared their very low abundance of *R. lepidophyta* in Svalbard to the similarly low abundance at its range base inception in Belgium (Streel & Loboziak, 1996). However, the assemblage from Svalbard still lacks any other age diagnostic distinctive middle and late Famennian spores. These would include the *Diducites* and *Auroraspora* morphons, *Vallatisporites*, *Knoxisporites*, *Rugospora*, and the relatively long spined species of *Grandispora* such as *G. cornuta*. Therefore this late Famennian age based on *Retispora lepidophyta* can be firmly rejected.

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Allen, K.C., 1967, Spore assemblages and their stratigraphical application in the Lower and Middle Devonian of North and Central Vestspitsbergen: Palaeontology, v. 10, p. 280-297.

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Pčelina, T.M., Bogach, S.I. and Gavrilov, B.P., 1986, New data on the lithostratigraphy of Devonian deposits in the Mimerdalen Region of the Spitsbergen Archipelago, *in* Krasil'shchikov, A.A. and Mirzaev, M.N., eds., Geology of the sedimentary cover of the Spitsbergen Archipelago. Sevmorgeologija, Leningrad, p. 7-19.

Piepjohn, K., Brinkmann, L., Grewing, A., and Kerp, H., 2000, New data on the age of the uppermost ORS and the lowermost post-ORS strata in Dickson Land (Spitsbergen) and implications for the age of the Svalbardian deformation, *in* Friend, P.F. and Williams, B.P.J., eds., New perspectives on the Old Red Sandstone: Geological Society of London Special Publication, v. 180, p. 319-332.

Playford, G., 1976, Plant microfossils from the Upper Devonian and Lower Carboniferous of the Canning Basin, Western Australia: Palaeontographica Abt. B, v. 158, p. 1-71.

Schweitzer, H.-J., 1999, Die Devonfloren Spitzbergens: Palaeontographica Abt. B, v. 252, p. 1-122.

Streel, M. and Loboziak, S., 1996, Middle and Upper Devonian miospores. *in* Jansonius, J., and McGregor, D.C., eds., Palynology: Principles and Applications; American Association of Stratigraphic Palynologists Foundation, v. 2, p. 575-587.

Vigran, J.O., 1964, Spores from Devonian Deposits, Mimerdalen, Spitsbergen: Norsk Polarinstitutt Skrifter, v. 132, p. 1-33.

**DR4 Additional photographs of, and data from, the fossil forest localities.**

Locality AF1
GPS locality 33X 0525237 8733334

AF1-A a) Close up of *Protolepidodendropsis* stem with swollen base, and yellow weathering products (jarosite) of pyrite in the otherwise inconspicuous soil horizon below. The soil is truncated by the oblique fault plane on the right of the photograph.
b) View of trees *in situ*. Because several are oblique, only those which could be mapped near the base were included in Fig. 6 in the main text.
c) Overview of locality, view looking SW along the west bank of the Munin braidplain.

Locality AF2
GPS locality 33X 0524709 8734578
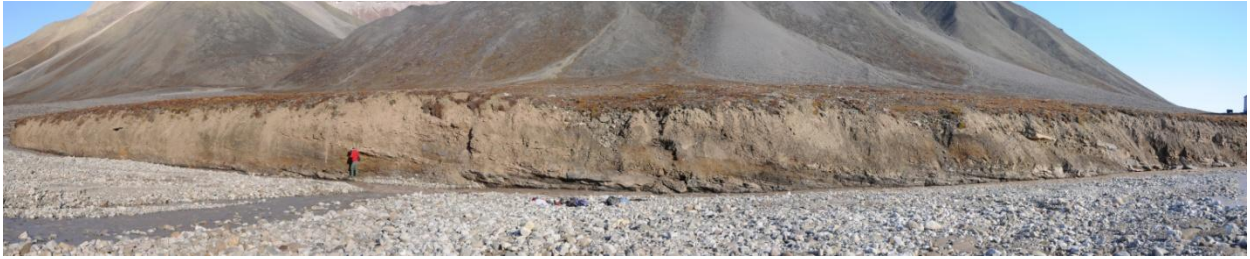
AF2-A. General location on the eastern side of the Munin braidplain looking east. Head of figure marks the stratigraphic level in which the most important standing trees occur, although examples are found along the whole exposure. The major thrust bringing Lower Devonian sediments over the Middle and Upper Devonian occurs in the hillside behind the outcrop.
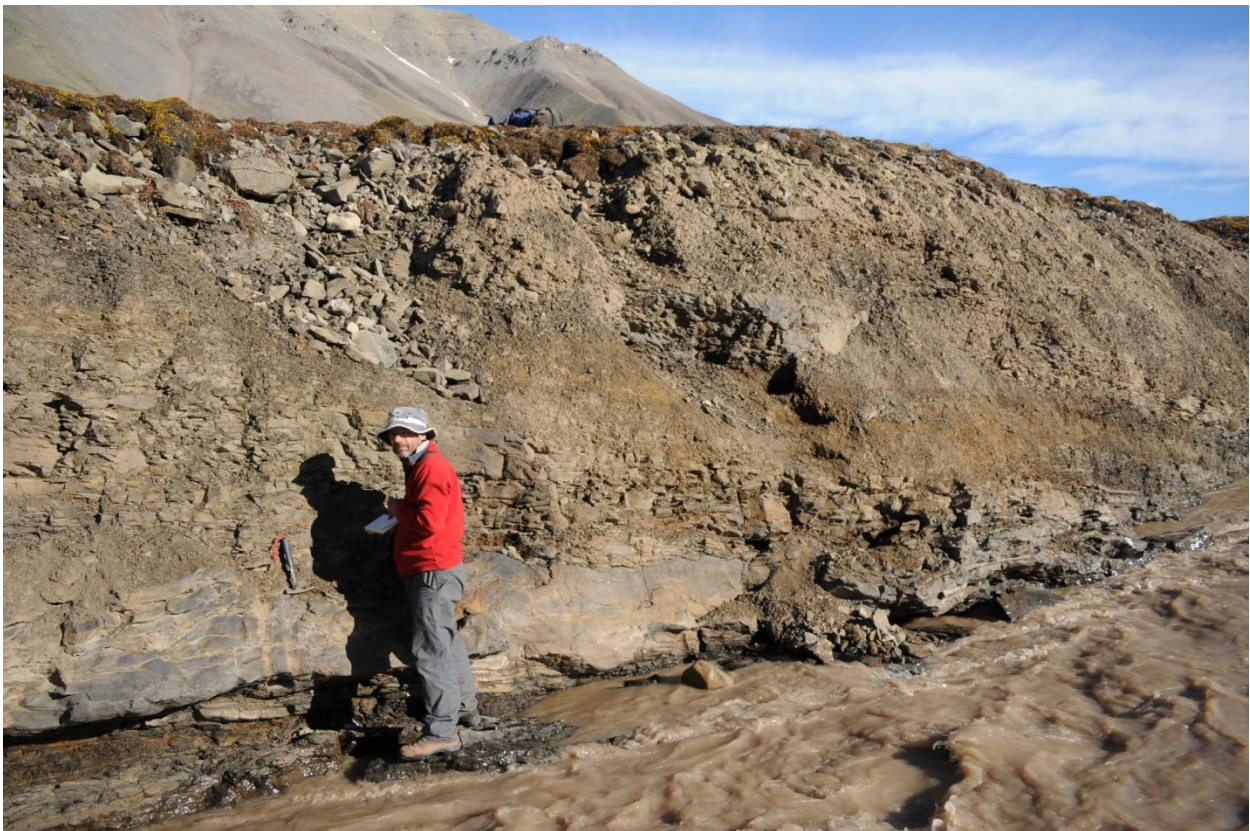

AF2-B Three vertical tree casts are visible in the sandstone bed beneath hammer (see right-hand group in fig. 4L in main text). Further tree casts were seen going upwards within the sandstone bed when observed from within the cleft where the less competent shaley layers of paleosol beneath have been eroded out. Spacing of trees was plan mapped at this locality where the same sandstone bed reaches the level of the river on the right-hand side of this photograph (see below).

AF2-C a) dental rubber internal mould of upright *Protolepidodendropsis* stem made in the field. Scale is 50 mm long. b) left-hand of the groups of upright *Protolepidodendropsis* stems seen in fig. 4L, showing paleosol below. Width of right hand trunk is 55 mm.
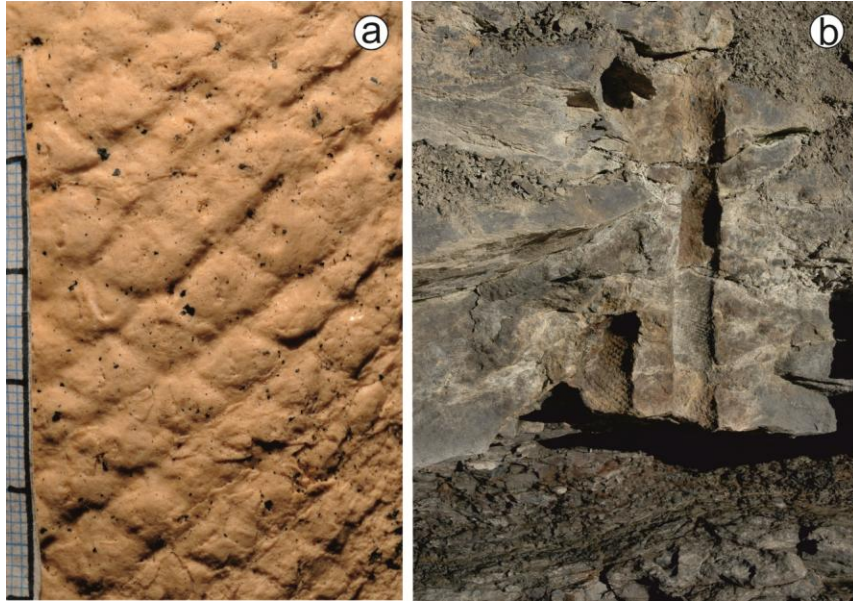
AF2-D. View of upright lycopsid axes (arrows) photographed from above bedding surface. Note also the sub-horizontal lycopsid axis seen on the right.
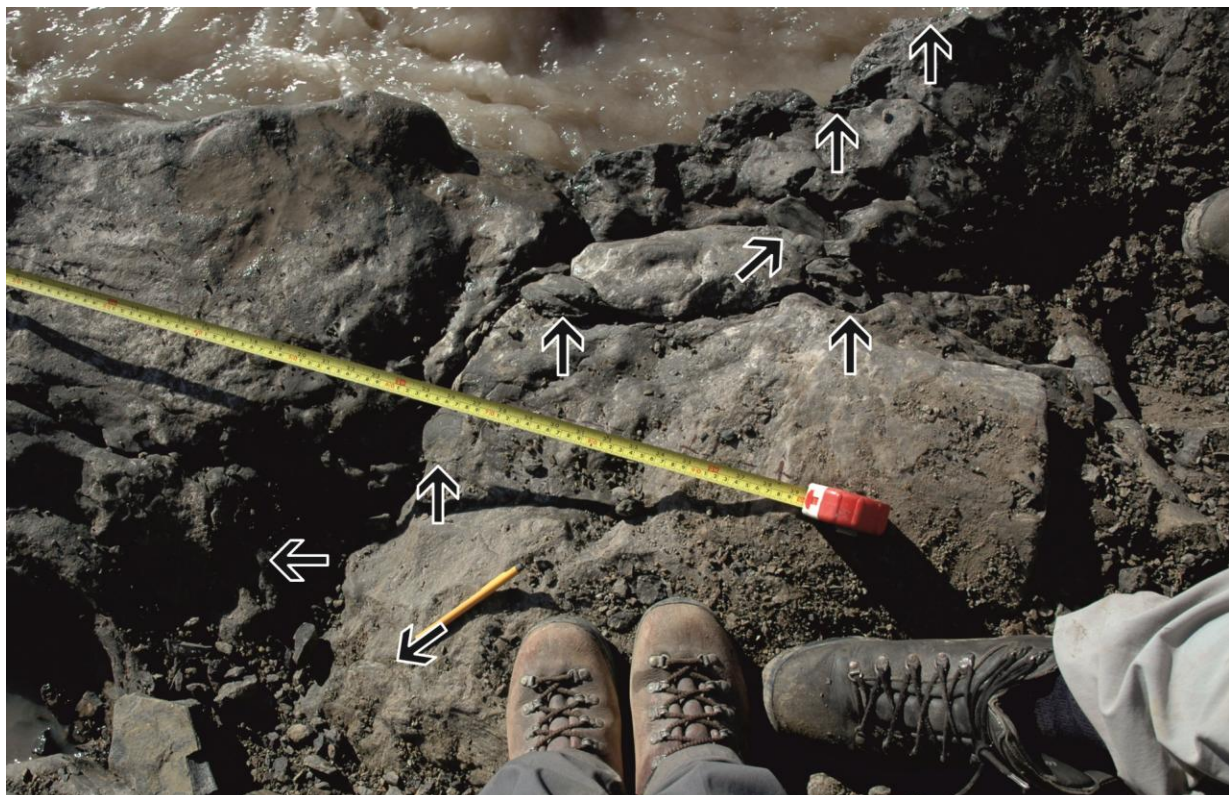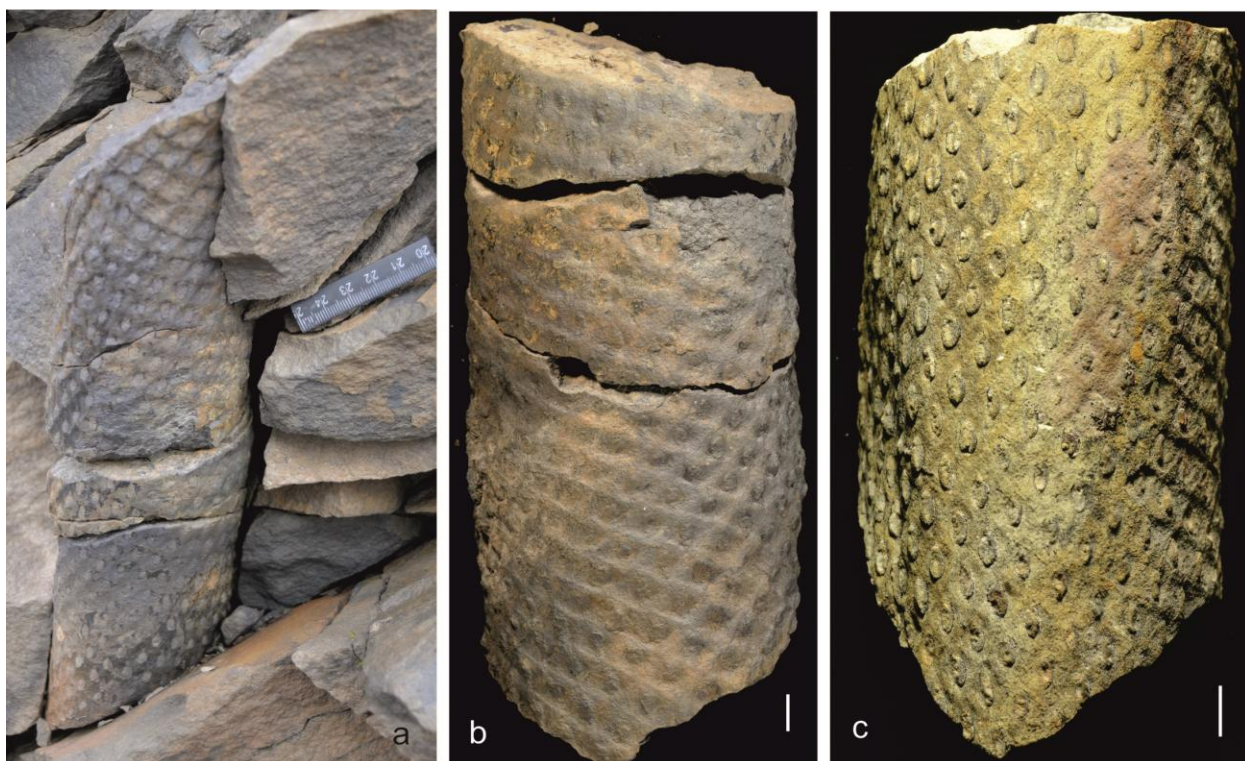
Locality AF3
GPS locality 33X 0524997 8733583

AF3-A General view of locality, looking south along the west side of the Munin braidplain. Hammer in same position as following photograph.

AF3-B Position of 12 vertical *Protolepidodendropsis* trunks (arrows). *P* shows the occurrence of sub-horizontal branches as *Protolepidodendropsis* sensu Høeg 1942.

AF3-C a) Detail of *Protolepidodendropsis* axis photographed in the field, truncated at its base by oblique thrust plane dipping east. b) Detail of upper part of same axis (inverted), studio photograph, showing combination of diamond-shaped pattern of reinforcing tissues in the cortex, together with oval sediment-filled leaf base parenchyma visible on the right. The occurrence of these two features is dependent on preservational conditions and history. Both these features are also visible in the preceding field photograph. c) **For comparison**, a view of PA1246 collected by Vogt's expedition of 1928 from the 'Plantekløfta' locality (the type locality), showing both diamond pattern cortical tissues and oval leaf base parenchyma (Palaeontological Museum, Oslo – see Høeg 1942, Pl. LI fig. 2).


AF3-D Detail of area marked with letter *P* in AF3-B above, showing 4 subparallel c. 10 mm wide axes of lycopsid branches similar to those axes named *Protolepidodendropsis pulchra* by Høeg (1942), since demonstrated to be the distal branches of larger stems, identical to those illustrated above, by Schweitzer (1968). Field photograph.

Density of trees
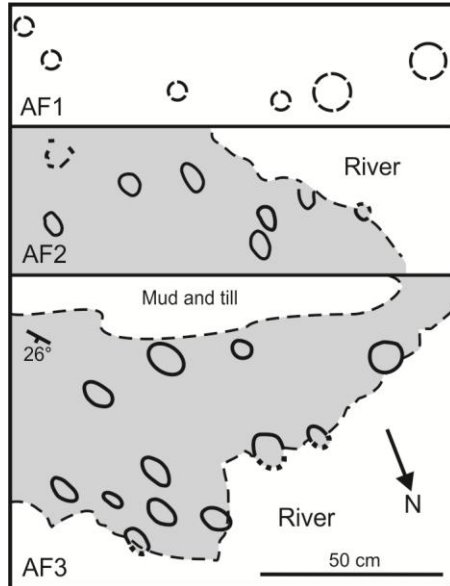
Density of trees was calculated by dividing the number of vertical tree trunks recorded by the area of exposed bedding plane (the shaded area above was measured using the images analysis software Leica Application Suite v4). For AF2 the density is 20.2 trunks m^{-2}, and for AF3 the density is 20.5 m^{-2}. For the two sites combined density is 20.4 m^{-2}. This is considered a minimum figure because some tree trunks may have been obscured by the river debris, and where the outline was unweathered, very difficult to recognise.

DR5 Tectonically shortened megaspores
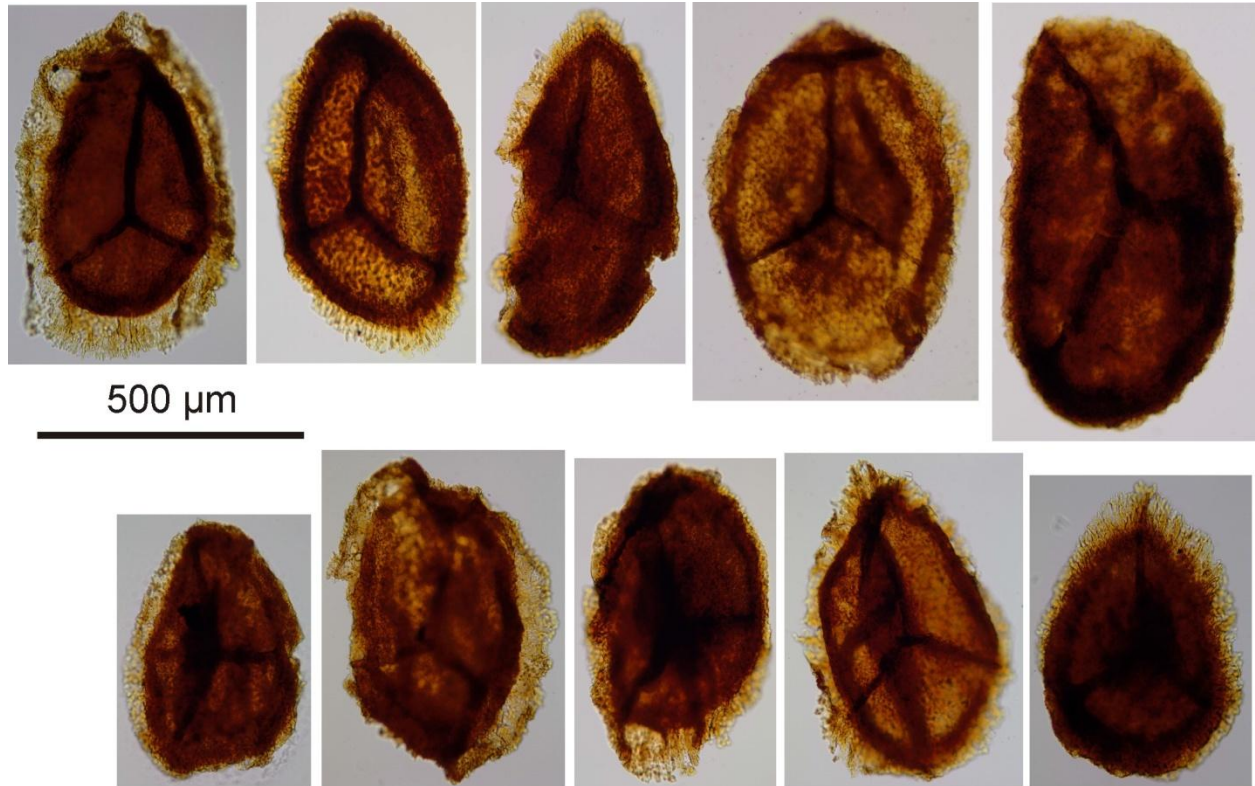
Megaspores of *Triangulatisporites rootsii* from AF2, sample Mimer-77. These megaspores are from a lycopod forest locality where there has been considerable early tectonic E-W shortening of the *in situ* trunks. These megaspores are normally radially symmetrical with angles of 120° between the trilete rays. The shortening has compressed the spores (which would have been bedding parallel but randomly orientated) and both removed the triradiate symmetry and altered the 120° angles.

DR6 Preservation of fossil trees

Cartoon showing formation of the Munindalen forest. This represents just one single episode of deformation and burial, multiple forests horizons are preserved in Munidalen.
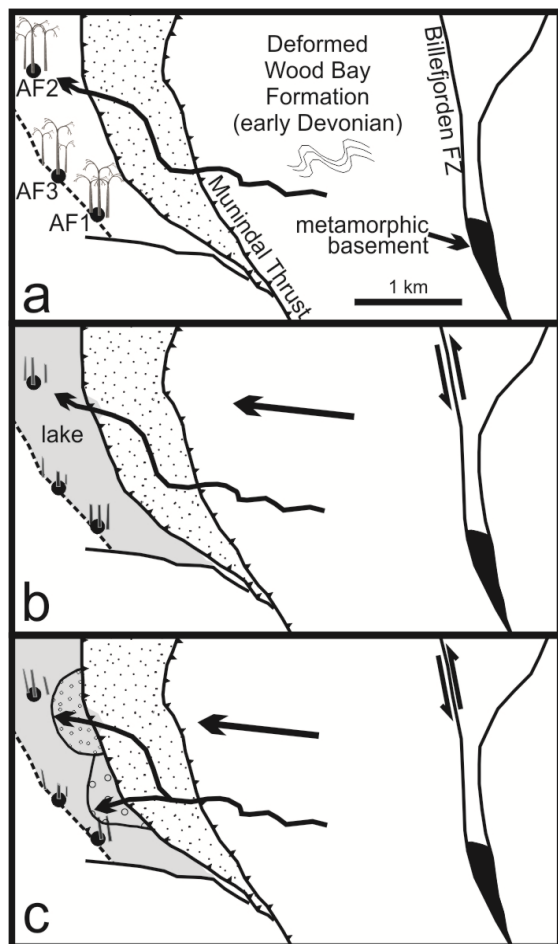
a. There is an established fluvial system eroding deformed sediments that are mostly of Wood Bay Formation but include some underlying Mimerdalen Subgroup. This uplift and erosion deposited coarse debris to the west of the Munindalen Thrust. The forests are growing on the more stable flood plain areas in this system as evidenced by the paleosols beneath them. **b.** A further episode of strike-slip fault movement along the Billefjorden Fault Zone again deforms the Wood Bay Formation generating coarse debris. Lower and Middle Devonian sediments caught up in this deformation are heated by shearing and eroded as mudstone clasts. This tectonic movement suddenly drops the relative base level of the forest and the forested area floods deep enough to give a permanent stratified lake as evidenced by the AOM (amorphous organic matter) content in some samples. This flooding killed the trees, and the associated tectonic deformation deformed the tree stumps. **c**. Coarse sediment continued to be shed from the thrust burying the dead forests in conglomerate. Geological base after Bergh et al., 2011.

Bergh, S.G., Maher, H.D., Braathen, A. 2011. Late Devonian transpressional tectonics in Spitsbergen, Svalbard, and implications for basement uplift of the Sørkapp–Hornsund High: Journal Geological Society, London, v. 168, p. 441–456.

DR7 Climate

Middle Devonian
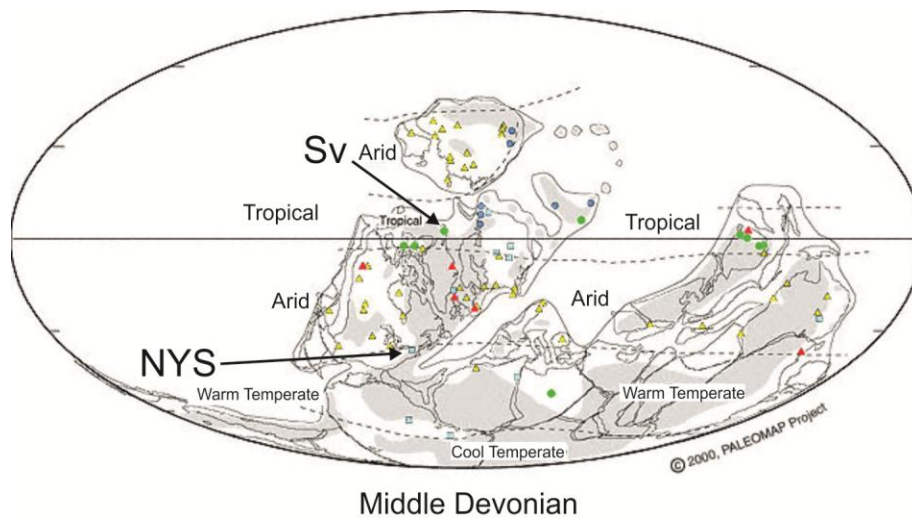
Paleogeographic reconstruction and palaeoclimatological interpretation based on climatically sensitive sediments from Scotese, Boucot and Chen (http://www.scotese.com/mdevclim.htm).

Devonian lycopsid forests on Svalbard (Sv) in paleo-equatorial tropical zone contrast with position of fossil forests of New York State, e.g. Gilboa (NYS) on the southern boundary between arid and warm temperate zones.

For meaning of other symbols see http://www.scotese.com/legend.htm