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Davies, N.S., Berry, C.M., Marshall, J.E.A. et al. (2 more authors) (2021) The Devonian landscape factory : plant–sediment interactions in the Old Red Sandstone of Svalbard and the rise of vegetation as a biogeomorphic agent. Journal of the Geological Society, 178 (5). jgs2020-225. ISSN 0016-7649

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Figure 1 – Bedrock geology of NW Spitsbergen showing localities and constituent formations of the Old Red Sandstone.

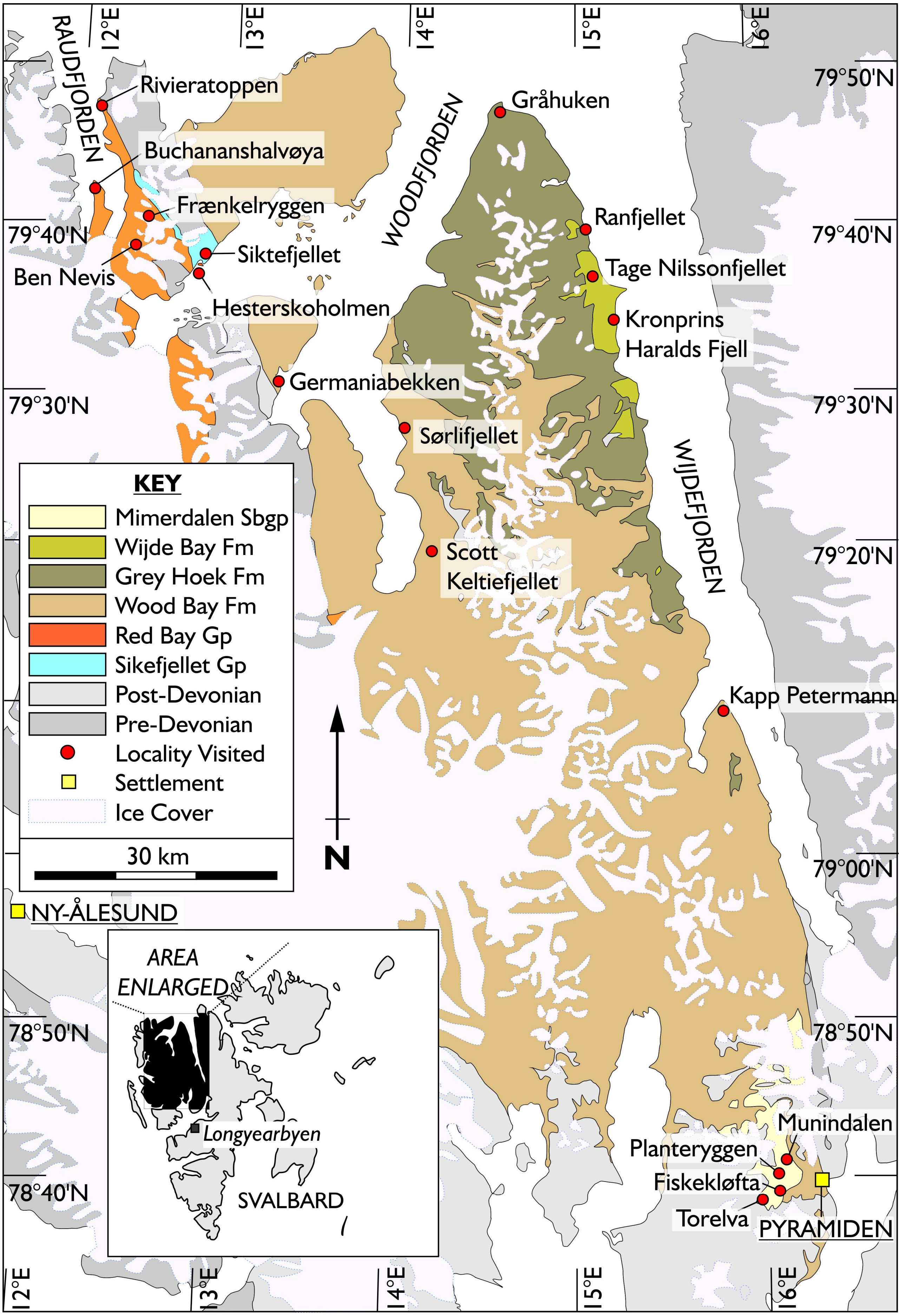


Figure 2 – Stratigraphic relationships within the Old Red Sandstone in NW Spitsbergen (lithostratigraphy after Piepjohn and Dallman (2014); revised dating after Berry and Marshall, (2015)). Vertical scale proportional to time in Ma. Timing of earliest global fossil evidence for evolutionary innovations in vegetation shown on right hand side of figure: details on timing from Berry and Fairon-Demarat (1997, 2002), Gerrienne (2012), Stein et al., (2012, 2020), Strullu-Derrien (2014), Matsunaga and Tomescu, (2016), and Hetherington and Dolan (2018).

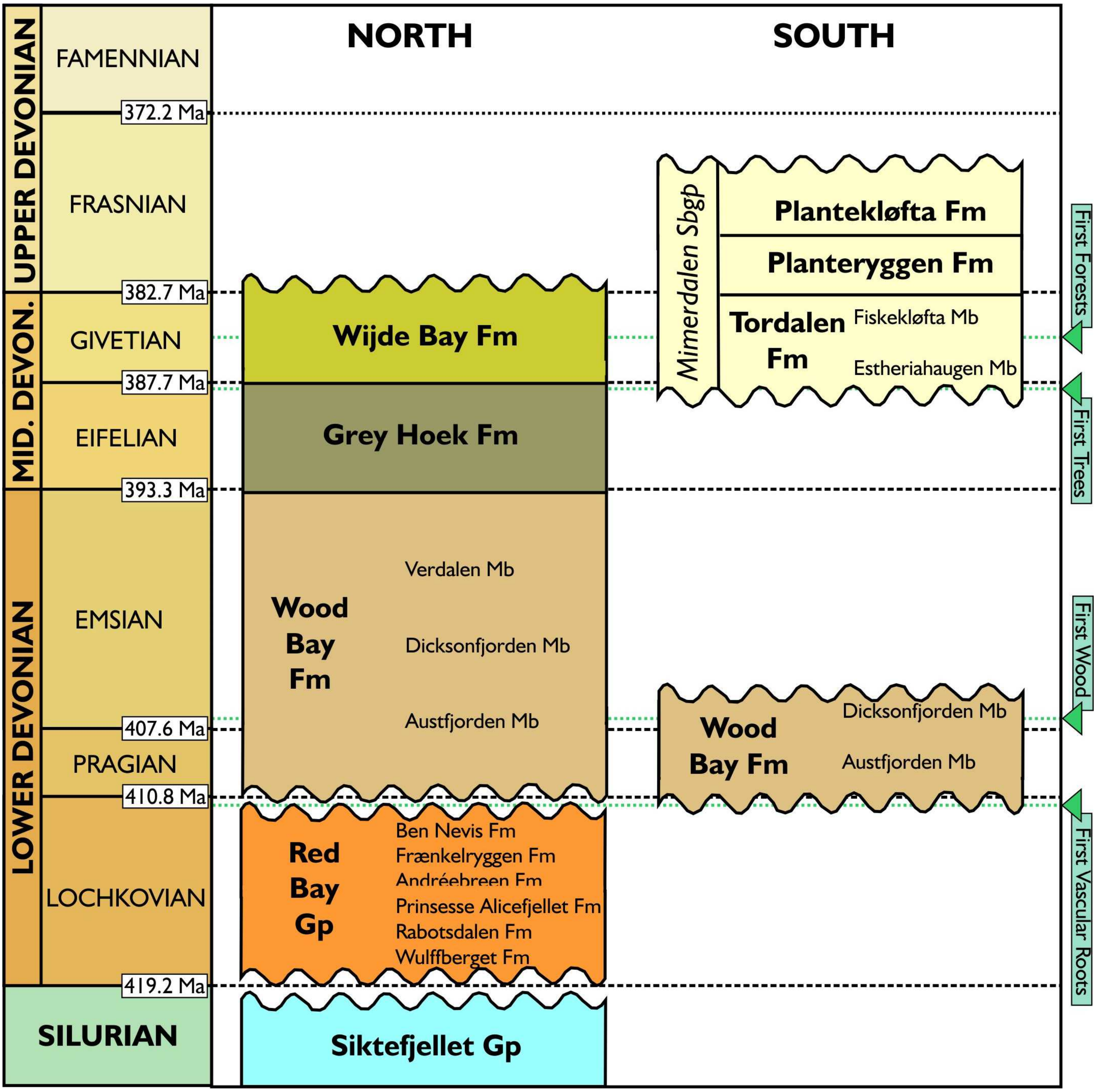


Figure 3 – Outcrop appearance of the constituent units of the Old Red Sandstone in NW Spitsbergen. A) Grey sandstones and recessive shales of the Siktefjellet Group, Siktefjellet. B) Basal debris flow conglomerate of the Red Bay Group: Wulffberget Formation, Rivieratoppen. C) Red mudrocks and subordinate sandstones of the upper Red Bay Group: Frænkelryggen Formation, Frænkelryggen. D) Thick fluvial sandbodies within drab mudrocks of the uppermost Red Bay Group: Ben Nevis Formation, Ben Nevis. E) Thick succession of red heterolithic strata within the Wood Bay Formation: Dicksonfjorden Member, Roosfjella. F) Frost-shattered, scree covered outcrops of the Wood Bay Formation: Dicksonfjorden Member, Scott Keltiefjellet. G) Red-drab transition between the Wood Bay Formation (Verdalen Member) (foreground) and Grey Hoek Formation (background), Woodfjorden. H) Gradational transition between red palaeosols of the Wood Bay Formation (Verdalen Member) and grey ostracod-bearing shales of the Grey Hoek Formation, Sørlifjellet. I) Heterolithic succession of yellow sandstones and grey shales of the Wijde Bay Formation, Tage Nilssonfjellet. J) Finely laminated lacustrine sandstones of the lower Tordalen Formation: Fiskekløfta Member, Fiskekløfta. K) Sandstones of the Plantekløfta Formation, formerly ascribed to the Planteryggen Formation, Planteryggen. L) Typical actively-eroding riverbank outcrop of heterolithic strata of the Plantekløfta Formation, Munindalen.

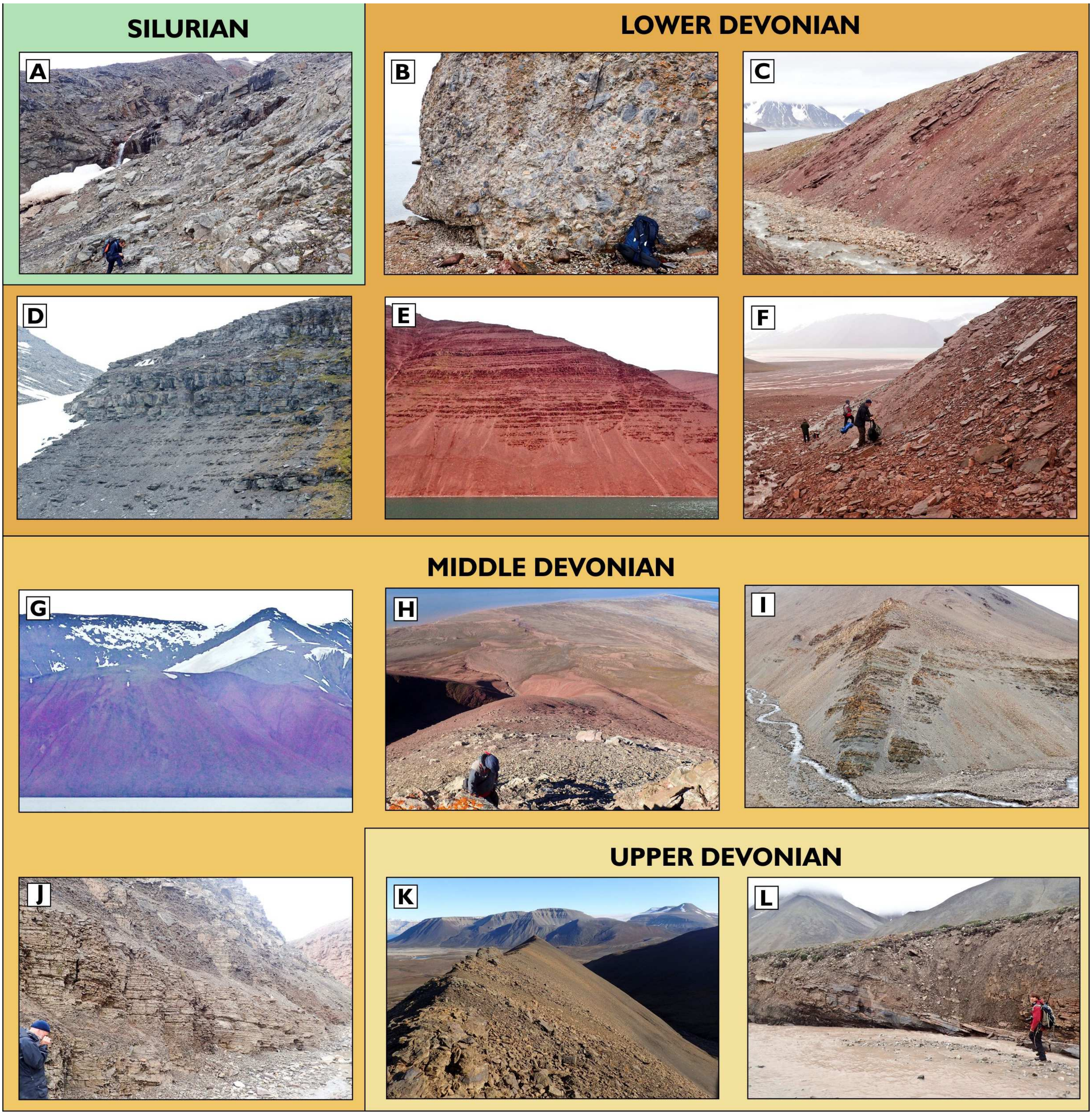


Figure 4 – Representative plant fossils **To be made using others pics**

Figure 5 – Lochkovian plant-sediment interactions in the Red Bay Group (Andréebreen Formation) at Buchananhalvøya. A-B) Laterally-continuous braided fluvial sandbodies (highlighted yellow) and minor shales (grey). C-D) Detail of boxed area highlighted in B: Two braid bar deposits, separated by bar-top fines. E) Detail of the base of the upper barform, showing basal lag of intraformational calcrete conglomerate resting on grey shale. F) Abundant *in situ* zosterophyllum fossils, preserved within the bar top shales. G-H) Biogenic signatures associated with bar top zosterophyllum include casts of *Cruziana* arthropod furrows in base of overlying sandstone (G) and helical fish coprolites within the plant-bearing shales (H).

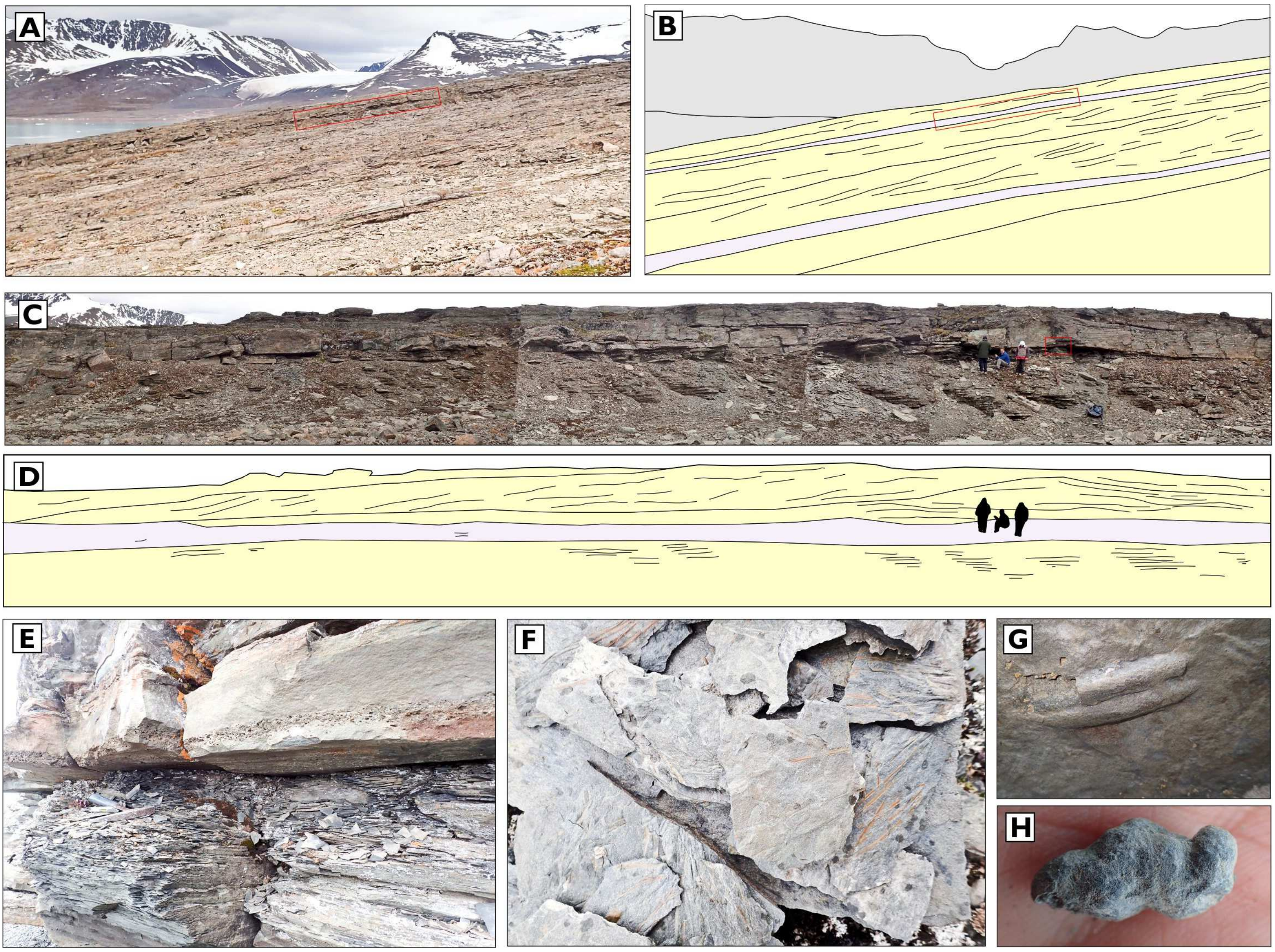


Figure 6 – Sedimentary context of plant fossil remains in the Pragian-Emsian Wood Bay Formation (Austfjorden Member) at Kapp Petermann. A-D) *In situ* remains restricted to inflection point of a downstream accreting sand barform (A-B), and consist of relatively complete specimens of small ?psilophytes (C-D), that would have been growing at the bar top and margins. E-H) Stratigraphically further up the same section, braided alluvial in-channel sandy bedforms form a discrete unit within vertic palaeosols (E-F); within these, plant remains are restricted to reworked instances of comminuted carbonaceous matter along trough cross-bed foresets (G) or small fragmentary remains within planar-bedded sandstones.

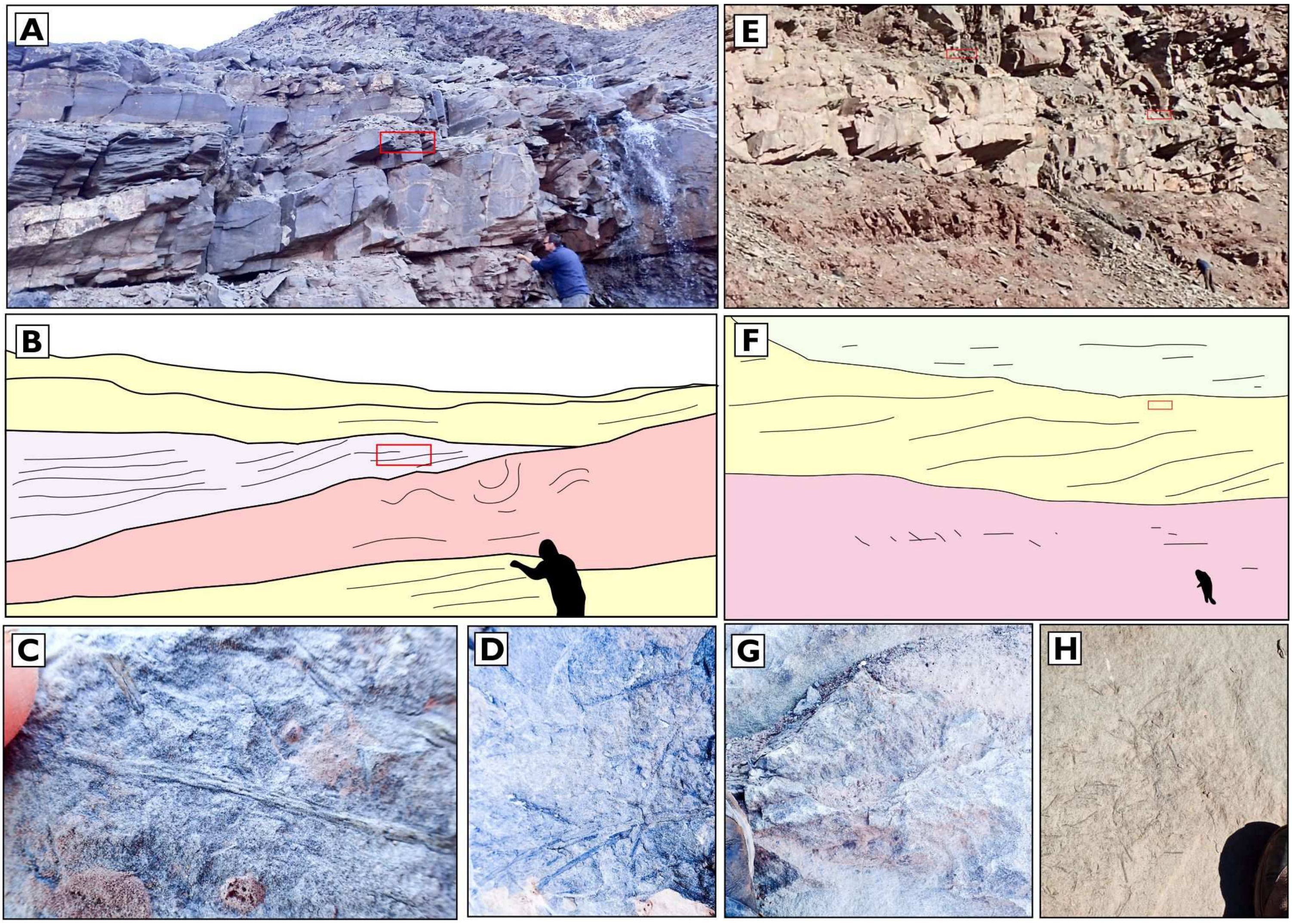


Figure 7 - Sedimentary context of plant fossil remains in the Eifelian Grey Hoek Formation at Ranfjellet. A-B) Heterolithic succession bearing ostracod fauna and consisting of IHS-LA, recording deposition by small meandering estuarine channels. C) Plan view of preserved ridge-and-swale topography of scroll bar top of one such channel. D) Fragmentary transported plant debris preferentially accumulates in sheltered swales of the scroll bars.

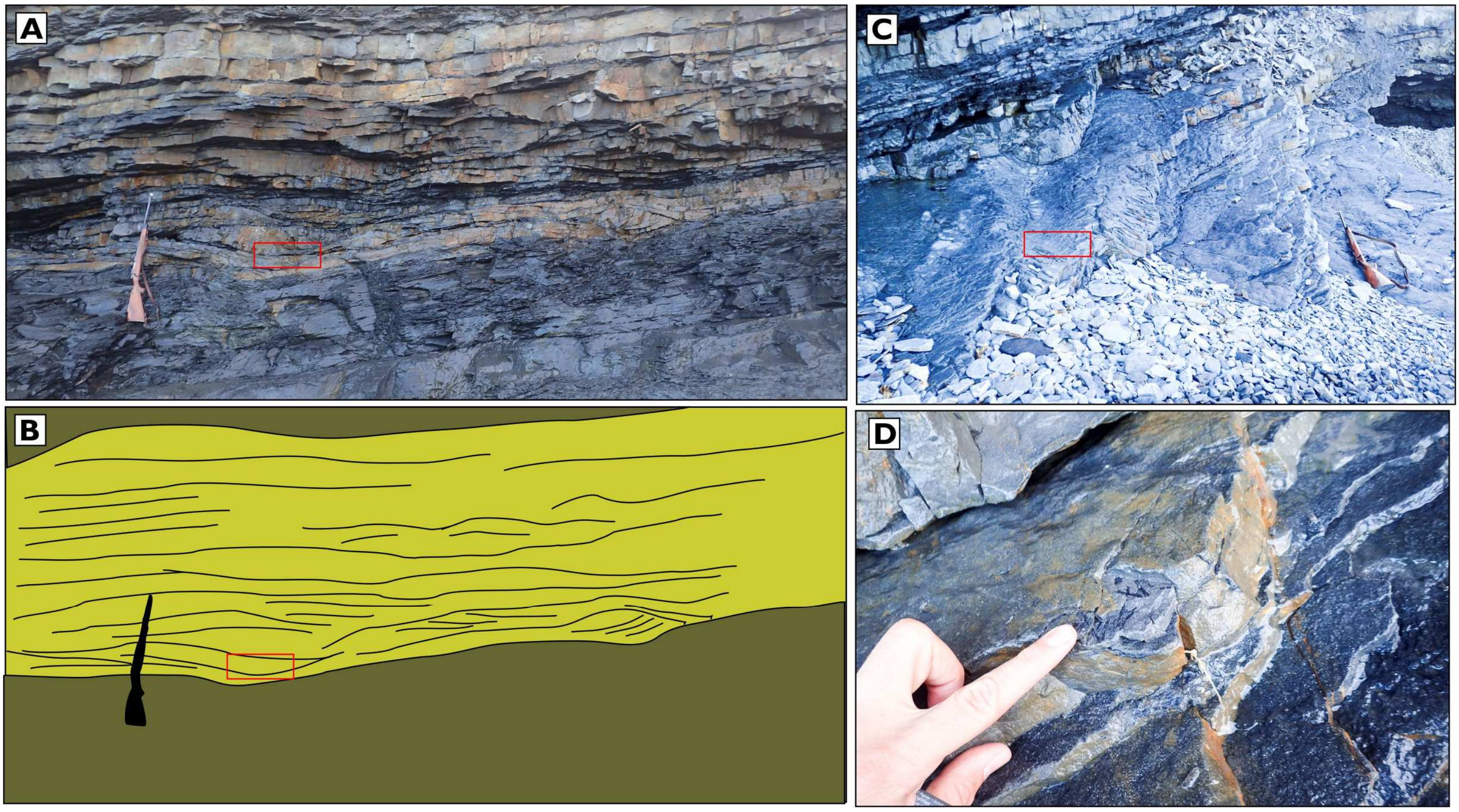


Figure 8 – Earliest woody debris in the Old Red Sandstone of NW Spitsbergen. A) Eifelian: Individual strands of xylem with frayed edges from unknown tree, up to 15 cm wide and 40 cm long. Grey Hoek Formation, Ranfjellet. B) Givetian: Individual clasts of woody debris up to 40 cm long and 17 cm wide within marine-influenced facies of the Wijde Bay Formation, Kronprins Haralds Fjell. C) Givetian: Largest woody debris in the succession: 2 metre-long log of *Archaeopteris* within the deposits shown in Fig. 20D, Tordalen Formation (Fiskekløfta Formation), Fiskekløfta.

Figure 9 – Drifted accumulations of woody debris within the Old Red Sandstone of NW Spitsbergen. A-C) Givetian accumulation of smaller woody debris within flat-bedded (A) heterolithic strata of the Wijde Bay Formation at Kronprins Haralds Fjell, comprising unoriented compressed wood material up to 40 cm in length (B-C). D-F) Oldest known driftcretion deposit (Givetian) within the Tordalen Formation (Fiskekløfta Formation) at Fiskekløfta. Individual accumulation of dominantly archaeopterid wood, up to 2 metres length (D) persist within a series of eleven sandstone beds that form a 5 metre-thick amalgamated succession (E). Some of the drifted logs can be seen to have rested on subaerially-exposed bars, as shown by close association with true substrates of extensive aeolian adhesion marks (F). Inset rose diagram in (D) shows axial orientation of 151 individual pieces of woody debris measured throughout the 5 metre-succession.

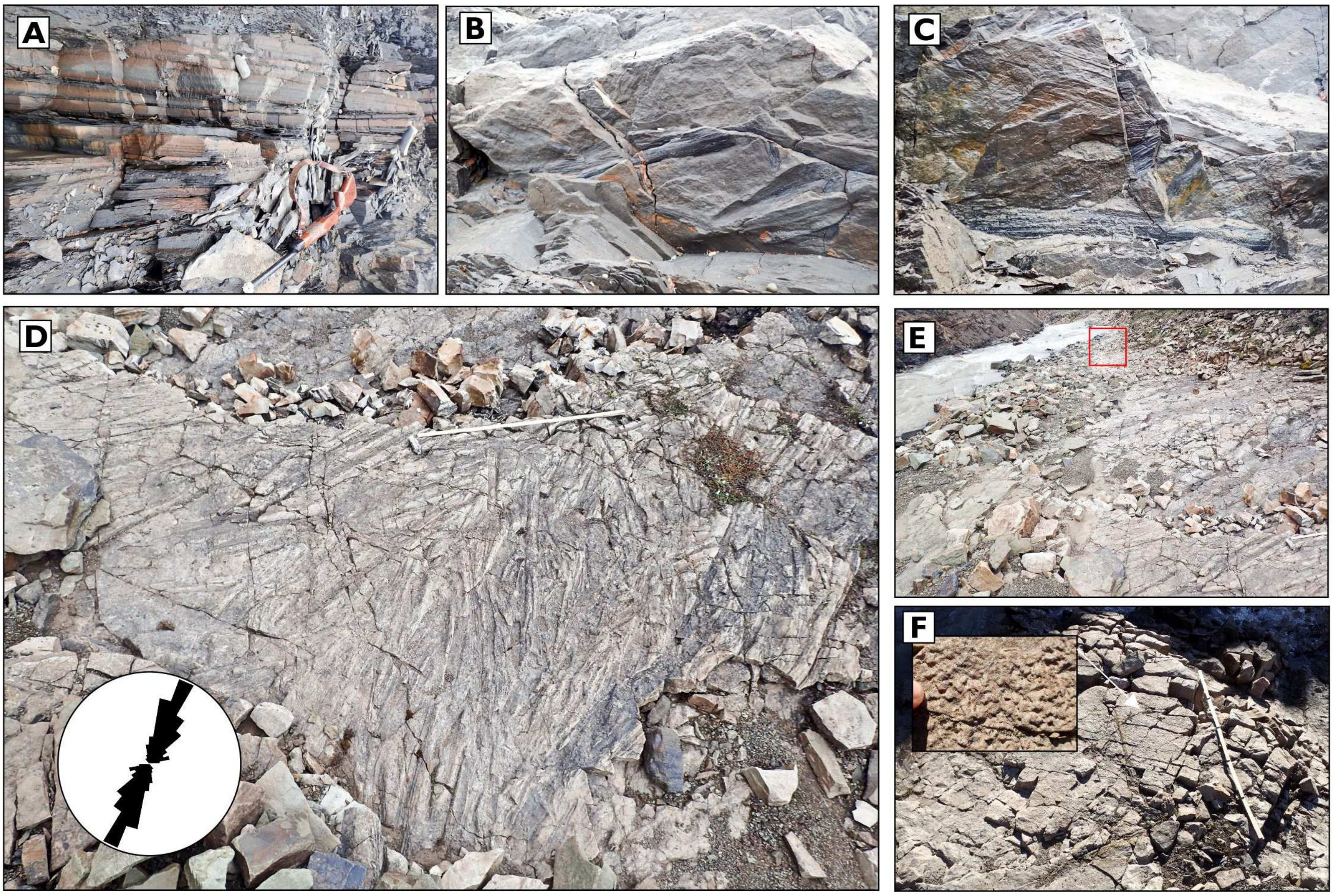


Figure 10 – Rooting structures throughout the Old Red Sandstone of NW Spitsbergen. A) Lochkovian: Possible 5 cm root structure at the top of a sandstone braid bar, immediately underlying the zosterophyll-bearing shales shown in Fig. 4. Red Bay Group (Andréebreen Formation), Buchananhalvøya. B) Pragian-Emsian: Dense assemblages of clay-lined root structures (up to 50 cm in depth in isolated instances), common within vertic palaeosols and associated strata of the Wood Bay Formation (Austfjorden Member) at Kapp Petermann. C) Eifelian: Suspected root structures (bifurcating downwards), forming 5 cm thick mantle within ostracod-bearing and carbon-rich marine influenced strata, possibly recording early salt marsh vegetation. Grey Hoek Formation, Ranfjellet. D) Givetian: Similar forms in similar marine-influenced facies to C, but extending up to 10 cm depth. Wijde Bay Formation, Tage Nilssonfjellet. E) Givetian-Frasnian: Two horizons of densely root-mottled palaeosols separated by sandbodies, implying root penetration to at least one metre. Boundary between Tordalen Formation and Planteryggen Formation, Fiskekløfta.

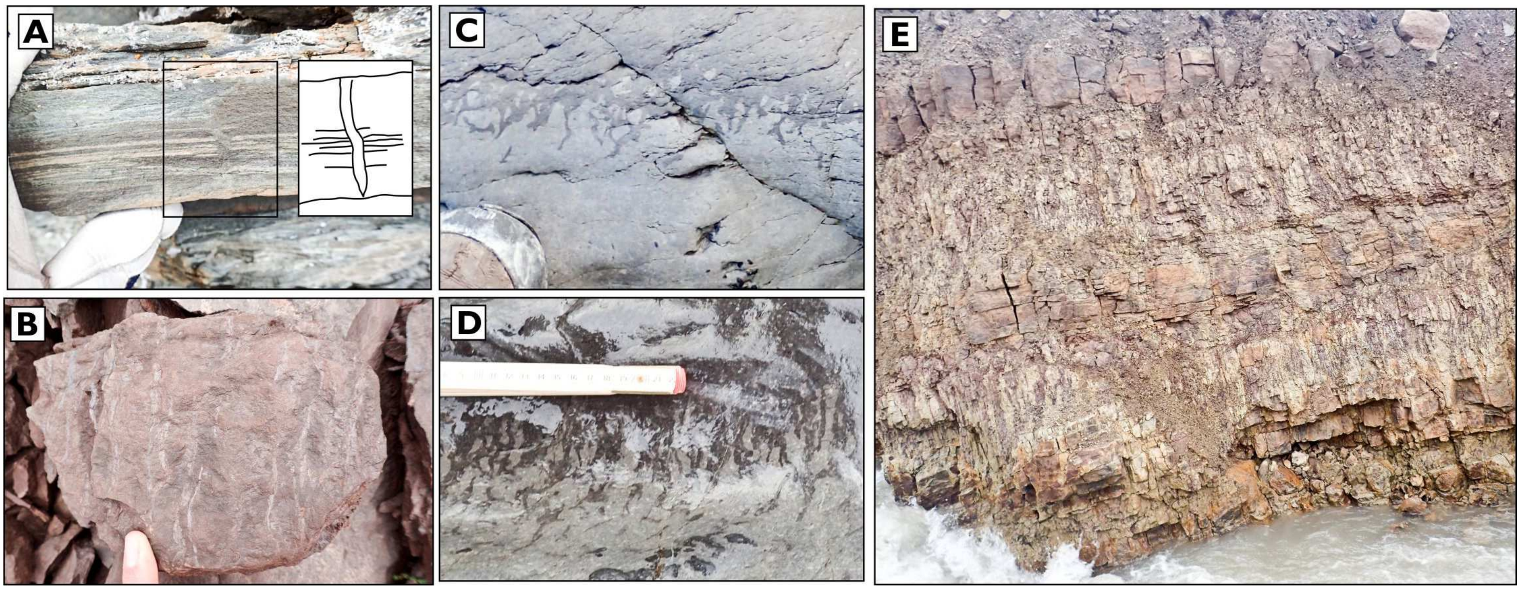


Figure 11 – Detail of rooting structures in the Pragian-Emsian Wood Bay Formation (Austfjorden Member) at Kapp Petermann. A) Succession consists of alternating blocky red palaeosols, punctuated with thin sandstones representing crevasse splay deposition. B-C) Details of crevasse splay sandstones showing penetration by clay-lined roots (B) and climbing ripple-laminated (C). Succession shows how near-instantaneously flood-deposited sands were afterwards colonized by rooted plants, which then persisted on the floodplain, promoting mud deposition and soil development over at least decadal timescales.

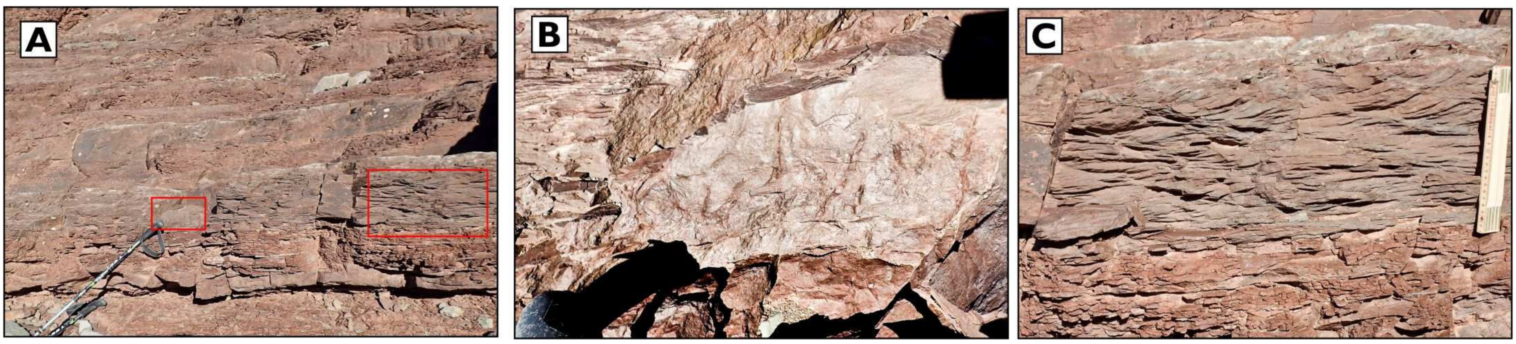


Figure 12 – Emsian VISS: Primitive VISS in the form of gently hummocky synoptic topography to a root-mottled inceptisol (A) in the Wood Bay Formation (Dicksonfjorden Member), Germaniabekken. Detail of hummock above root mottle shown in B.

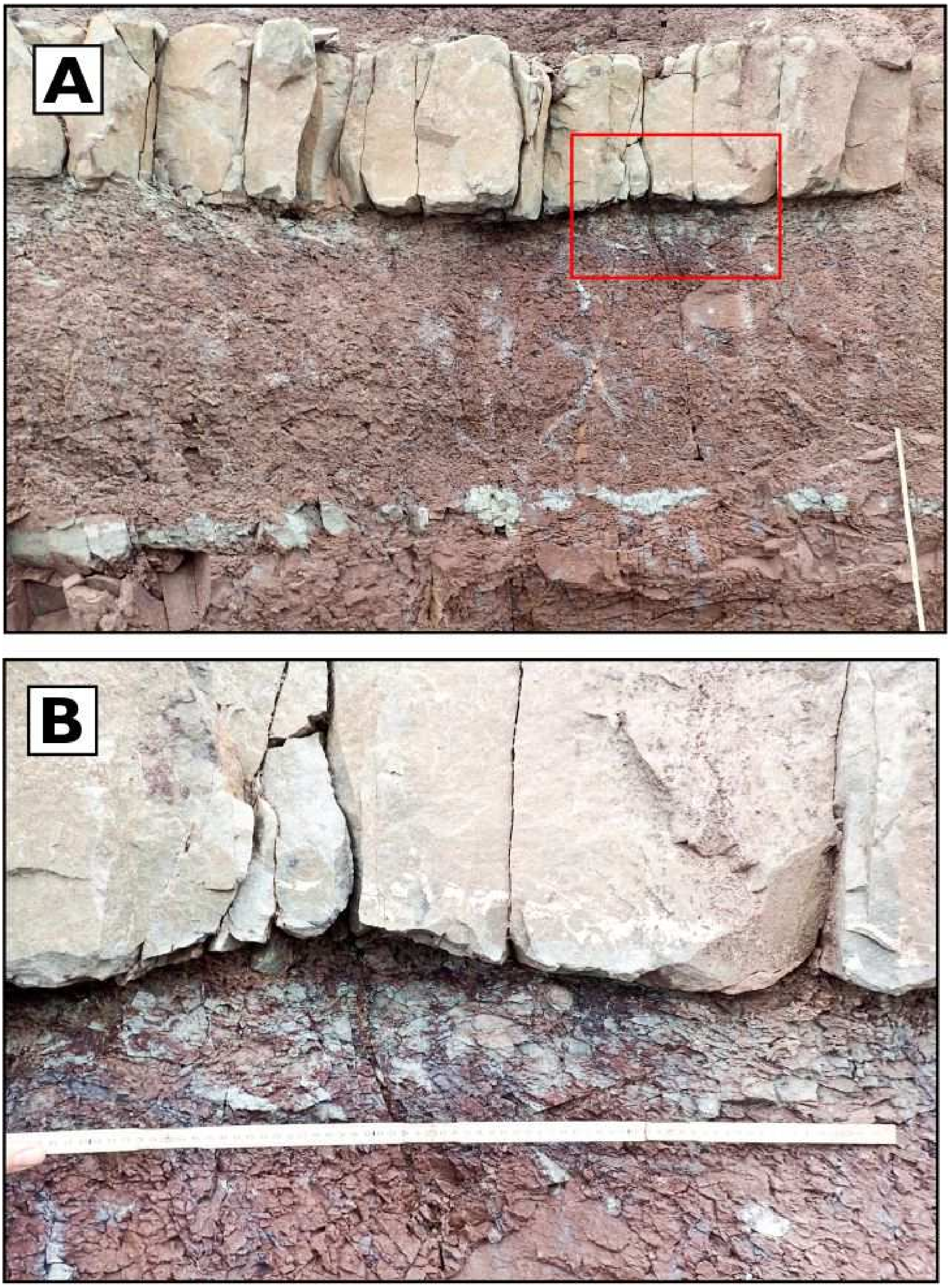


Figure 13 – Givetian VISS: Decay-related VISS formed as hollow plant stem filled with mud and decayed, causing downturning of beds. Asymmetry of downturning and tilt of plant cast suggests that the plant toppled as it decayed. Wijde Bay Formation, Tage Nilssonfjellet.

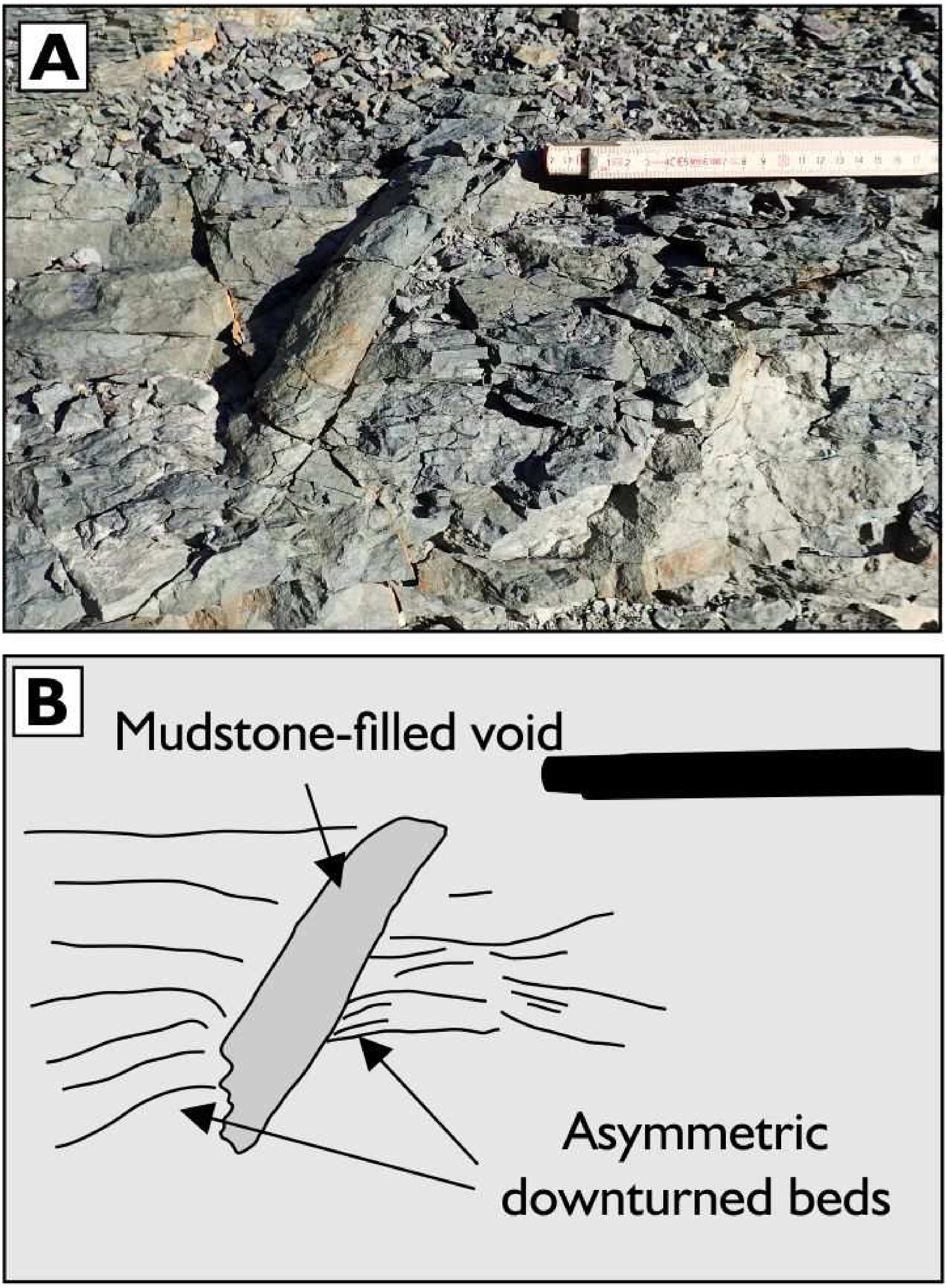


Figure 14 – Frasnian VISS associated with standing archaeopterid flora: A-B) Narrow archaeopterid stem with steeply upturned laminae (hydrodynamic VISS). Plantekløfta Formation, Munindalen. C-D) Buckled and steeply upturned laminae on either side of small archaeopterid stem apparently with some flexibility and bent into flow. Plantekløfta Formation, Munindalen. E-F) Large archaeopterid encased in sandstone and flanked by upturned laminae (hydrodynamic VISS). Plantekløfta Formation, Munindalen.

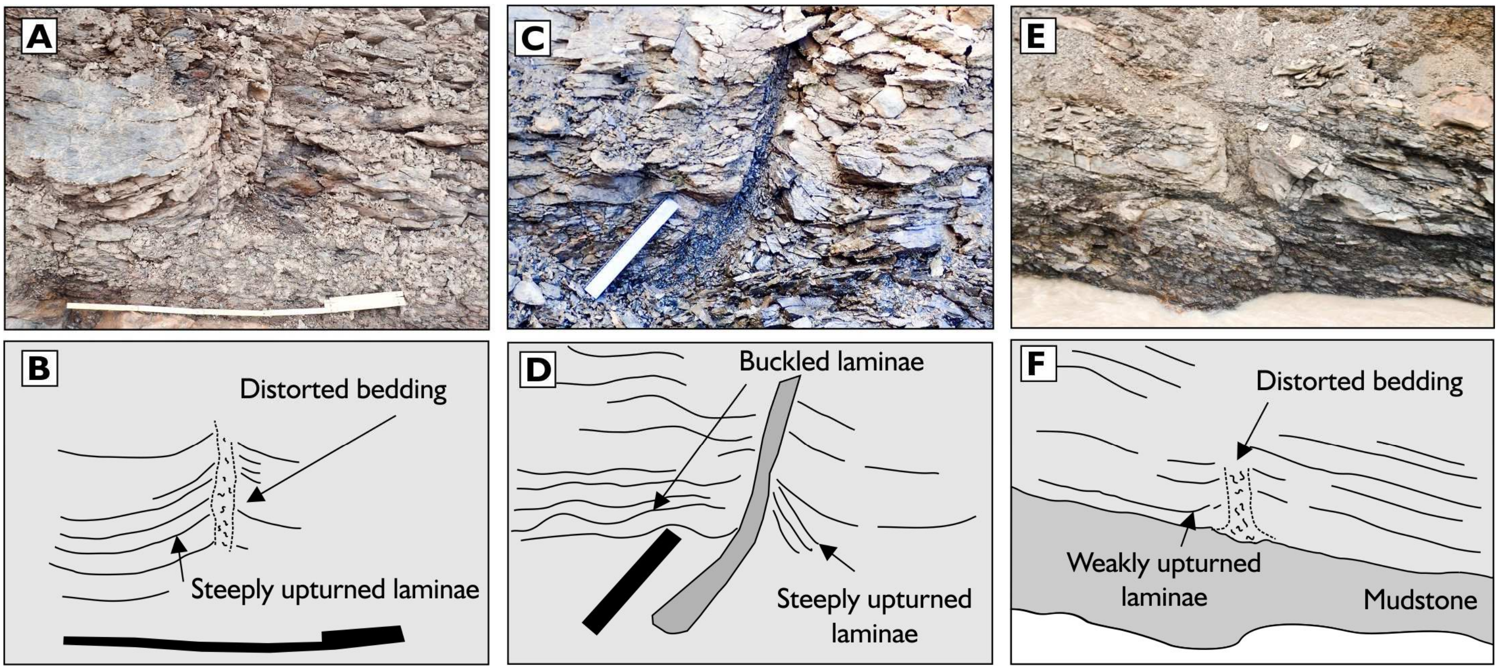


Figure 15 – Hydrodynamic VISS associated with standing archaeopterids, buried by a debris flow. Plantekløfta Formation, Munindalen. A-B) Three archaeopterid stems are seen within sandstones, containing VISS that indicated they interacted with the flows that deposited the sandstones. The fossil trees have been truncated by an over-riding debris flow, preserved as a thick conglomerate, with prominent clusters of cobbles preferentially deposited around topographic obstructions provided by the decapitated tops of the tree trunks. C-J) Details of the image shown in A, demonstrating how the archaeopterids were rooted in mudrock (E-F) and persisted as sand was deposited around the, before being truncated during the individual debris flow event.

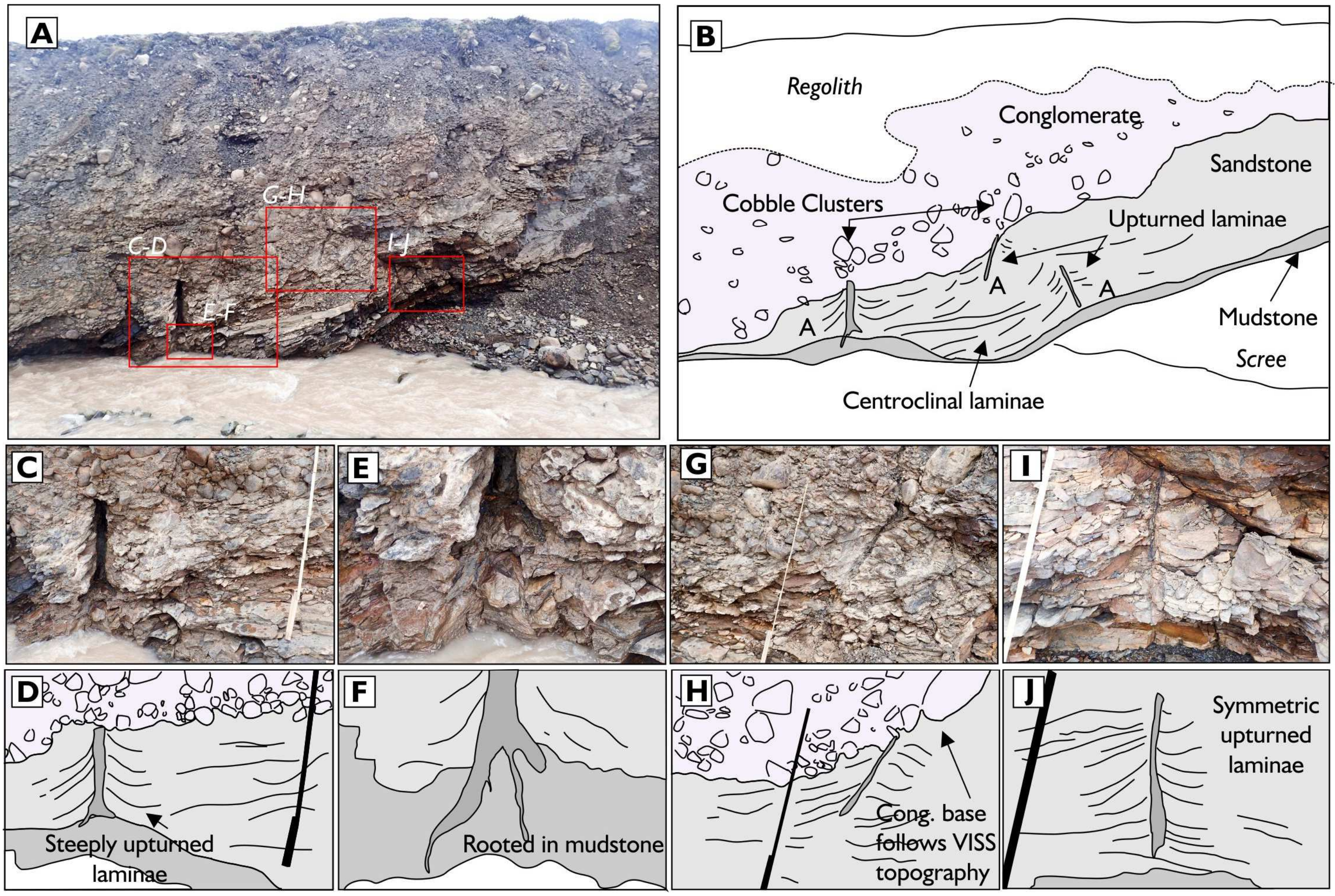


Figure 16 – Frasnian VISS associated with standing lycopsid flora: A-B) Small lycopods provide armoured mantle to muddy substrate, preserved as synoptic topography of small hummocks and swales. Plantekløfta Formation, Munindalen. C-D) Hydrodynamic VISS showing upward transition from centroclinal fill of scour to upturned laminae. Plantekløfta Formation, Planteryggen. E-F) Buckled and upturned laminae developed on the stoss side of a buried flexible stem. Plantekløfta Formation, Planteryggen.

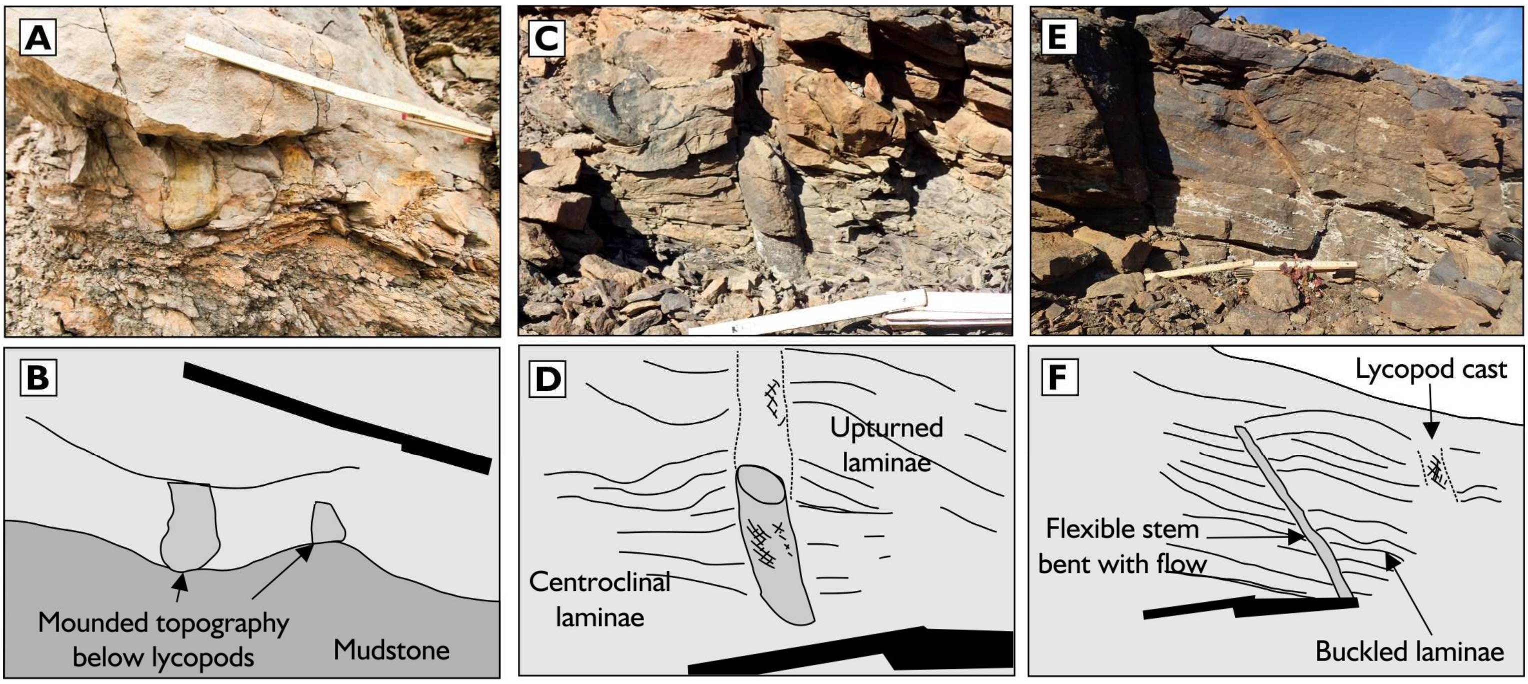


Figure 17 – Various forms of hydrodynamic VISS associated with standing lycopsids in the Plantekløfta Formation at Munindalen, demonstrating how distorted bedding persists even where fossil plant material is lost. A-B) Images of the same cliff face taken 6 years apart, showing erosion of the lycopsid bearing sandstone bed by bank collapse into the Mimer River. C-H) Details of the fossil bearing bed taken in 2016 showing hydrodynamic VISS in direct association with plant triggers (C-F), as well as instances along he same horizon where features are likely to be hydrodynamic VISS despite the absence of direct fossil evidence (G-H).

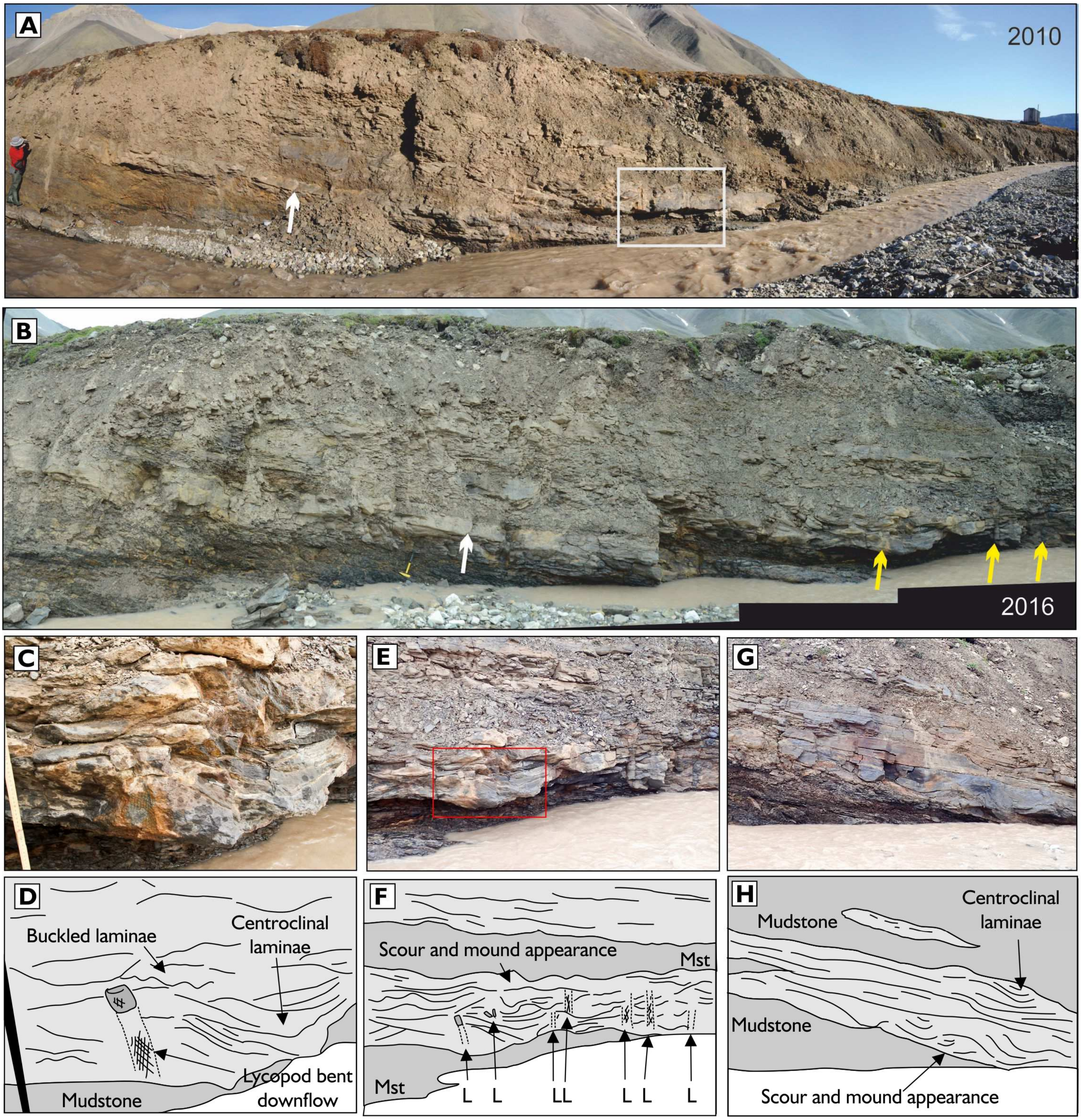


Figure 18 – Evidence for tree uprooting in the earliest Frasnian, revealed by fallen lycopsid crown that had toppled onto a small meander point bar (IHS-LA in Fig. 22E). Plantekløfta Formation, Munindalen. A-D) Upwards deflected lycopsid branches, encase by both mud and sand. E-F) Details of the above, showing minimal deflection of sedimentary laminae by the small flexible lycopod branches.

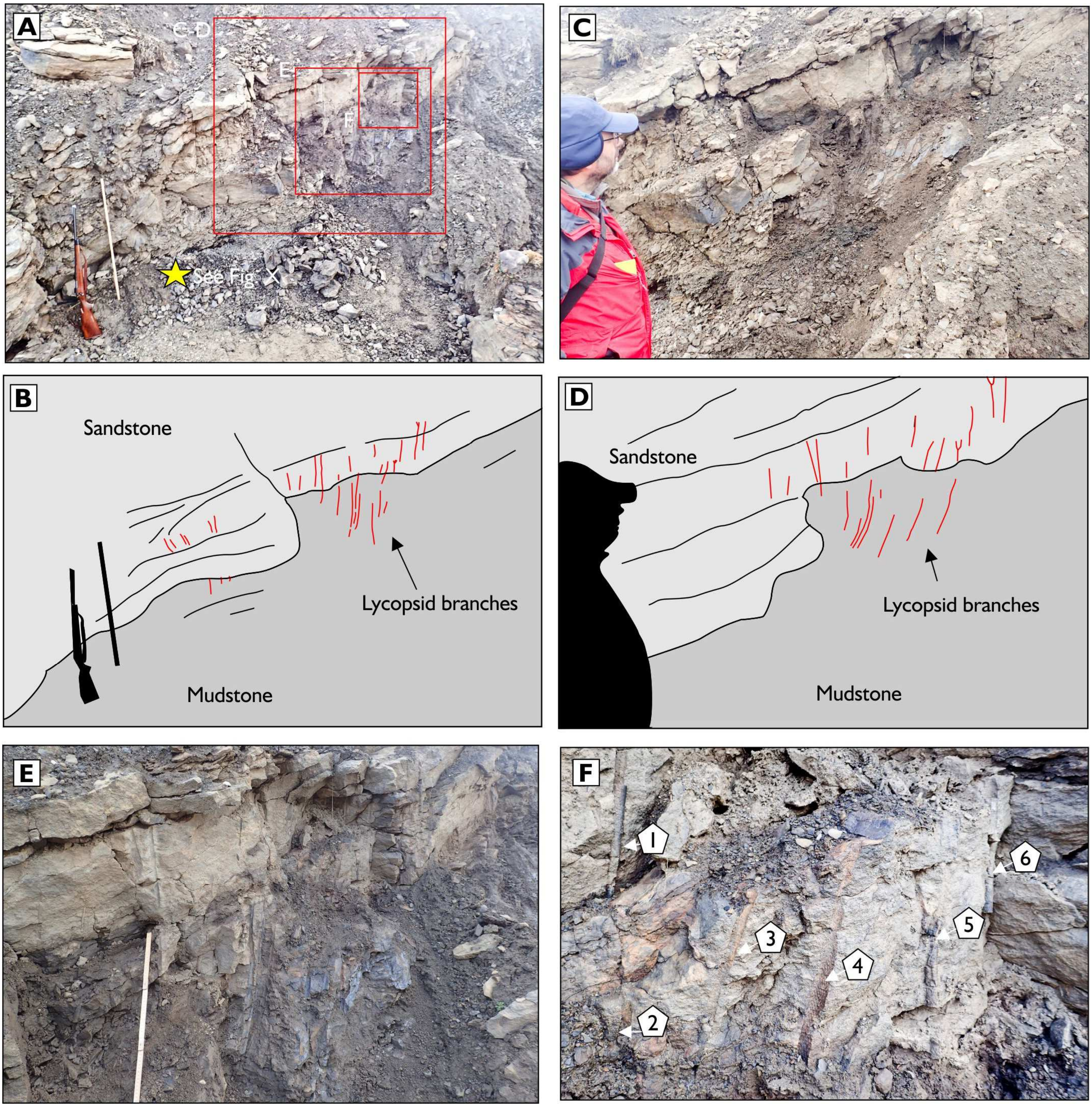


Figure 19 – Frequently oversteepened concavo-convex bedding within amalgamated sandstone bodies that appear too irregular, localized and individually unique to be formed by undisturbed hydrodynamic flow. These are putative VISS as they contain abundant evidence for standing vegetation or woody debris, but lack direct association with unequivocal plant triggers. A-C) Putative VISS in the Givetian Wijde Bay Formation, Tage Nilssonfjellet: convex-upwards mound in centre of A-B contains 10 cm carbonaceous root structures (C). D-F) Putative VISS in the latest Givetian Tordalen Formation (Fisklekløfta Member) at Torelva, comprising thick convex-up mounds of steep-margined sandstone beds with frequent woody debris (F) between beds. Mounds appear to be a result of flow diversion around woody debris, possibly in addition to decay- or compression-related deformation of the woody sediment pile. G-H) Putative VISS in the latest Givetian Tordalen Formation (Fisklekløfta Member) at Fiskekløfta (similar stratigraphic horizon to D-F). Continuous scour-and-mound topography persists across same amalgamated sandbody that contains log jam or driftcretion accumulations of woody debris on the opposite side of the river (Figure XXX).

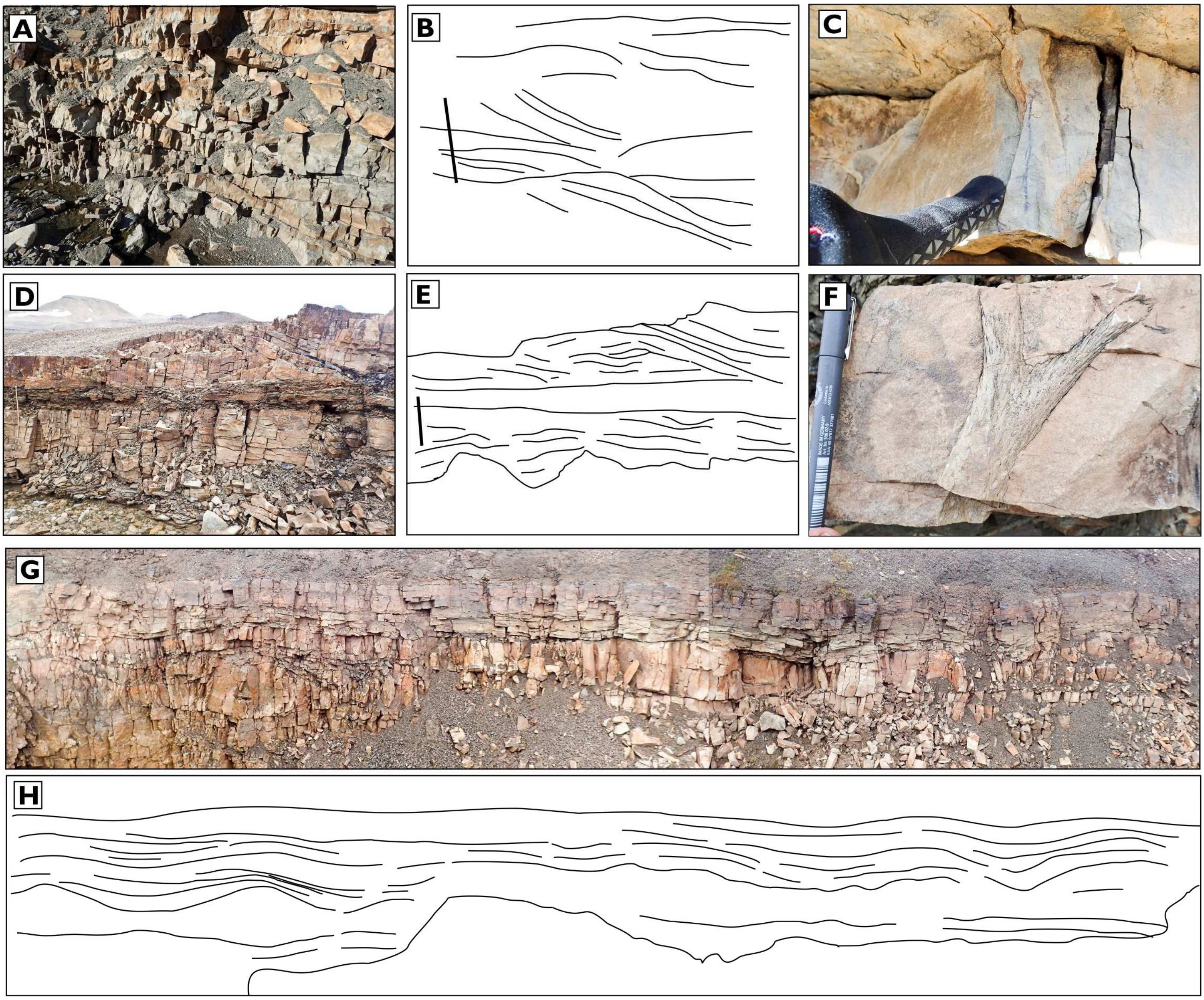


Figure 20 – Potential variability in influence of standing vegetation physiology on fluid flow and bed shear stress, illustrated with (non-exclusive) examples of Devonian flora known from the Spitsbergen Old Red Sandstone.

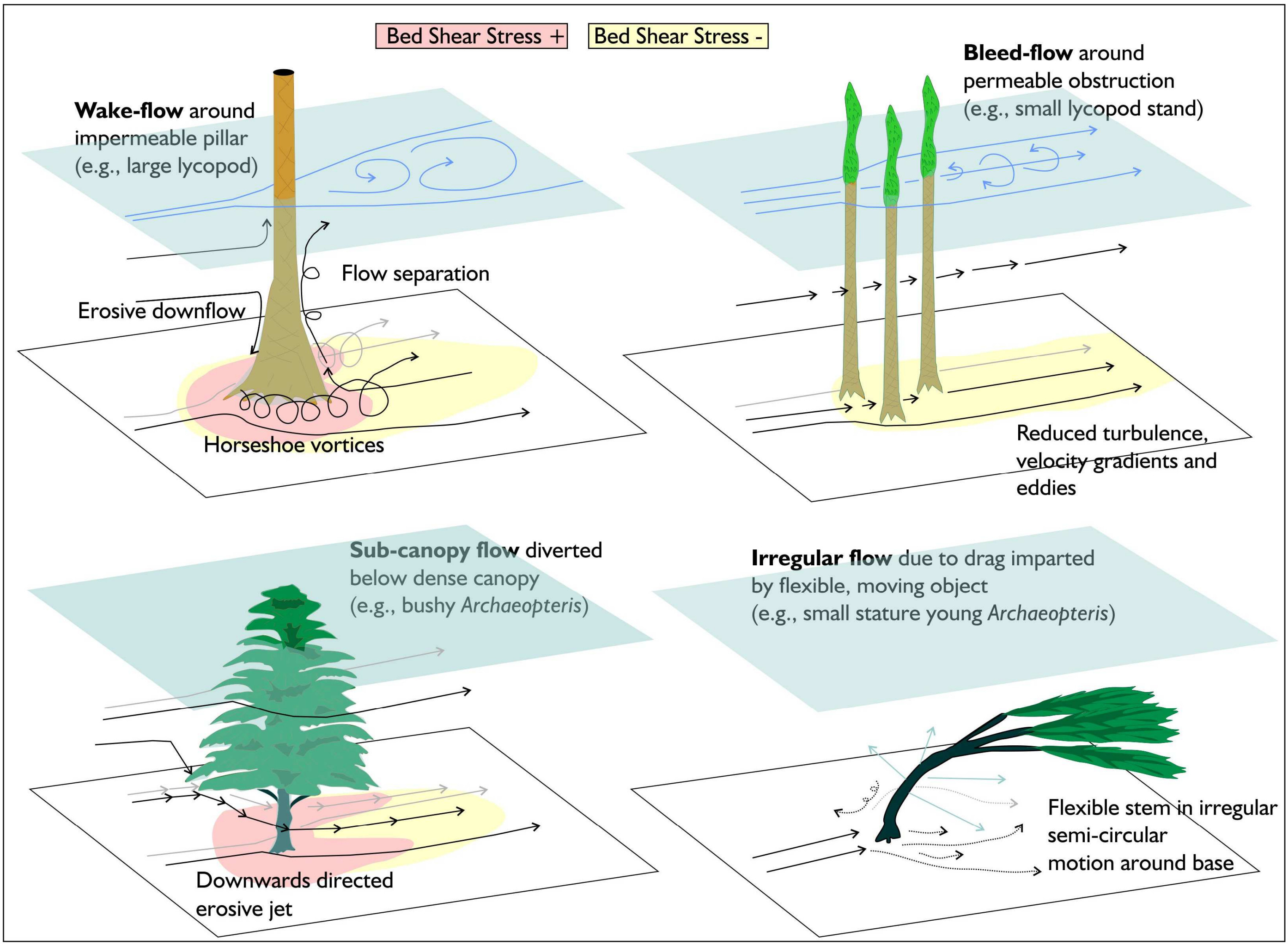


Figure 21 – Development of cannel coal in Givetian strata of the Tordalen Formation (Estheriahaugen Member) at Munindalen. A) Outcrop. B) Hand specimen.

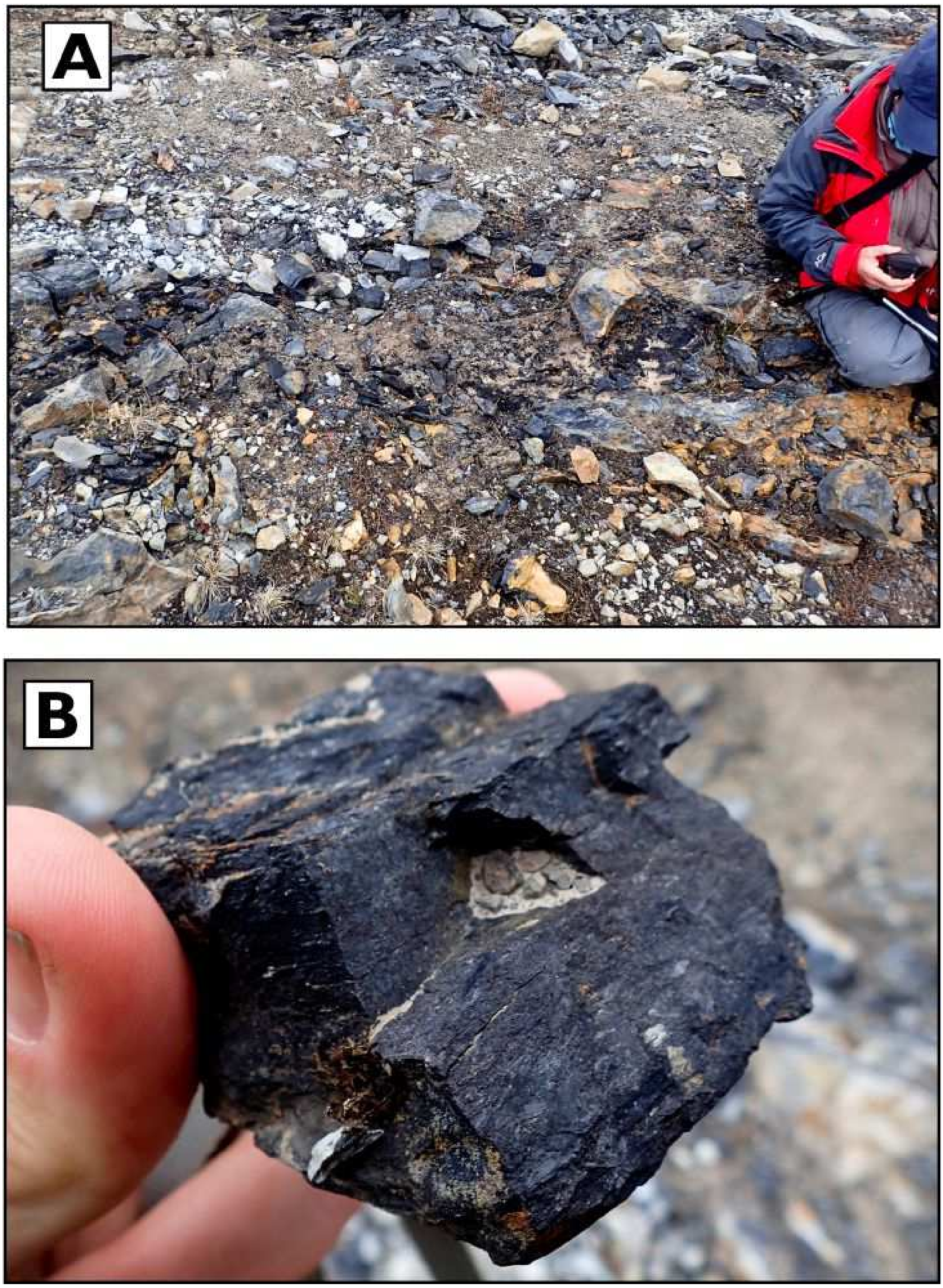
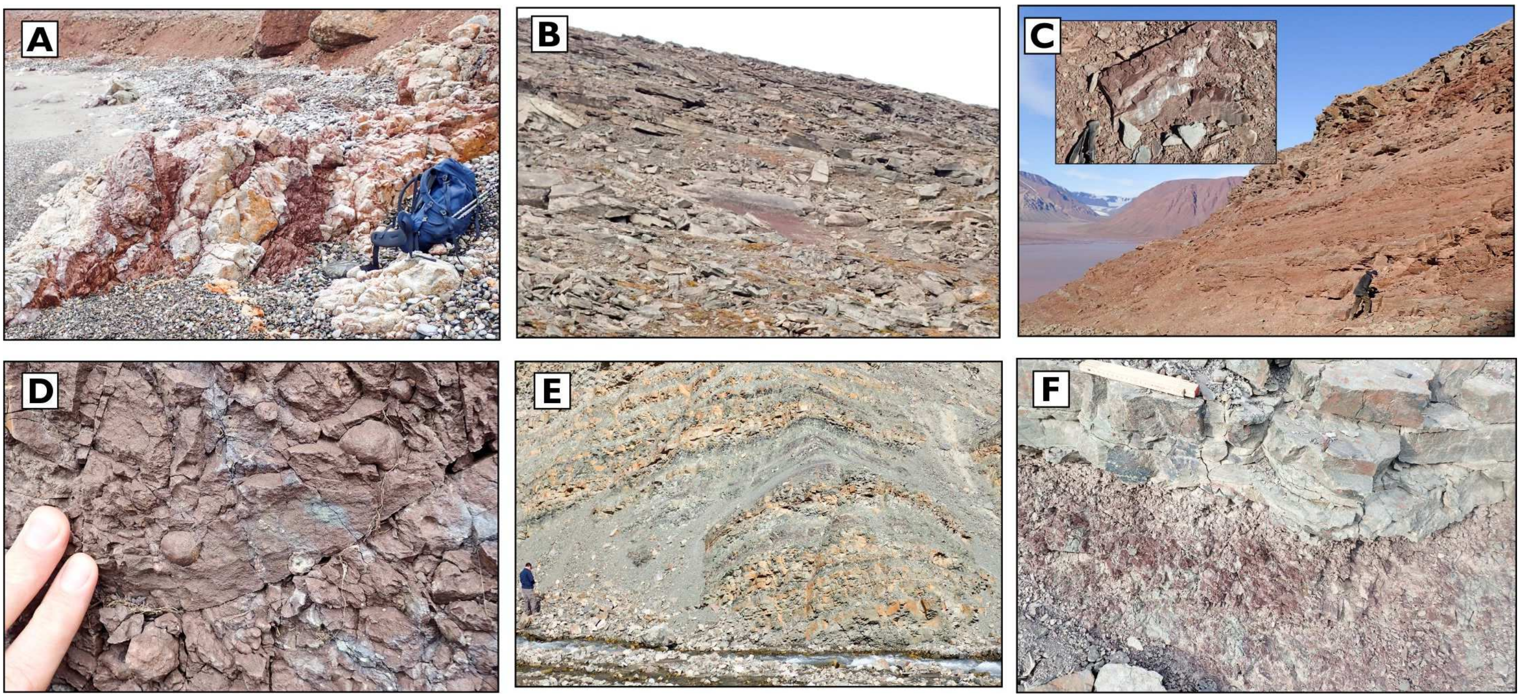


Figure 22 – Palaeosols and other weathering phenomena in which land plants would have played a role, recorded in the Old Red Sandstone in NW Spitsbergen. A) Lochkovian: Palaeokarst surface developed in basement marble of the Mesoproterozoic Richarddalen Complex, prior to the deposition of basin margin red mudstones and conglomerates of the lowermost Red Bay Group. Wulffberget Formation, Rivieratoppen. B) Lochkovian: Patch of blocky red inceptisol, preserved under erosional base of alluvial sandstone. Red Bay Group (Andréebreen Formation), Buchananhalvøya. C) Pragian-Emsian: Slickensides (inset) within vertisols preserved between crevasse splay sandstones. Wood Bay Formation (Austfjorden Member), Kapp Petermann. D) Emsian: Nodules of calcrete and elongate calcareous rhizoliths within blocky red aridisol. Wood Bay Formation (Dicksonfjorden Member), Germaniabekken. E-F) Givetian:Red and drab coloured entisols between sandstones, within marine-influenced facies: detail shown in F. Wijde Bay Formation, Tage Nilssonfjellet.



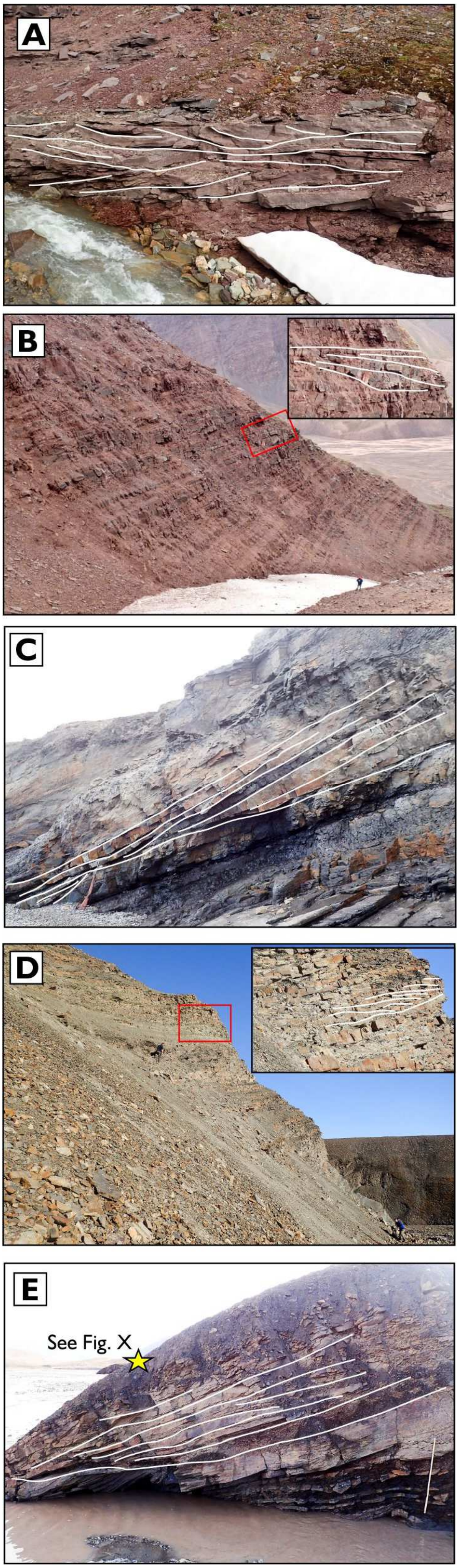


Figure 23 – Occurrences of IHS-LA sets throughout the Old Red Sandstone in NW Spitsbergen. A) Lochkovian: 80 cm-thick IHS-LA within the upper Red Bay Group. Frænkelryggen Formation, Frænkelryggen. B) Emsian: 5 metre-thick IHS-LA within the Wood Bay Formation. Dicksonfjorden Member, Scott Keltiefjellet. C) Eifelian: 2 metre-thick marine-influenced IHS-LA. Grey Hoek Formation, Ranfjellet. D) Givetian: 1 metre-thick marine-influenced IHS-LA. Wijde Bay Formation, Tage Nilssonfjellet. E) Frasnian: 2 metre-thick IHS-LA associated with both standing and fallen lycopsid and archeopterid vegetation. Plantekløfta Formation, Munindalen.

Figure 24 – Early Devonian plant-sediment interactions in the Spitsbergen Old Red Sandstone. A) Reconstruction of the general alluvial palaeoenvironmental setting of the Red Bay Group and Wood Bay Formation. B) Detail of plant interactions in the Red Bay Group, showing colonization of braid bar tops and margins by small zosterophylls with little resistance to erosion during flood stages. C) Duration of re-establishment of geomorphic phases after flood disturbance for riparian vegetation in the Early Devonian (see Fig. 23D and Corenblit et al., 2007 for details). D) Key to Figures 24-26.

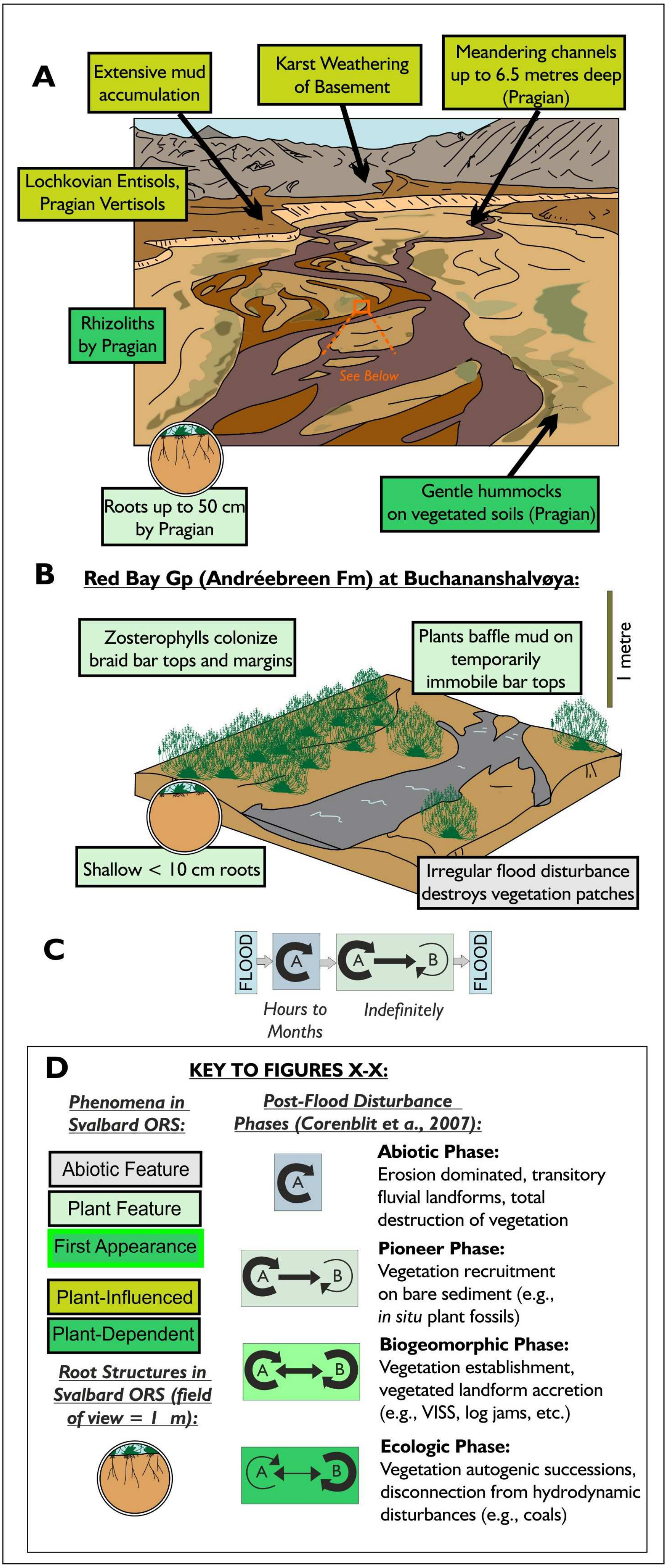


Figure 25 – Middle Devonian plant-sediment interactions in the Spitsbergen Old Red Sandstone. A) Reconstruction of the general nearshore and alluvial palaeoenvironmental setting of the Grey Hoek and Wijde Bay formations, with nearshore lacustrine/lagoonal and deltaic setiing of the Tordalen Formation. B) Detail of plant interactions in the Tordalen Formation, showing delta-top driftcretion of large woody debris. C) Duration of re-establishment of geomorphic phases after flood disturbance for riparian vegetation in the Middle Devonian (see Fig. 23D and Corenblit et al., 2007 for details).

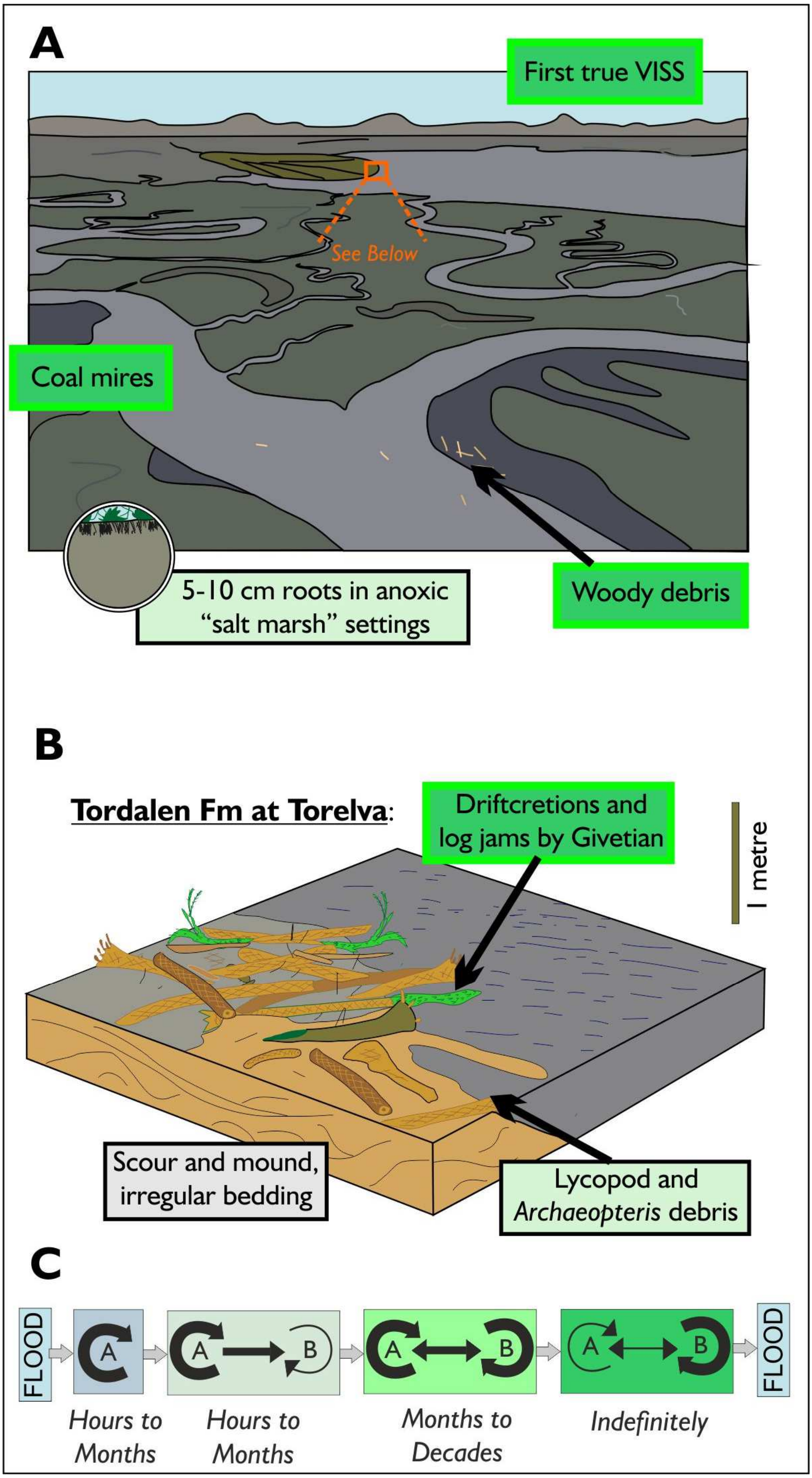


Figure 26 – Late Devonian plant-sediment interactions in the Spitsbergen Old Red Sandstone. A) Reconstruction of the general alluvial and debris flow palaeoenvironmental setting of the Planteryggen and Plantekløfta formations. B) Detail of plant interactions in the Plantekløfta Formation, showing trees rooted in floodplain fines, interacting with flood deposited crevasse splay sands, and uprooting of large trees on meander bends. C) Duration of re-establishment of geomorphic phases after flood disturbance for riparian vegetation in the Late Devonian (see Fig. 23D and Corenblit et al., 2007 for details).

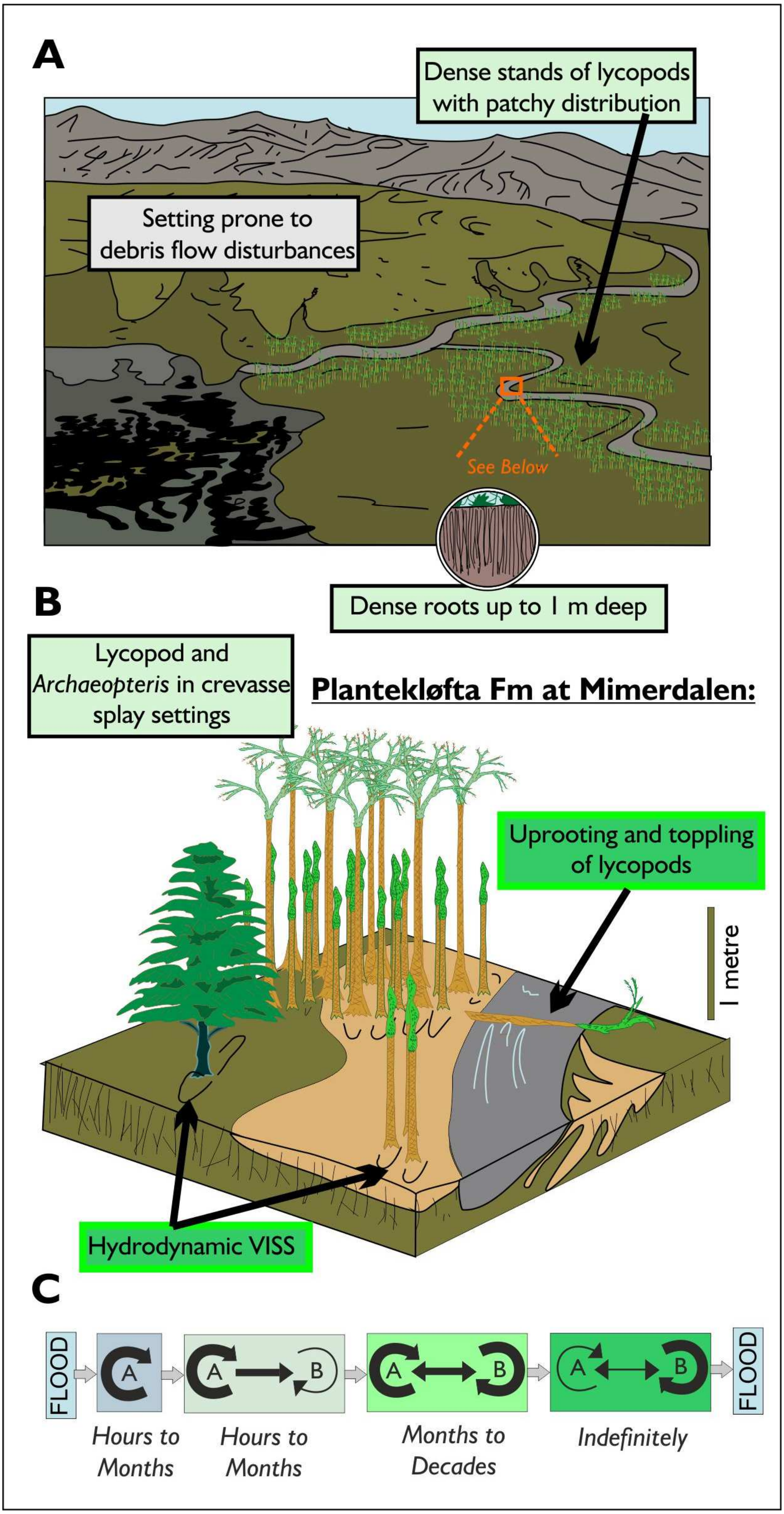


Table 1 – Characteristics of the formations of the Old Red Sandstone in NW Spitsbergen (compiled using information from Worsley (1970); Friend and Moody-Stuart (!972); Friend et al. (1997); Blomeier et al. (2003a,b)); Bergh et al. (2011); Piepjohn & Dallman (2014); Berry & Marshall (2015); Blumenberg et al., (2018)).

Age	Unit	Thickness	Lithology	Depositional Setting
Frasnian	Plantekløfta Formation	> 300 m	Dark mudrocks (c. 55%), sandstones, conglomerates.	Meandering rivers, forested floodplains, debris flows
Frasnian	Planteryggen Formation	335 m	Drab to red mudrocks (c. 45%), grey-green arkose sandstones.	Poorly exposed and delineated, but likely fluvial
Givetian	Tordalen Formation	c. 640 m	Drab to red mudrocks (c. 40%), grey-green arkose sandstones. Some coal.	Brackish to freshwater lacustrine strata with fluviodeltaic deposits and coal mires
Givetian	Wijde Bay Formation	600 m	Grey to yellow sandstones and dark mudrocks (c. 45%)	Coastal, estuarine setting
Eifelian	Grey Hoek Formation	1000 m	Grey sandstones and dark mudrocks (c. 50%)	Fluvial deposition in brackish coastal swamp
Pragian-Emsian	Wood Bay Formation	3000 m	Predominantly red mudrocks (c. 50%) and sandstones. Some calcrete.	Multiple different fluvial (braided and meandering) and floodplain settings
Lochkovian	Red Bay Group	3250 m	Basal conglomerate units, red and drab mudrocks (c. 40%) and sandstones. Reworked calcrete.	Alluvial fans, dominantly seasonal braided rivers, minor sporadic marine influence
Silurian	Siktefjellet Group	1825 m	Grey sandstones, conglomerates and mudrocks (c. 20%).	Poor and localized exposure, limited palaeoenvironmental evidence: reported as braided fluvial deposition.

Table 2 – Known fossil plants of the Old Red Sandstone in NW Spitsbergen. To be added from Chris's info

Table 3 – Distribution of plant-influenced and plant-dependent phenomena in the formations of the Old Red Sandstone in NW Spitsbergen.

		Fossil Plant Material			Biologically Influenced Phenomena			Biologically Dependent Phenomena					
Age	**Units**	**Comminuted debris**	**Fragmentary remains**	**Standing fossils**	**Alluvial mudrock**	**Palaeosols**	**IHS-LA**	**Putative VISS**	**Hydrodynamic VISS**	**Decay-related VISS**	**LWD**	**Driftcretions**	**Coal**
Frasnian	Plantekløfta, Planteryggen	•	•	•	•		•	•	•	•	•		
Givetian	Tordalen, Wijde Bay	•	•		•	•	•	•		•	•	•	•
Eifelian	Grey Hoek	•	•		•	•	•				•		
Pragian-Emsian	Wood Bay	•	•		•	•	•						
Lochkovian	Red Bay	•	•		•	•	•						
Silurian	Siktefjellet	•			•								