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Stratigraphy and palaeosol profiles of the Upper Triassic Isfjorden Member, Svalbard

Gareth S. Lord[1,4], Atle Mørk[2], Turid Haugen[1,2], Marit A. Boxaspen[1,3], Berit Husteli[1,3], Cathinka S. Forsberg[2], Bård Heggem[2], Snorre Olaussen[1,4]

[1] Department of Arctic Geology, The University Centre in Svalbard (UNIS), Longyearbyen, Norway.

[2] Department of Geoscience and Petroleum, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

[3] Department of Earth Science, University of Bergen, Bergen, Norway.

[4] Research Centre for Arctic Petroleum Exploration (ARCEx), Tromsø, Norway.

Corresponding Author(s): gareth.s.lord@gmail.com / atle.arctic@gmail.com

Abstract

The Isfjorden Member forms the upper part of the De Geerdalen Formation in Svalbard and is well exposed throughout central and eastern Spitsbergen, including the island of Wilhelmøya. We examine palaeosol profiles identified in the Isfjorden Member and compare these to profiles seen in the remainder of the De Geerdalen Formation. In addition, we address the nuances of the Isfjorden Member, its practicality as a stratigraphic interval and attempt to constrain the unit's presence, as well as the nature of its lower boundary throughout outcrops in Svalbard. The Isfjorden Member is easily recognised by its conspicuous beds of alternating red and green coloured palaeosols, occasional caliche profiles and bivalve coquina beds. These beds have commonly been used to identify the unit in outcrop and we explore their relevance to the formal stratigraphic definition. The lower boundary is typically difficult to identify, especially when using the original definition; however, we find that placing it at the top of the last major sandstone in the De Geerdalen Formation is a practical solution. The boundary is conformable throughout Spitsbergen with no obvious erosion or break in sedimentation observed.

The abundance, thickness and maturity of palaeosols increases upwards through the De Geerdalen Formation. Mature palaeosol and occasional caliche horizons are found to dominate within the Isfjorden Member. Immature palaeosols are in general constrained to the strata below. The position of palaeosols in relation to sedimentary successions is typically restricted to floodplain and interdistributary bay deposits, or atop upper shoreface deposits.

The transition from immature palaeosols with common histosols to mature palaeosols and caliche reflects the development of the delta plain from a dynamic paralic setting to a more stable proximal system.

Key words: Soil profile, paleosol, ancient soils, stratigraphic relationships, Triassic delta, Spitsbergen.

Running head: The Isfjorden Member in Svalbard

Introduction

In geological terms, Retallack (2001) defines soils as, *"material forming the surface of a planet or similar body and altered in place from its parent material by physical, chemical or biological processes*." As water is the vital medium in soil-forming processes (pedogenesis), rainfall, groundwater level, soil-drainage, evaporation and climate will all be controlling factors. Additionally, time, sedimentation rate and erosion are also important in allowing soils to develop. Detailed studies of ancient soils (palaeosols) might therefore improve interpretation of the depositional environment, sequence-stratigraphic surfaces, palaeoclimate, palaeogeography, and overall basin development. Furthermore, improved understanding of these facets will better refine stratigraphic boundaries and definition. The latest Carnian to earliest Norian aged paralic deposits of the Isfjorden Member are assigned to the uppermost part of the Upper Triassic De Geerdalen Formation, a unit that is well exposed throughout Svalbard (Figure 1, Mørk et al., 1999). The common presence of palaeosols within the De Geerdalen Formation and the Isfjorden Member makes these ideal units to study the development of ancient soils, in relation to depositional environment and palaeoclimate. Furthermore, field-based studies from Svalbard are applicable to the offshore and near-time equivalent Snadd Formation in the Norwegian Barents Sea.

As an entirely conformable and uninterrupted succession, the Carnian aged rocks in Svalbard were deposited throughout the period in which the Carnian Pluvial Event (CPE) occurred (Simms & Ruffell, 2018). This major climatic event during the Upper Triassic is largely associated with an unusually humid and wetter climate, as opposed to the more arid climatic conditions seen throughout the rest of the Triassic period (Mueller et al., 2016 a,b). The CPE is identified as having occurred during the middle part of the Carnian, spanning the boundary between the Julian and Tuvalian sub-stages (Simms & Ruffel, 1989). From magnetostratigraphic studies, the Tschermakfjellet and De Geerdalen formations are assigned a Julian to Tuvalian age (see Mueller et al., 2016b; Hounslow et al., 2022), with the Isfjorden Member being entirely Tuvalian in age (Mueller et al., 2016b; Hounslow et al., 2022) thus post-dating the CPE.

Based on an extensive field database from localities in Svalbard and cores from boreholes (Figure 1), we attempt to characterise and understand the development of palaeosols within the De Geerdalen Formation and the Isfjorden Member throughout Svalbard. Data presented here represent a compilation of nearly a decade's worth of field data and geological knowledge collected in Svalbard by master thesis and doctoral studies namely, M. Boxaspen, J. Enga, C. Forsberg, T, Haugen, B. Heggem, B. Husteli, I. Hynne, S.K. Johansen, C. Mc Cabe, G.S. Lord, R. Rød, H. Stensland and S.J. Støen.

Previously, little specific attention has been given to palaeosols in the De Geerdalen Formation and never in respect to their stratigraphical implications and relevance to the Isfjorden Member. The objectives of this study are to: (1) Characterise palaeosol profiles within the De Geerdalen Formation and Isfjorden Member at locations visited in Svalbard. (2) Compare and contrast palaeosol types seen in the Isfjorden Member to those in the remainder of the De Geerdalen Formation and discuss implications for depositional style and palaeoclimate during the late Carnian to early Norian. (3) Discuss the Isfjorden Member and its nuances as a stratigraphic unit within the De Geerdalen Formation, following its original definition by Pčelina (1983) and subsequent revision by Mørk et al. (1999).

Geological setting

The exposed Carnian to lower Norian De Geerdalen Formation in Svalbard (Figure 1) represents the northernmost exposures of the northwestern prograding Triassic succession in the Greater Barents Sea. The formation is also part of the largest known deltaic system that has existed on Earth, covering an estimated area of 1,650,000 km^2 (Klausen et al., 2019). Sourced from denudation of the Urals and Siberia in the east and Fennoscandia in the south, the Triassic units prograded across and above an erratic surface of Upper Permian carbonates and spiculites. Consequently, an extensive succession of deltaic sediments developed in the Greater Barents Sea from the latest Permian (Changhsingian) to the beginning of the Norian (Riis et al., 2008; Glørstad-Clark et al., 2010; Høy & Lundschien 2011; Lundschien et al., 2014; Klausen & Mørk 2014; Vigran et al., 2014; Mørk, 2015; Anell et al., 2016; Klausen et al., 2016; Eide et al, 2018; Gilmullina et al., 2020; 2021).

Following the Permian-Triassic extinction event, the onset of the Triassic succession in Svalbard marks the change from Permian carbonate and silica-rich deposits to a siliciclastic paralic/deltaic depositional environment. This transition was accompanied by a change in climate from relative cold temperate in the Upper Permian, to warm temperate throughout the Triassic as the Earth recovered from the major global extinction event (Steel & Worsley, 1984; Stemmerik & Worsley, 2005;). At this time, Svalbard was juxtaposed against Greenland (Torsvik & Cocks, 2004; Torsvik et al., 2012) and palaeolatitude reconstructions suggest that Svalbard and the Greater Barents Sea lay at approximately 55-60°N.

The Upper Triassic basin fill is composed of successive Transgressive-Regressive (T-R) sequences, controlled by subsidence accompanied by minor movements of the hinterland, eustatic sea-level and climatic changes. The T-R sequences identified in Svalbard are found to be correlative throughout the wider Arctic (Mørk et al., 1989; Egorov & Mørk, 2000; Mørk & Smelror, 2001) and some sequence boundaries have been correlated worldwide (Embry, 1997).

At the Triassic-Jurassic boundary, the Barents Sea as well as Svalbard experienced a slowing in the rate of basin subsidence (Ryseth, 2014) and this process likely started near the Carnian-Norian transition. As a result, the basin may have become overfilled with an overspill of sediments to adjacent basins farther to the west (Gilmullina et al., 2021, 2022). The gradual diminishing of accommodation space in the latest Carnian changed the delta system from a progradational to a retrogradational system. This is seen as a westwards trend in the Isfjorden Member, where condensed facies associations are seen in the paralic deposits with common palaeosols, thin coal seams, carbonate beds (e.g., coquinas), phosphate nodules and common glauconite (Mørk et al., 1999; Rød et al., 2014; Lord et al., 2017), all consistent with a condensed succession.

Upper Triassic Stratigraphy

The stratigraphy and sedimentology of the Upper Triassic succession in Svalbard can largely be considered as well studied. Early works by Buchan et al. (1965), Worsley (1973), Smith (1975), Smith et al. (1975), Lock et al. (1978), Pčelina (1980, 1983) and Mørk et al. (1982, 1999, 2013) conducted primary mapping studies and identified the first Triassic stratigraphic units, whilst Mørk et al. (1982), Anell et al. (2014, 2016, 2020), Klausen & Mørk (2014), Klausen et al. (2015, 2016, 2019), Rød et al. (2014), Lord et al. (2014a, b, 2017) focused on the nuances of facies studies and correlation of Upper Triassic sequences throughout

Svalbard and the Barents Sea. The Longyearbyen CO_2 Lab Dh4 well and the diagenetic properties of a proposed Upper Triassic to Lower Jurassic reservoir interval were investigated by Mørk (2013). The present nomenclature of the Mesozoic succession of Svalbard is described in the Lithostratigraphic Lexicon of Svalbard (Dallmann, 1999; Mørk, et al. 1999) and this scheme is applied herein (Figure 2), with revisions from Krajewski (2008) and Mørk et al. (2013).

The De Geerdalen Formation in Svalbard represents a succession of overall upwards-coarsening shallow-marine to delta-plain deposits that lie conformably atop the lower Carnian (~237 - ~227 Ma) pro-delta shale of the Tschermakfjellet Formation. The well-exposed fluvial channels and delta-plain deposits observed on Hopen are the most proximal part of the succession exposed in eastern Svalbard, being overlain by the more marine-influenced Hopen Member. A transition to lobate deltaic and shallow-shelf deposits is observed as the succession becomes increasingly distal towards the west and northwest (Rød et al., 2014; Lord et al., 2017) with thinner and more discrete intervals of fluvial and delta-plain deposits.

The Isfjorden Member comprises the upper Carnian to lower Norian (~227 - ~208 Ma) part of De Geerdalen Formation in Svalbard (Figure 2). The unit was originally defined by Pčelina (1983) as a ’suita’ (formation), which included a large portion of the De Geerdalen Formation. Pčelina defined the Isfjorden ’suita’ based on the dominating deltaic facies observed and presence of multicoloured bedding. During the revision of Svalbard’s stratigraphic nomenclature by Mørk et al. (1999), the Isfjorden ’suita’ was assigned member status within the upper part of the De Geerdalen Formation.

The member is described by Mørk et al. (1999) as consisting of alternating shales and thin- to thickly bedded siltstone and sandstone beds, with a siderite nodule bed occurring above the base. Bivalve coquina beds also occur in several sections. Shales are described as multicoloured and featuring reddened mudstones. Carbonate beds, phosphate nodules and gravel or conglomerate lenses were also given as being characteristic of the member. In addition, features such as thin carbonate beds with cone-in-cone structures and calcareous nodular beds are also present.

The unit was interpreted as having been deposited in a shallow-marine shelf to locally lagoonal environment (Mørk et al., 1999). The base of the member in the type-section is defined at a bivalve coquina bed which occurs above a thick cross-bedded sandstone in the

De Geerdalen Formation. Despite the detailed observations of Knarud (1980) and Pčelina (1983), both noting the prominent colouration of beds and presence of carbonates (caliche and calcretes) in the upper part of the member, a continental origin for the unit was not reported. Thus, the member was largely regarded as having been deposited in a lagoonal to shallow-marine environment.

The Hopen Member, defined by Lord et al. (2014a), is not present at any of the localities visited in this study – nor are the characteristic facies of the Isfjorden Member present on the island of Hopen. The Hopen Member is described as a marine equivalent to the Isfjorden Member, with the lateral facies transition between the two being enigmatic due to erosion of the upper part of the De Geerdalen Formation throughout eastern areas of Svalbard (Lundschien et al., 2014; Lord et al., 2014a, 2017).

With the advent of new dating by magnetostratigraphy and detrital zircon data (Hounslow et al., 2022; Klausen et al., 2022), it is conceivable that the Hopen Member may in fact post-date the Isfjorden Member. In this case, the member would be eroded from Spitsbergen and Wilhelmøya (See Figure 2), thus indicating a significant hiatus at the boundary to the Wilhelmøya Subgroup. The Hopen Member is preserved in the east on the Edgeøya Platform where it is present in cores recovered from the region offshore Kong Karls Land (Lundschien et al., 2014) and Kvitøya. The Hopen Member has also been interpreted as representing the early-Norian transgression (N1 surface of Klausen et al., 2015, 2022) that preceded the pronounced mid-Norian flooding recorded in the Wilhelmøya Subgroup.

Pedogenic features in the De Geerdalen Formation and Isfjorden Member

Soil structures

An important observation regarding soil structures is the size and shape of agglomerations. In the De Geerdalen Formation these structures can be described as, platy, angular blocky, sub-angular blocky and granular. The diameter of agglomerations is typically in the range of 1 mm and up to 1-2 cm. Platy structures are typically seen throughout the soil profile as well as in the lower parts of the soil horizon. Angular and subangular blocky structures occur frequently both in palaeosols within the lower part of the De Geerdalen Formation and in the calcareous and non-calcareous palaeosols of the Isfjorden Member. A granular soil structure is found in all palaeosol types within this study, except for calcrete and caliche soil profiles. It is also noteworthy that all horizonated soils observed in the De Geerdalen Formation appear to feature a granular soil structure in at least one horizon (e.g., Figure 3a, b).

The size and shape of agglomerations in palaeosols can be linked to the modification of parent material in relation to processes and disturbances to the local environment. Bioturbation by plants or animals, as well as seasonal or flood-related wetting and drying of the delta-plain, will impact their development (Retallack, 2001). Modification by these processes causes many palaeosols to feature a hackly (rough and jagged) appearance upon first sight (Retallack, 1988) and this structure originates from the presence of open spaces or weaker zones surrounded by more stable aggregates in the original soil.

A platy structure indicates that relict bedding of the parent material is present (Retallack, 1988). Palaeosols observed in the De Geerdalen Formation, with prominent relict bedding, are considered to have formed under conditions where the pedogenic modification of the parent material was too weak to overprint the original soil structure.

Both angular and subangular blocky structures are associated with swelling and shrinking of the soil profile, with cracking around roots and burrows being common (Retallack, 1988). Such angular or subangular blocky structures are rare within palaeosols in the lower part of the De Geerdalen Formation but are common to soils observed in the Isfjorden Member.

Granular palaeosols indicates high biological activity and thus high soil fertility and ultimately soil maturity (Retallack, 1988). The granular soil structure seen in all the horizonated soils observed throughout the De Geerdalen Formation and Isfjorden Member is interpreted as indicating the maturity of this soil type.

Structures observed in the present high-Arctic area of Svalbard may, however, have been altered by Quaternary processes, such as seasonal freezing and thawing in the active layer of the permafrost disturbing the primary texture of the sediment.

Rhizoliths

Rhizoliths, representing ancient root traces and root structures, are observed in palaeosol horizons throughout the De Geerdalen Formation. They are seen to fall into three distinct categories:

1) Rhizoliths representing coalified, downward-branching and tapering rootlets, with a length of approximately 20 cm. These are typically observed in the lower part of the De Geerdalen Formation (Figure 3a).

2) Irregular coloured features with a diffuse pattern in the upper soil horizon, commonly observed in palaeosols in the De Geerdalen Formation and are interpreted as rhizoliths. An important observation of these features is that they are composed of the same material as the remainder of the palaeosol (Figure 3b), and therefore represent the trace of a root.

3) Vertically elongate and irregularly shaped rhizoliths representing calcareous cemented roots, ranging in size from a few cm to tens of cm. These are observed in the Isfjorden Member at Deltaneset, Teistberget, Šmidtberget and Friedrichfjellet (Figures 3c, d).

Rhizoliths, indicating the presence of ancient roots, are a reliable diagnostic feature when identifying palaeosol profiles, as their presence in continental deposits represents direct evidence of subaerial exposure and plant growth, meeting almost all the requirements for soil definition (Retallack, 1988, 2001). Calcite-cemented nodules, forming around roots, are commonly found in red-bed successions and especially paralic flood-plain deposits. A downward elongation is typical for nodules with a rhizogenic origin (Tucker, 2011) and this is observed in calcareous nodules from the De Geerdalen Formation, most notably the Isfjorden Member (Figures 3c, d). Thus, any vertically elongate calcareous nodules are interpreted as rhizoliths (c.f. Wright, 1992; Retallack, 2001; Kraus & Hasiotis, 2006).

Irregular colouration with a diffuse pattern in palaeosols is referred to as mottles (or mottling) and are related to an uneven distribution of minerals in the soil profile. Mottling may originate from chemical processes related to the microenvironment surrounding living roots, or the gleying of sediments due to anoxia caused by decay of organic matter soon after burial or poor drainage (Retallack, 1988, 1997). Mottling in palaeosols of the De Geerdalen Formation are primarily considered to be rhizogenic in origin when other pedogenic features are evident.

Soil Classification

The soil classification system of Mack et al. (1993) is specific to palaeosols, despite being based on the understanding of modern soil development. Throughout the De Geerdalen Formation and Isfjorden Member several palaeosol types are recognised, primarily; vertisols, argillisols, protosols, gleyed non-calcareous, gleyed calcareous mudstones and caliche/

calcrete (including calcareous mudstones). In addition, we also identify coal-shale/ coal. A summary of the palaeosol types encountered in the De Geerdalen Formation is presented in Table 1.

Vertisols

Vertisols observed in the De Geerdalen Formation are recognised by having a homogenous, dark-coloured and commonly organic-rich matrix (Figure 4a, b). These soils lack clear evidence of horizons; however, a thin layer of coal shale is often seen in upper parts. These soils are observed at Teistberget and Šmidtberget, where they are seen to feature mottles. At other localities in the study area, vertisols featuring a blocky soil structure are common. Thickness ranges from 20 to 110 cm. This soil type is commonly observed below the Isfjorden Member and is generally associated with barrier-bar, distributary channel and flood-plain facies.

A homogenous appearance due to pedoturbation is the main feature of vertisols. This appearance is attributed to shrinking and swelling of expandable clay minerals. However, a blocky structure is commonly observed in this soil type, a feature which is also associated with soils that have undergone shrinking and swelling (Retallack, 1988) (Figure 4b). A signature feature of vertisols is slickensides (Mack et al., 1993; Soil Survey Staff, 2014); however, slickensides, at present, have not been found in any vertisol profile in the De Geerdalen Formation. This may be due to the destruction of these features by recent weathering or permafrost-related processes. Vertisols with slickensides are, however, found in correlative beds cored in the Hammerfest Basin, which has not been subjected to such weathering processes.

Modern vertisols are commonly found in the tropical and sub-tropical climatic zones but have also been recognised and described in temperate regions (Khitrov & Rogovneva, 2014). Their formation has been suggested as only requiring some few hundred years (Retallack, 2001) which may explain their prevalence in association with paralic interdistributary facies with short-lived periods of subaerial exposure.

Argillisols

Argillisol profiles are easily identified in the De Geerdalen Formation due to the presence of prominent horizonation. Argillisols feature a minimum of three clear soil horizons, where at least one layer is clay-rich and leached (Figure 4c, d). These soil profiles also feature a granular structure in at least one horizon. Mottling is common and relict bedding may also be present. Rhizoliths are also common, and these are abundant in argillisol profiles observed at Šmidtberget. Wood fragments are also found in-situ at some localities, e.g., at Tumlingodden on Wilhelmøya. The thickness of argillisols seen in the study area ranges from 40 to 100 cm and they are typically confined to the Isfjorden Member.

The development and complexity of soil horizons increases with time. Leaching of clay minerals downwards through the soil profile by the percolation of water is believed to require several thousands of years (Harden, 1982). Rhizoliths, mottling and wood fragments also indicate a relative maturity for this palaeosol type (Retallack, 1988), whilst the presence of mottling attests to a relatively high water table (or soil saturation) and overall poor drainage of the soil. Combined, these facts suggest that argillisols observed in the De Geerdalen Formation represent an extensive period of soil development on the delta-plain and thus a prolonged period of subaerial exposure.

Protosols

Palaeosols in the De Geerdalen Formation observed as lacking any distinct pedogenic features have been defined as protosols. This type is mainly recognised in outcrop as featuring horizons with a yellow, grey or brown colouration and contrast with the underlying sedimentary deposits. Mottles and an organic-rich upper soil horizon are common but are not as prominent as in argillisols. Relict bedding is also common within protosols seen in the De Geerdalen Formation and these palaeosols are common within and below the Isfjorden Member. Their thickness ranges from 10 to 70 cm. Examples of immature palaeosols are seen in Figures 4e and 4f.

In protosols, up to three different horizons may be found within individual soil profiles. The upper horizon is usually notably darker and rich in organic material with a sharp contact (Figure 4f). Lower horizons display a greater diversity of colouration with grey, brown or yellow horizons being present, and commonly with a gradual transition. Soil horizons in protosols with a grey or yellow colouration have a viscous or tacky composition due to a matrix of water-wet clay, which in the field can be likened to modelling clay.

As an immature soil type, protosols typically occur in areas where conditions do not favour soil-forming processes. These conditions are typically related to the short time available for their formation or rapid burial due to high sedimentation rates (Retallack, 2001). Even though protosols observed in the De Geerdalen Formation show poor pedogenic development, they are useful to facies or sequence-stratigraphic studies as they serve as evidence of periodic and short-lived subaerial exposure.

Non-calcareous mudstones

Consisting of alternating red and green coloured mudstone horizons, this palaeosol type is restricted to the Isfjorden Member. They are extensive and typically form 0.3 – 2 metre-thick successions of alternating red and green beds. These beds are interpreted as having a pedogenic origin based on the presence of kaolinite, goethite and hematite minerals. The striking colour is derived from the oxygenation or reduction of ferric minerals (Figure 5a, b). Thicknesses of up to 5 m are observed in some places. Discrete beds containing only red or green mudstones do occur, with thicknesses in the range of some few to tens of cm (Figure 5c) and this is sometimes in association with other palaeosol horizons. The typical structure of this palaeosol is blocky or fissile, with common mottles. These palaeosols are interpreted as representing a gleyed soil due to their characteristic alternating colour pattern, which is attributed to groundwater saturation and periodic exposure. Examples of non-calcareous red and green mudstones are seen in Figures 5a-e and these generally occur in association with calcretes, caliches and calcareous gleyed calcareous and non-calcareous mudstones.

The green colour of these palaeosols seen in the Isfjorden Member is attributed to the reduction of ferric minerals and elements under anaerobic conditions, due to lack of drainage and a high groundwater table. The red colouration likely indicates dehydration and recrystallisation of hydroxide minerals such as goethite. As goethite converts to the iron oxide mineral hematite, it forms coarse grains when weathered (Retallack, 2001). Red colouration is known from well-developed palaeosol profiles formed in a dry, tropical climate. An alternative origin for red colouration in palaeosols may be attributed to diagenetic processes (Retallack, 2001); however, it is not possible to distinguish diagenetically formed hematite from that formed at the surface (Retallack, 2001).

The genesis of gleyed soil profiles generally requires an extensive period of soil-forming conditions from some hundreds to thousands of years, with even millions of years proposed by Birkeland (1984). However, the presence of gleyed palaeosols (both calcareous and non-calcareous) in the Isfjorden Member indicates a prolonged wetland environment on the delta plain, with periodic exposure allowing for gleying of soil horizons to occur.

Despite gleyed soil horizons being azonal, the precipitation of both hematite and goethite is common in palaeosols formed in a warm climate, in comparison with those interpreted as forming in more temperate climate zones. However, goethite is preferably formed in a warm and humid climate, whilst hematite typically requires warm and dry conditions (Collinson, 1996).

Calcareous mudstones, calcrete and caliche

Calcareous horizons typically feature a similar red and green colouration (due to gleying) as non-calcareous mudstones based on their mineralogy. However, they are differentiated due to their extensive carbonate content (see Figures 6a-d). This results in a strong effervescent reaction with hydrochloric acid when tested in the field. Nodules, mottling, and peds are common within these soil profiles. Deltaneset is the only locality in this study where carbonate soils are seen to dominate the succession (Figure 6a). At Friedrichfjellet, Šmidtberget and Teistberget in eastern Spitsbergen only a few discrete beds of calcareous mudstone are identified, based on their reaction with hydrochloric acid. In this area, non-calcareous mudstones are the dominating soil type in the Isfjorden Member (e.g., Figures 5b-e). Calcretes or caliche are commonly brown, yellow or dark red in colour with an irregular bed geometry and a nodular or blocky appearance (Figures 6a-d). In some cases, they may contain some coarser clastic material.

Examples of palaeosols interpreted as calcrete or caliche are shown in Figures 6a-d. In thin-section (Figures 7a-d) several features consistent with calcrete soil profiles are observed. In the De Geerdalen Formation, these features are seen as alveolar structures, carbonate cement and aggregates interpreted as cemented root-casts representing rhizoliths (Figure 7b).

Calcrete formation can involve both pedogenic and non-pedogenic processes (Leeder, 1975; Carlisle, 1983). Non-pedogenic processes are mainly related to extensive calcium carbonate precipitation (early cementation) in the shallow phreatic zone in a semi-arid to arid climate (Wright & Tucker, 1991). Pedogenic calcretes form due to the downwards percolation and precipitation of carbonate minerals through a soil profile during its genesis (Arakel & McConchie, 1982).

Thin-sections of carbonate nodules recovered from red and green coloured mudstones within the Isfjorden Member at Deltaneset, show features common to fossil and modern calcrete beds (Figures 7a-c). Microscopic features present in calcretes can be subdivided into two microfabric types; alpha-microfabrics that lack biogenetic features and beta-microfabrics dominated by biogenetic processes (Alonso-Zarza & Wright, 2010). All samples recovered from the Isfjorden Member display both alpha-microfabrics and beta-microfabrics. A groundmass of crystalline carbonate is the most prominent evidence of alpha-microfabrics seen in the thin-sections from carbonate nodules present in the Isfjorden Member (Figure 7a).

Beta-microfabrics are seen to include alveolar septal structures, coated grains, calcified filaments, calcified roots, spherulites and faecal pellets. Coated grains containing relics of the host-rock, micrite or parts of alveolar-septal features are an important component of beta-microfabrics. Alonso-Zarza et al. (1998) reported biogenetic grains as thinly coated with carbonate and having a gradual to diffuse contact to surrounding matrix. Examples of such coated grains are observed in samples from the Isfjorden Member at Deltaneset (see Figures 7c, d). Millimetre-sized calcite filaments, consisting of straight or interconnecting sinuous tubes, are also observed (Figure 7b). These are believed to originate from fungi within the soil profile, but they may also be attributed to roots or other micro-organisms (Verrecchia & Verrecchia, 1994).

Studies of pedogenic mudstone beds seen in core, interpreted to have been deposited in dryland river systems in the North Sea, were conducted by Müller et al. (2004). Here it was shown that it is possible to differentiate in-situ mud-aggregates related to pedogenic processes in palaeosols from reworked aggregates deposited on the floodplain (Bown & Kraus, 1987; Müller et al., 2004). Similar observations of mud-aggregates believed to have been formed in-situ in this study are presented in Figure 7d. Here, thin carbonate coated grains with diffuse and gradual contact to the surrounding matrix are interpreted as being biogenetic in origin while mud-aggregates interpreted as being potentially reworked are shown in Figure 7c.

Histosols – Coal-shale and coal

Thin fissile beds of organic-rich shale are typically 3-10 cm in thickness and often occur in association with vertisols, argillisols and protosols where they cap upward-coarsening mudstone to sandstone successions (parasequences). Histosols in the form of coal-shale are also found as isolated beds within fine-grained facies. Coal and coal shale histosols typically feature an underlying palaeosol in association. It is common for vitreous coal to be seen surrounded by a light-grey clay, whilst coalified rootlets indicating rhizoliths also occur. Coals typically indicate preservation of peat, formed during humid and wetter climatic periods. Coal and coalified mudstones seen in the Carnian succession of Svalbard provide evidence for the revival of peat-forming plants and conditions, following the global coal gap that extended from the Permian-Triassic Boundary to the Ladinian (Retallack et al., 1996).

Following the classification of Mack et al. (1993), we define coal and coalified shale observed in the study area as histosols. Coal and coal-shale histosols are found throughout the De Geerdalen Formation on Svalbard; however, they are constrained to the middle and upper part of the formation and are commonly found to overlie palaeosols.

Regional distribution of the Isfjorden Member

A correlation panel with localities throughout Spitsbergen and Wilhelmøya with the De Geerdalen Formation and Isfjorden Member present is shown in Figure 8.

The Festningen section, a protected geotope, this locality features vertically tilted beds of the De Geerdalen Formation and Isfjorden Member. The Isfjorden Member is considerably thinner in this part of Spitsbergen and is considered condensed (Figures 8, 9a). The unit's base is interpreted below gleyed red and green coloured mudstones and calcareous mudstones atop a tidal-channel complex containing thin beds of mud-flake conglomerate (Mørk et al., 1999; Mørk & Grundvåg, 2020). The overlying Slottet Bed is observed to consist of a 20 cm-thick bed of clast-supported, gravel to pebble phosphate conglomerate, overlain by a strongly bioturbated calcareous sandstone (Mørk et al. 1999, Mørk & Grundvåg, 2020).

Longyearbyen CO_2 Lab Dh4 Well. The Dh4 well, drilled by the Longyearbyen CO_2 Lab (Braathen et al., 2012), cored almost the entire De Geerdalen Formation. Core observations have identified a series of multi-coloured mudstone beds that are seen to occur at the top of the formation and are defined to be within the Isfjorden Member (Figure 8). The member in this part of Spitsbergen is interpreted to represent lagoon and delta-plain deposits (Braathen et al., 2012). Upwards in the core, root horizons, minor coal beds (histosols) and the vertical trace fossil *Skolithos* are also observed in the member.

Central Spitsbergen. Outcrops near the meltwater delta at Deltaneset in Sassenfjorden display well-exposed cliff sections of the Isfjorden Member along the coastline and in adjacent valleys. This area was the original type locality for the 'Isfjorden Suita' defined by Pčelina (1983).

The shoreline section east of Deltaneset (Figures 5a and 8) constitutes the lower part of the Isfjorden Member, whilst the upper part is exposed in the valley of Konusdalen. At Deltaneset, good examples of calcareous and non-calcareous mudstones can be observed, in addition to well-developed caliche profiles and the gravel conglomerate of the overlying Slottet Bed. Throughout Vendomdalen, the Isfjorden Member is seen in good quality mountainside exposures (e.g., Dalsnuten; Figure 9b). However, the characteristic red and green palaeosol beds are generally found only in scree at the very top of the mountain. The unit is found to be at its thickest in this area without the same extent of erosion as seen in eastern Spitsbergen.

Mountains surrounding the valley of Fulmardalen feature well-exposed Triassic strata, with most mountains in this area being capped by the Isfjorden Member. The original type-section of the Isfjorden Member is in this area and was defined at Storfjellet on the northern side of Fulmardalen. The section was initially logged and defined by Knarud (1980); the locality has been revisited in this study (see Figure 10).

Eastern Spitsbergen. The valley of Agardhdalen in eastern Spitsbergen is surrounded by mountains consisting of Triassic to Lower Cretaceous strata. Here, the upper 120 metres of the De Geerdalen Formation and the transition to the Wilhelmøya Subgroup was measured at Klement`evfjellet, Friedrichfjellet and Šmidtberget (Figure 8). On the easternmost mountains of Spitsbergen, e.g., at Teistberget to the north of Agardhdalen, the Isfjorden ’suita’ was also described by Pčelina (1983). This locality has been revisited during this study in 2015 (see also Lord et al., 2017) where the Isfjorden Member was found to be present along with the Wilhelmøya Subgroup.

Wilhelmøya. The island of Wilhelmøya features the northernmost exposures of the Isfjorden Member in Svalbard. Several sections have been measured on this island and there is considerable similarity in overall lithologies when comparing the member here to outcrops elsewhere (Figure 8). A dolerite sill, of the Cretaceous Diabasodden Suite, penetrates the outcrops just below the Isfjorden Member.

Edgeøya, Barentsøya & Hopen. Svalbard’s eastern islands of Edgeøya, Barentsøya and Hopen consist almost entirely of Triassic rocks of the Sassendalen and Kapp Toscana groups, except for a few exposures of Permian rocks. Due to erosion, only the lower part of the De Geerdalen Formation is believed to remain in this area with a considerable portion of the Upper Triassic considered missing (Lundschien et al., 2014; Lord et al., 2017). The Isfjorden Member has not been documented on Edgeøya or Barentsøya, nor has any palynological evidence suggesting the units’ presence been found (Vigran et al., 2014).

Non-calcareous mudstones in association with a caliche profile, characteristic of the Isfjorden Member, have been observed in the De Geerdalen Formation at one locality in southern Edgeøya. However, these are thin, sparsely distributed and less readily identified than those present in the Isfjorden Member and likely indicate localised development as opposed to the regional extent of those seen in Spitsbergen later in the Triassic. Palaeosol types on Edgeøya are typically found to be vertisols or protosols with an associated histosol (e.g., Figure 4a) and these have also been identified by Anell et al. (2020). Limited observations of palaeosols have been made from Hopen; however, well-developed albeit thin coal seams (as histosols) are observed in association to rootlets on the flanks of fluvial channels, indicating a terrestrial setting and subaerial exposure.

Discussion

The Isfjorden Member as a stratigraphic interval

A summary of the Isfjorden Member, its thickness and description of top and base observed in logged sections is presented in Table 2. The unit is well-dated as being late Carnian to early Norian in age and this is supported by palynology, magnetostratigraphy and detrital zircon dating (Hounslow et al., 2007, 2022; Vigran et al., 2014; Rismyhr et al., 2018; Klausen et al., 2022). The Isfjorden Member can be identified throughout most of central Spitsbergen where the unit is not eroded. Towards the northwest, it is present in Oscar II Land where it is found along the coastline and on mountains north of the Festningen section. On Svalbard's eastern islands it is largely eroded but is well preserved on Wilhelmøya and most mountains along the easternmost part of Spitsbergen.

In western Spitsbergen (e.g., Festningen and Dh4, Figure 8), the Isfjorden Member is considered condensed, whilst in central parts of Spitsbergen the unit is considerably thicker, e.g., at Dalsnuten and Storfjellet (Figures 8 and 10). At these locations the overlying Wilhelmøya Subgroup is not encountered in outcrop and the summits of mountains are typically capped by characteristic nodular red and green mudstones (both calcareous and non-calcareous palaeosols).

Throughout Spitsbergen many localities feature the upper boundary (Slottet Bed) to the Wilhelmøya Subgroup (Figures 8 and 9a). This surface is interpreted as being erosive with significant erosion into the Isfjorden Member in eastern Spitsbergen and Wilhelmøya being identified by Rismyhr et al. (2018), Hounslow et al. (2022) and Klausen et al. (2022).

The definition for the base of the Isfjorden Member in the unit's stratotype at Storfjellet is at a siltstone coquina bed overlying a thick, cross-bedded, sandstone unit (see log Storfjellet I, Figure 10). During fieldwork, we attempted to adhere to this definition when identifying the base of the Isfjorden Member throughout the study area. However, it was found that when addressing the stratigraphic subdivision in the field, the present boundary definition is impractical as the siderite or coquina beds used in the type-section are not laterally extensive and are therefore not present in nearby sections. In Figures 8 and 10, the base of the unit has been correlated and here it is found to conform somewhat closely to the original definition.

At all locations where the boundary to the member has been identified, it is regarded as conformable and largely represents a transition from sand-dominated deltaic deposits to a predominantly thinner bedded and heterolithic succession. Figure 10 shows the transition to the Isfjorden Member and highlights the lateral changes in facies seen at the boundary in mountains local to the type-section, which in many cases complicates its identification.

The paralic nature of the De Geerdalen Formation is largely regarded as the main cause for significant lateral variations in facies development and architecture as seen throughout the succession (Knarud, 1980; Mørk et al., 1982; Rød et al., 2014; Lord et al., 2017). At localities throughout Spitsbergen, where the boundary to the Isfjorden Member is present, local depositional environments such as distributary channel, delta-plain and delta-front deposits interdigitate and, therefore, there is no clear transition or boundary surface to the Isfjorden Member visible in the field (Figure 10).

In addition, many locations lack the siltstone coquina bed overlying the cross-bedded sandstone described in the original boundary definition at the type-section, despite some sections being local to this (e.g., Ryssen, Figure 10). It may therefore be relevant for practical purposes to consider the boundary at, or slightly above, the last major sandstone interval in the De Geerdalen Formation; or, at the siltstone coquina bed as defined in Mørk et al. (1999) if it is seen to be present. The boundary throughout Spitsbergen can be considered conformable with no hiatus or obvious break in sedimentation evident (that cannot be attributed to short-term processes related to deposition in a paralic deltaic setting).

The De Geerdalen Formation in Spitsbergen is primarily composed of upward-coarsening intervals of mudstone to medium-grained sandstone deposited in a paralic deltaic environment (Mørk et al., 1999; Rød et al., 2014; Lord et al., 2017; Anell et al., 2020). In this study, these upward-coarsening successions are usually found to be capped by a palaeosol and in some instances thin coal beds representing an associated histosol. This indicates that, during deposition, these regressive successions evolved to a stable subaerial exposure in a delta-plain environment, for a period significant enough to allow for pedogenic processes and soil genesis to occur.

The Isfjorden Member, in contrast to the underlying succession, is typically composed of finer-grained siliciclastic material and its base marks an apparent change in dominant lithology in the upper part of the De Geerdalen Formation. In the Isfjorden Member, mudstone beds, interspersed with thin upward-coarsening successions of silt to fine-grained sandstone become the dominant lithologies and represent shallow-marine, lagoonal and delta-plain depositional environments (Rød et al., 2014; Lord et al., 2017).

Within these upward-coarsening successions are intermittent mudstone beds, commonly red and green in colour, and these are interpreted to represent the abundant palaeosol profiles discussed herein (e.g., calcareous and non-calcareous mudstones; Figures 5 and 6). Calcretes, nodule clusters, nodular beds, thin coal laminae and minor coal beds (histosols) are also observed throughout the member; as are several beds composed of bivalve coquina. The upper boundary to the Isfjorden Member is marked by the Slottet Bed (Figure 9a), a transgressive lag, deposited during the early Norian and is the basal bed to the Wilhelmøya Subgroup (Mørk et al., 1999). Regionally, the Slottet Bed is seen to feature local erosional contacts with the Isfjorden Member (Hounslow et al., 2022; Klausen et al., 2022; Rismyhr et al., 2018).

Vertisol, protosol and argillisol profiles are found throughout the De Geerdalen Formation and Isfjorden Member. The number of palaeosols increases upwards through the De Geerdalen Formation, as does their apparent maturity and thickness which should be expected, given the increasingly proximal depositional environment of the upper part of the formation (Rød et al., 2014; Lord et al., 2017). Within the Isfjorden Member, however, vertisol, protosol and argillisol soils are seen to be most abundant in the lower part, whilst gleyed calcareous and non-calcareous palaeosols as well as caliche, dominate in the upper part of the member. Immature protosols are distributed relatively evenly throughout the Upper Triassic succession, whilst argillisols are more frequently observed within the Isfjorden Member. In general, palaeosols in the De Geerdalen Formation occur in association with a broad range of delta-plain depositional facies where they are typically found overlying distributary channel, barrier-bar and interdistributary deposits (see Rød et al., 2014; Klausen et al., 2015; Lord et al., 2017 and Anell et al., 2020 for detailed sedimentology of the De Geerdalen Formation).

To the northeast, the Upper Triassic succession on Wilhelmøya features the most proximal deposits observed throughout the study area (Lord et al., 2017) and these deposits also contain the most mature palaeosols identified by this study. Mature palaeosols in Spitsbergen occur contemporaneously with floodplain deposits and in many cases feature an associated histosol. Combined, these features imply mature floral growth on the floodplain and prolonged periods where sedimentation and drainage rates have allowed for peat development and soil genesis. Farther east, well-preserved in-situ tree remains are observed in the De Geerdalen Formation on the mountain Blanknuten, Edgeøya (Rød et al., 2014) and this supports the hypothesis of mature floral development on the Upper Triassic delta-plain during the Carnian. It is uncertain if their occurrence is associated with any palaeosol horizon as these remains are observed to protrude from an exposed ridge in three-dimensions, with surrounding beds being scree covered. Large tree remains have also been reported in fluvial facies from Hopen (Lord et al., 2014b); however, these were not in-situ. A first-look study of Carnian flora from Hopen indicates that a well-developed ′North Atlantic floristic sub-province' believed to have been well-established by the Rhaetian, was already developing during the Carnian (Launis et al., 2014; Launis & Pott, 2014).

There is a shift from the development of immature palaeosols (vertisols and protosols) below the Isfjorden Member to the development of mature palaeosols (argillisols, gleyed mudstones and caliche) within the member. Only one argillisol has been observed in the lower part of the De Geerdalen Formation on Wilhelmøya, likely due to the overall proximal nature of facies seen throughout succession here. Argillisols in the Isfjorden member are seen to be relatively homogeneous in appearance and this can likely be attributed to an alternating moisture regime in the soil. Seasonal rainfall, or a fluctuating water table occurring due to the paralic nature of the De Geerdalen Formation, may be the cause for this variable moisture regime within these soil profiles.

Vertisols in the De Geerdalen Formation are often found overlying sandstone beds that feature distinctive fluvial characteristics. According to studies by Kraus & Aslan (1999), soils formed on top of fluvial channels are likely to be poorly developed, when compared with soils located elsewhere on a floodplain. This may explain the presence of poorly developed soil horizons within vertisols identified in the study area. However, the high organic content and root structures found in many of these vertisols indicate floral development and verifies that pedogenic processes have occurred to some extent.

Protosols are found throughout the De Geerdalen Formation and at all localities except for Deltaneset. This is considered to reflect the wide range of environments in which protosols can form. Protosols are also the most common soil type with their frequent occurrence interpreted as reflecting the dynamic nature of the delta, as soil formation is not favourable if the sedimentation rate is too high (Kraus, 1999).

Throughout the study area, alternating beds of red and green coloured mudstones (and calcretes) are found to be restricted exclusively to the Isfjorden Member. The colour of these palaeosols was described by Pčelina (1983) as striking and easily recognised. These palaeosols are generally thicker than protosols, vertisols and argillisols and this may be due to reduced sediment input at this higher stratigraphic level (in comparison to the underlying succession), creating longer lasting soil-forming conditions.

The genesis of colouration in calcareous and non-calcareous palaeosols in the Isfjorden Member (one of its defining characteristics) is related to the process of gleying due to anoxic conditions and dehydration and recrystallisation of the mineral goethite to hematite under aerobic conditions. The non-calcareous palaeosols are proposed to have gained their strong colouration (e.g., Figure 9a) due to the dehydration and transformation of the mineral goethite to hematite. This process requires a humid environment and long periods of steady soil-forming conditions, which suggests an overall stable depositional and climatic setting. As a result, these soil types have been defined separately, due to their differing carbonate contents.

The presence of goethite and kaolinite in calcareous and non-calcareous mudstone palaeosols can be considered surprising and somewhat confuses subsequent interpretations. These palaeosols generally occur in association with calcrete and caliche which are typically associated with drier and more arid climates with a mean annual rainfall of 100 to 500 mm (Goudie, 1983; Alonso-Zarza & Wright, 2010). The formation of pedogenic kaolinite is typically ascribed to a warm and humid climate (Sheldon & Tabor, 2009) and kaolinite is also a dominating clay mineral in areas with seasonal precipitation between 1000 and 2000 mm (Retallack, 2001).

Calcrete is observed primarily at Deltaneset in central Spitsbergen whilst occurrences are seen at Šmidtberget, Friedrichfjellet and Teistberget in eastern Spitsbergen. The calcrete bed observed at Deltaneset is relatively thick in profile (Figure 6d) and appears to have a more mature development than those observed elsewhere. Since, however, the formation of calcrete is dependent on relatively dry conditions, its presence indicates a climate that allowed for prolonged dry periods.

The development of immature palaeosols and histosols, to mature carbonaceous palaeosols and caliche profiles, may indicate a subtle variation in climate at the Carnian to Norian transition in Svalbard. This may reflect a change from a poorly drained delta plain, with peat bogs and dense vegetation in a humid environment as seen in the underlying part of the De Geerdalen Formation, to a semi-arid climate, with better drainage and prolonged periods of subaerial exposure, during the deposition of the Isfjorden Member. In addition, the presence of immature palaeosols and coal in the lower to middle parts of the De Geerdalen Formation that span the time-period associated with the CPE (Mueller et al., 2016b; Hounslow et al., 2022), may be evidence for the impact of this event on the middle Carnian part of the succession in Svalbard. The transition to mature palaeosol types and caliche that are observed in the Isfjorden Member may speculatively be attributed to a waning of this event and the subsequent return to more contemporary arid climatic conditions associated with the Triassic period (Mueller et al., 2016b).

An alternative hypothesis is that the change in palaeosol types into the Isfjorden Member reflects the genetic development of the widespread Triassic paralic deltaic system, with an increasingly proximal depositional environment being present in Spitsbergen by the early part of the Norian. This would constitute a setting where better drainage, slower sedimentation rates and longer periods of subaerial exposure existed on the delta top. This would need to be in tandem with the presence of stagnant water bodies and fluctuations in water level that could be expected in a paralic setting. Such an environment also satisfies the complex relationship between the presence of caliche and gleyed mudstone palaeosols, without speculating on a climatic driver. Due to the limited climate-related data available, it is this hypothesis that is most favoured at present.

Conclusions

Palaeosols are found to be prevalent throughout the De Geerdalen Formation and are typically found overlying upward-coarsening successions. This suggests that stacked successions of deltaic facies which make up the formation often developed to a prolonged subaerial unconformity, allowing for pedogenesis to occur. The concentration, thickness and maturity of palaeosols increases in the Isfjorden Member. The unique colour of palaeosols make the unit easy to recognise in outcrop and represent a distinctive change in overall lithologies.

There is a change in the dominant palaeosol type, from vertisols and protosols seen in the lower part of the De Geerdalen Formation, to argillisols, gleyed calcareous or non-calcareous palaeosols, and calcrete within the Isfjorden Member. Calcrete horizons are somewhat unevenly distributed throughout the stratigraphy, though thick and mature calcretes are seen in central Spitsbergen. In outcrops farther east, calcretes are rare.

The transition from immature, organic-rich palaeosols present in the lower part of the De Geerdalen Formation to more mature carbonate soils and caliche profiles may hint at a subtle transition in climate at the time of deposition. This may suggest a change from well-vegetated soils developed in a water-logged warm-humid environment, to soils that have endured periods with a prolonged subaerial exposure in a more arid climate. However, we presently favour the genetic development of the deltaic succession as driving the differences in palaeosol types, as opposed to changes forced by climate (e.g., the CPE).

There is a notable thinning of the Isfjorden Member towards the west from 135 m to 55 m in thickness, attributed to condensation. Significant erosion of the member in eastern Spitsbergen and Wilhelmøya is also identified. Thus, its true stratigraphic thickness is presently unknown in eastern areas.

The upper part of the De Geerdalen Formation is dominated by interdistributary facies, particularly within the Isfjorden Member. This may imply lower sedimentation rates and a prevailing delta-plain environment interspersed with lagoonal and marginal marine deposits during the latest Carnian to earliest Norian. The lateral facies variations at the boundary to the Isfjorden Member mean this cannot be defined at one independent and laterally consistent bed or surface. We define the base of the Isfjorden Member at the top of the last major sandstone interval in the De Geerdalen Formation, where a clear trend to finer-grained lithologies can be seen above. This can be regarded as the most practical solution for stratigraphic orientation in the field. The base of the unit is regarded as conformable throughout Spitsbergen.

It is unclear if the Isfjorden Member correlates with the Hopen Member as previously interpreted. New dating implies significant erosion towards the east and may indicate that the Isfjorden Member correlates instead with the uppermost fluvial part of the De Geerdalen Formation on Hopen.

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Figure Texts

Figure 1: Simplified geological map of Svalbard indicating the key ages of strata and localities used in this study. The index map shows the high Arctic position of Svalbard in relation to the Norwegian mainland. Maps edited after Dallmann (2015).

Figure 2: Lithostratigraphic chart of the Middle Triassic to Jurassic succession in the study area. The stratigraphic subdivision is amended after Krajewski (2008), Mørk et al. (1999, 2013) and Lord et al. (2014a). Note the significant hiatus implied between the Isfjorden Member and the overlying Wilhelmøya Subgroup at the Slottet Bed. This is based on new dating from Hounslow et al. (2022) and Klausen et al. (2022). The stratigraphic interval covered by this study is indicated by the stippled magenta line.

Figure 3: A) A yellow-beige coloured protosol featuring thin coalified rootlets and capped by an organic-rich coal-shale (histosol) observed in the lower part of the De Geerdalen Formation at Blanknuten, Edgeøya. B) A protosol observed in the lower part of the De Geerdalen Formation featuring coalified roots indicating rhizoliths that extend into a bleached and irregular palaeosol horizon at Teistberget. C) Calcified rhizoliths observed within the upper part of the Isfjorden Member at Deltaneset. These root features were observed in a calcareous nodular bed situated immediately below the Slottet Bed, at the base of the Wilhelmøya Subgroup. D) Calcareous nodules with downward elongation observed within a red bed of the Isfjorden Member on the mountain Šmidtberget in Agardhdalen. These nodular rhizoliths likely formed from the uneven distribution of minerals within the soil profile. See map in Figure 1 for field locations.

Figure 4: A) A blocky vertisol observed in the lower part of the De Geerdalen Formation at Blanknuten, Edgeøya. Note the dark and relatively homogeneous colouration of the soil and lack of clear horizons, where a sub-angular blocky horizon grades gradually into a blocky, mottled upper horizon. Little or no organic material is present here. B) A vertisol observed in the De Geerdalen Formation at Tumlingodden on Wilhelmøya, featuring a dark homogeneous matrix with a fine-grained and sub-angular blocky soil structure. This is overlain by an organic-rich horizon. C) A horizonated argillisol in the Isfjorden Member at Hellwaldfjellet in eastern Spitsbergen, featuring a dark, organic-rich upper horizon overlying a mottled ochre-coloured horizon and a bleached lower horizon with a granular structure. D) A well-developed, horizonated argillisol observed in the Isfjorden Member at Šmidtberget in Agardhdalen. Note the clear horizonation of the soil profile consisting of a ~5 cm organic rich shale overlying a ~35 cm-thick bleached horizon with root traces. There is a coarser grained ochre-coloured horizon underneath with relict bedding/ host rock indicating the termination of soil-forming processes seen at the base of this palaeosol. E) An immature

protosol observed at Šmidtberget in Agardhdalen, featuring horizontal mottles and fine-grained, sticky texture. Relict bedding is present and weakly developed soil horizons indicate this palaeosol's apparent immaturity. F) Organic-rich horizons overlying mottled silty clay in a protosol observed in the De Geerdalen Formation in eastern Spitsbergen.

Figure 5: A) Several beds of fissile, non-calcareous, red and green (oxidised and reduced) coloured mudstone interpreted as gleyed non-calcareous palaeosol beds in the upper part of the Isfjorden Member at Deltaneset in central Spitsbergen. B) Alternating beds of fissile, red and green mudstone (oxidised and reduced) with calcareous nodules interpreted as rhizoliths, observed in the Isfjorden Member at discrete levels near the summit of Klement'evfjellet in Agardhdalen. C) Fissile non-calcareous mudstone beds with prominent red and green colouration (due to oxidation and reduction) lying atop a blocky calcareous palaeosol bed in the Isfjorden Member at Šmidtberget in Agardhdalen. The green colouration is attributed to gleying where the soil has remained water saturated for an extensive period, whilst the overlying horizon has been exposed to oxic conditions and has weathered to red. This indicates a fluctuating redox regime during genesis. D) Non-calcareous mudstone with a blocky structure in the Isfjorden Member at Šmidtberget in Agardhdalen. E) A yellow-beige protosol palaeosol overlain by thin, fissile, red and green non-calcareous gleyed palaeosols. These are subsequently overlain by an apparent blocky and calcareous palaeosol that is also overlain by an immature protosol. This succession of palaeosols was observed in the Isfjorden Member at Friedrichfjellet in Agardhdalen.

Figure 6: A) A calcareous soil profile overlying a siltstone host-rock observed at Deltaneset. B) Calcareous palaeosol and nodular calcrete beds observed in the Isfjorden Member at Deltaneset, note the presence of a red and green (gleyed) non-calcareous soil profile underlying the nodular carbonate beds. C) A calcareous mudstone soil profile observed in the Isfjorden Member at Friedrichfjellet in Agardhdalen, with red and green colouration featuring a blocky and angular structure. The apparent nodules may indicate the presence of roots. D) An irregular and blocky caliche profile overlying a siltstone host rock observed in the Isfjorden Member at Deltaneset. A secondary caliche bed is evident underlying this bed.

Figure 7: A) Elongate rootlet featuring a calcite fringe in a sample recovered from a calcrete soil profile at Deltaneset in central Spitsbergen. The larger crystals in the sample probably represent pore-filling carbonate precipitated at a later stage. The surrounding carbonate matrix is interpreted as an alpha-microfabric formed due to supersaturation of pore water. B) Alveolar features, carbonate cement (Ca) and biogenic aggregates observed in a sample recovered from the Isfjorden Member at Deltaneset. A carbonate fringe surrounding a root filament is indicated by the R. Plane-polarised light. C) Mud aggregates with biogenetic textures surrounded by non-biogenetic calcite micrite, interpreted as being reworked. D) Mud aggregates with thin carbonate coated grains with diffuse and gradual contact to the surrounding matrix interpreted as being biogenetic in origin.

Figure 8: Regional correlation panel of the De Geerdalen Formation and Isfjorden Member throughout Spitsbergen. The location of logs is presented on the index map. Stratigraphy has been flattened on the Brentskardhaugen Bed at the top of the Wilhelmøya Subgroup. This is a major regional surface that is easily traced throughout Spitsbergen and serves as a practical marker horizon for log correlation (this is due to the base of the De Geerdalen Formation being time transgressive and the underlying Tschermakfjellet Formation often being covered throughout at many localities visited in Spitsbergen). A tentative correlation of the base of the Isfjorden Member is also given; however, local facies variations and similarities to the Wilhelmøya Subgroup in sections from Agardhdalen complicate the correlation in this area.

Figure 9: A and A') The Isfjorden Member at the Festningen Geotope with the prominent beds of calcareous and non-calcareous mudstones (gleyed palaeosols) that are characteristic of the member being very well exposed. The base of the member is now covered due to recent erosion. B) The De Geerdalen Formation and Isfjorden Member at Dalsnuten in Vendomdalen. The very summit of the mountain is capped by remains of red and green calcareous beds with nodules (likely rhizoliths). Low-angle thrust faults of the Adventdalen Décollement Zone (ADZ) are also indicated. Note, the upper cliff forming part of the mountain indicates a sandier development in the Isfjorden Member and may correlate with fluvial channels observed in the member at Deltaneset. This indicates a more regional fluvial development in the middle of the member. It is recommended that this development be investigated further. C) The De Geerdalen Formation and Isfjorden Member at Storfjellet in

Fulmardalen. This locality is the type-section for the Isfjorden Member logged originally by Knarud (1980) and defined formally by Mørk et al. (1999).

Figure 10: Logged sections of the Isfjorden Member at the mountains of Storfjellet and Ryssen in Fulmardalen. The original type-section (Storfjellet I) presented in Mørk et al. (1999) is compared with a recent profile from the mountain (Storfjellet II) and a log from the neighbouring mountain Ryssen. The base of the Isfjorden Member (inset photograph) has been correlated at the two localities using the formal definition at the top of a major cross-bedded sandstone. Note the lateral change in facies above and below the boundary (tentatively correlated) highlighting the conformable nature of the lower boundary to the Isfjorden Member; the unit, however, lies conformably above the De Geerdalen Formation. The siderite bed above the boundary in the type section log noted by Mørk et al. (1999) is missing at Ryssen and not observed in the Storfjellet II log, further highlighting the changes that occur over a short distance along the presently defined boundary surface.

Table 1. Table summarising palaeosol types observed within the De Geerdalen Formation in this study. A soil classification and description of key pedogenic features is also presented.

Table 2: Table summarising the nature of the base and top boundaries to the Isfjorden Member at visited localities throughout the study area. Apparent thicknesses from logged sections are also given. Log numbers relate to those presented in Figure 8.

Figure 1: Map of study area

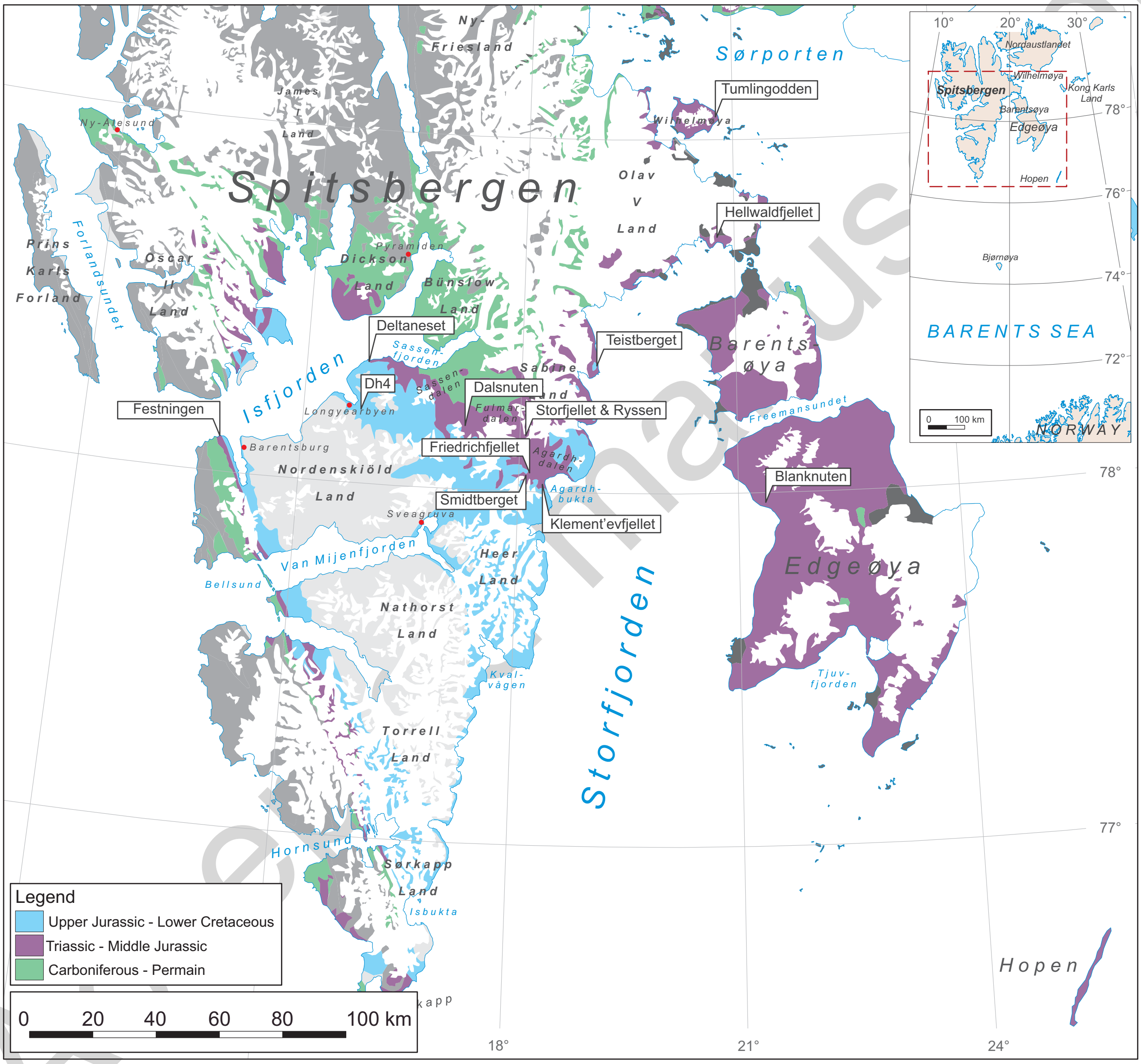

Figure 2: Lithostratigraphic chart

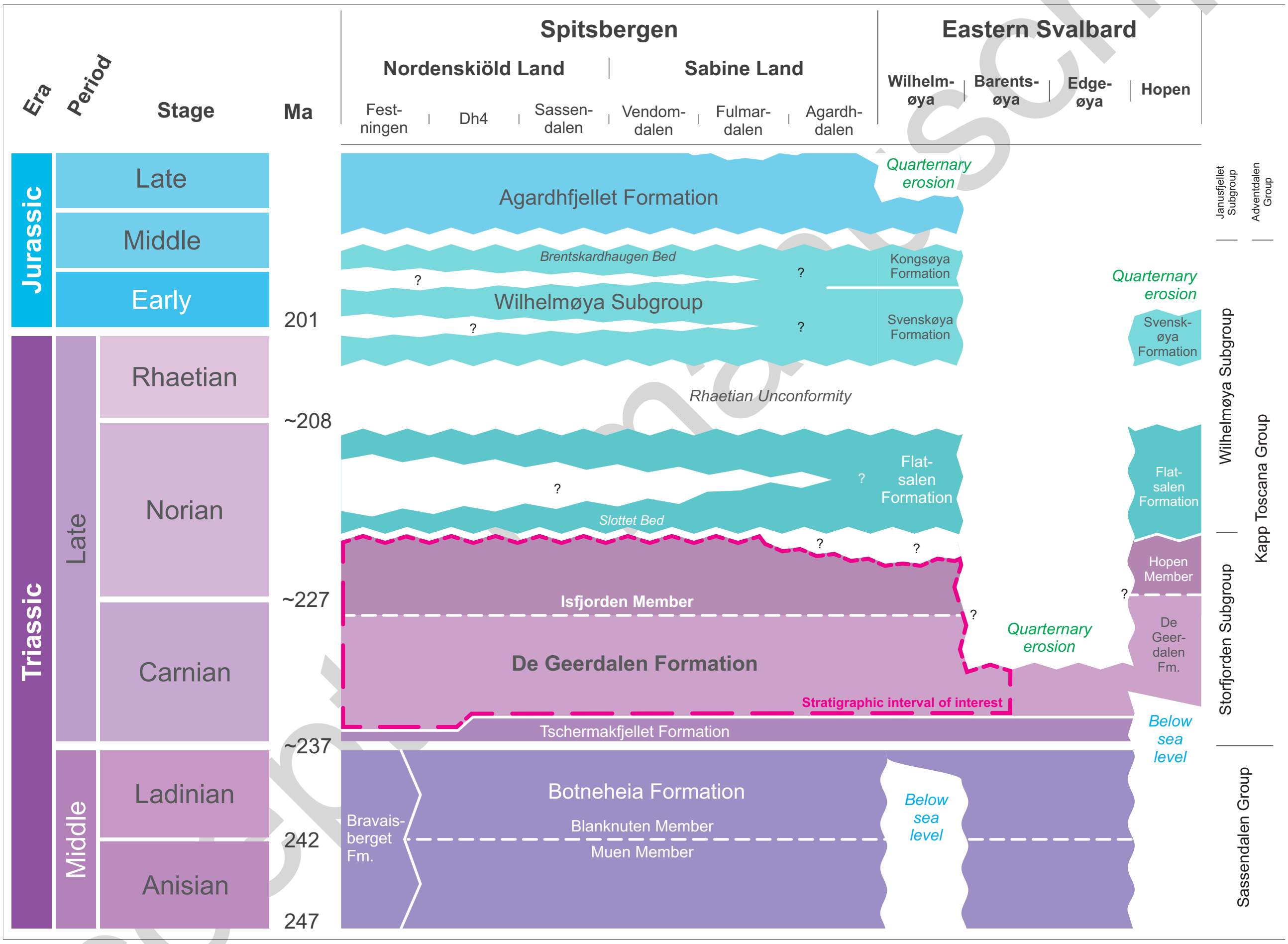

Figure 3: Roots photographs

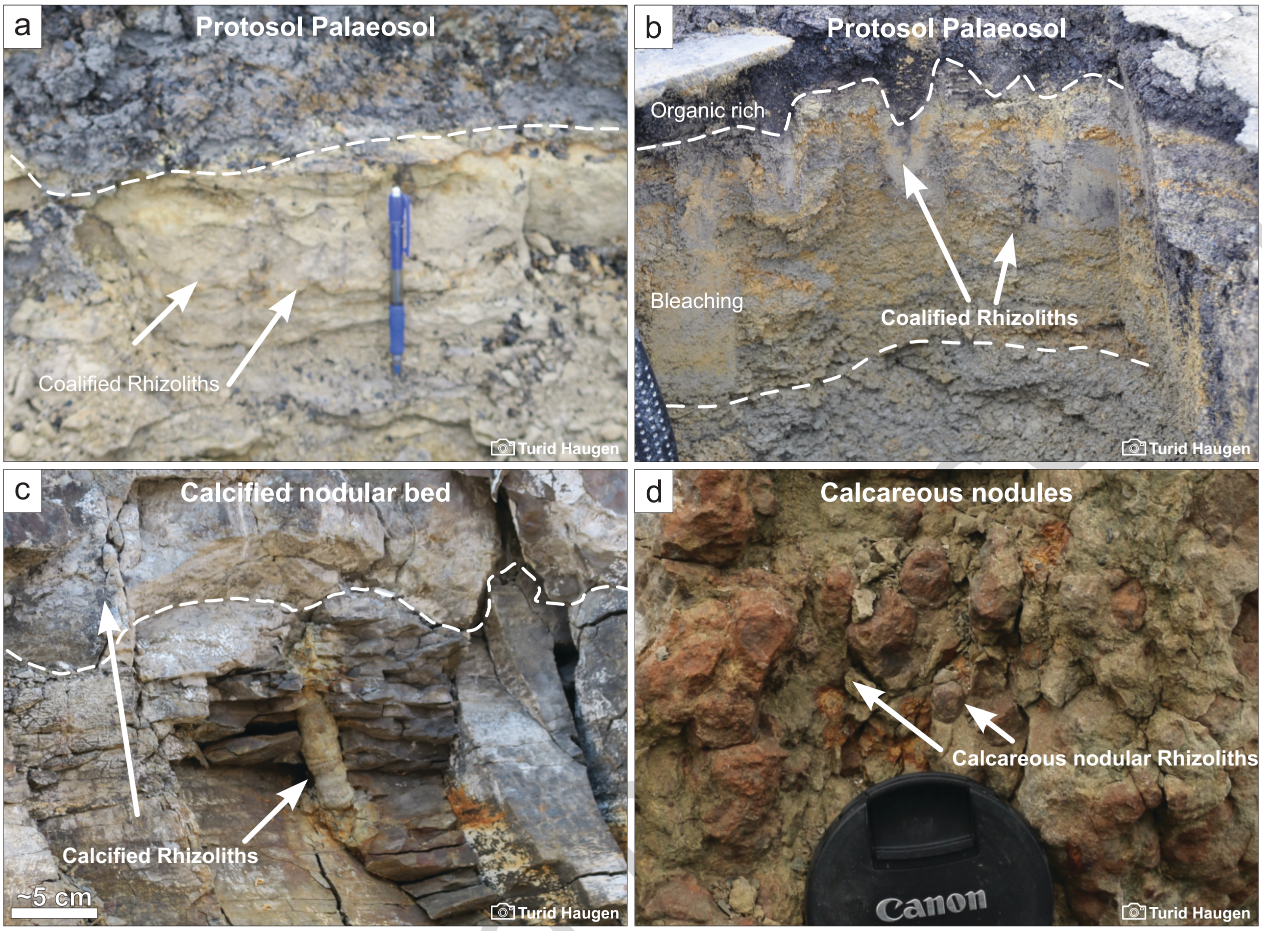

Figure 4: Verti-, Argi-, Protosols photographs

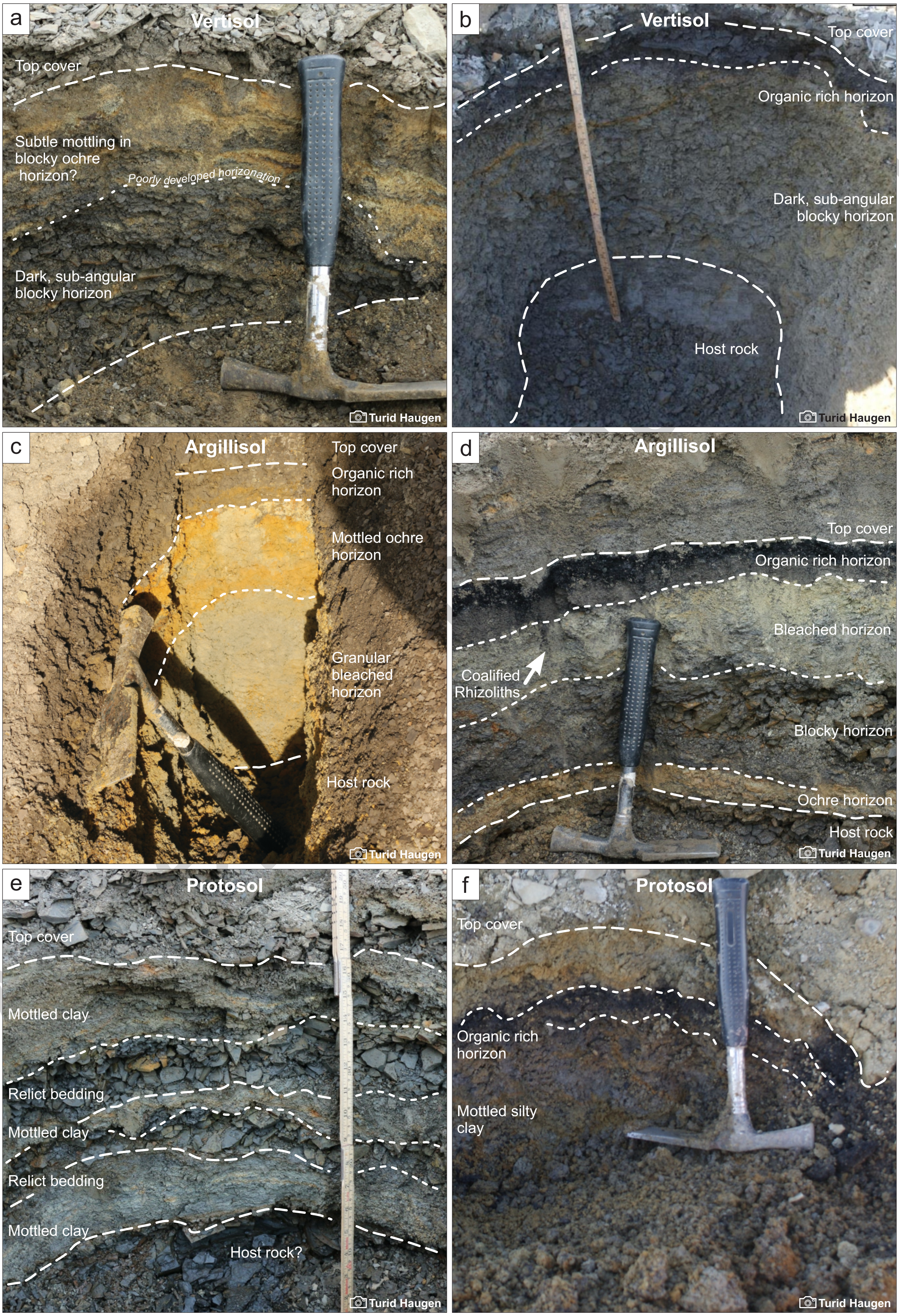

Figure 5: Non-Calcareous Mudstones

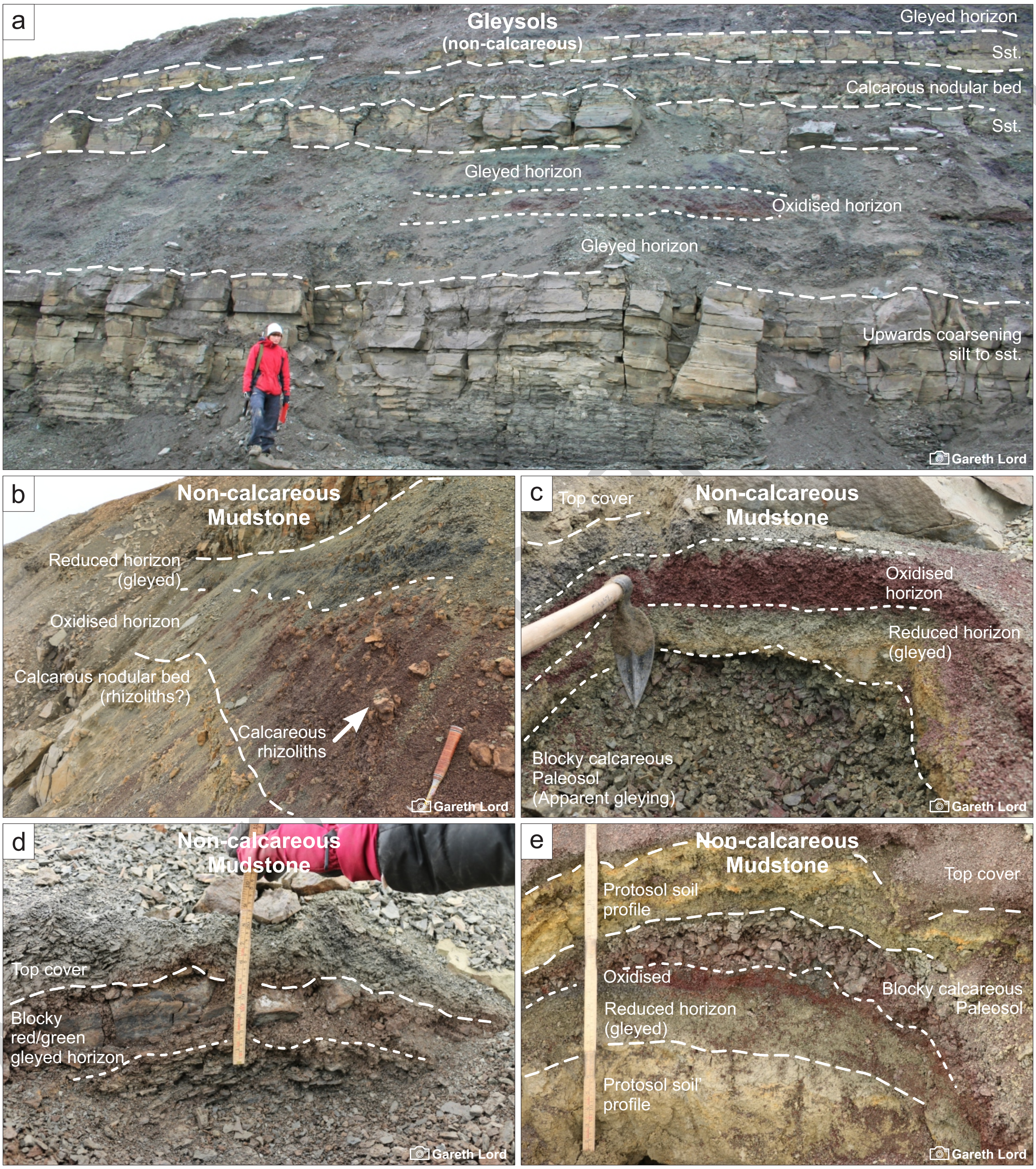

Figure 6: Calcrete photographs

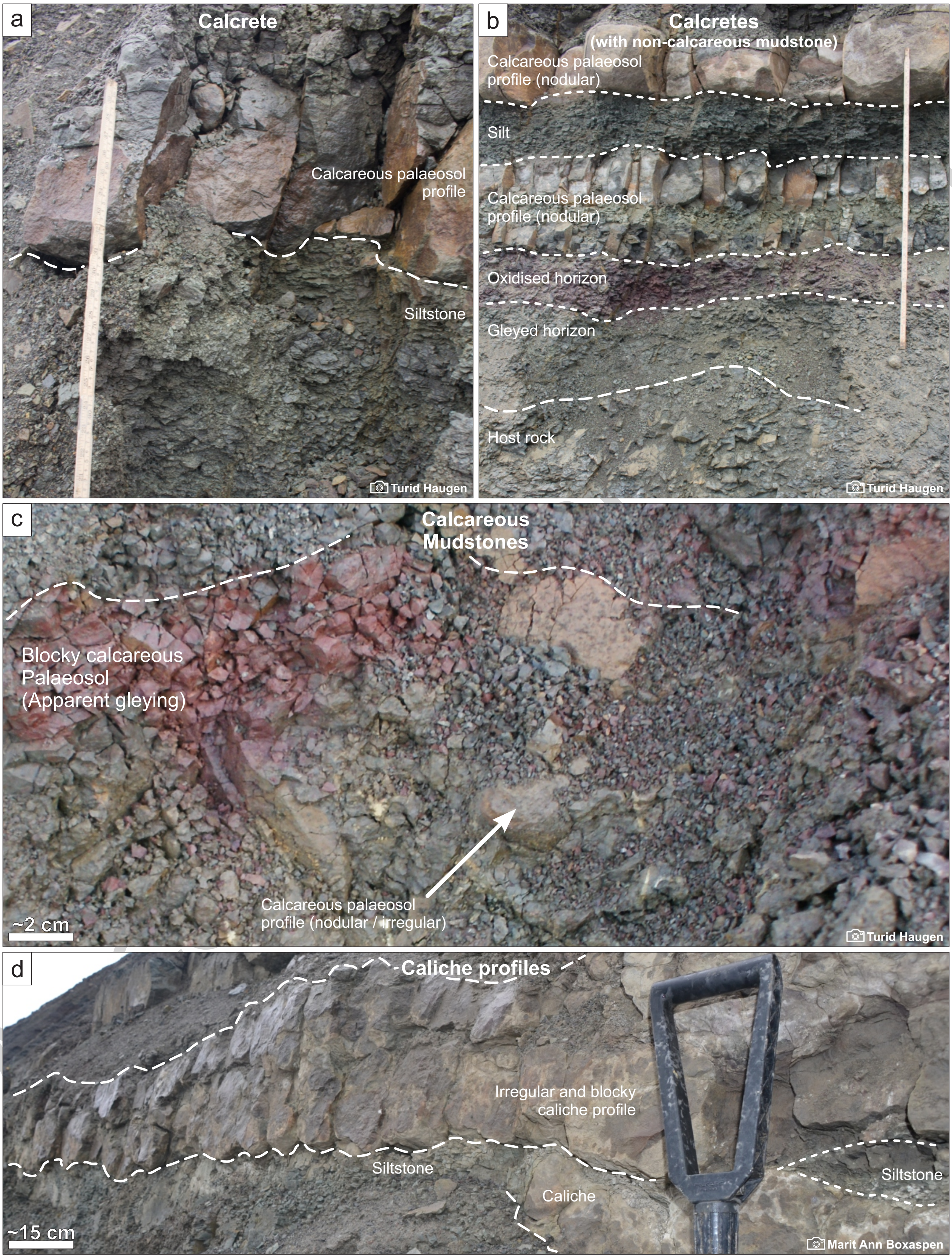

Figure 7: Thin section photographs

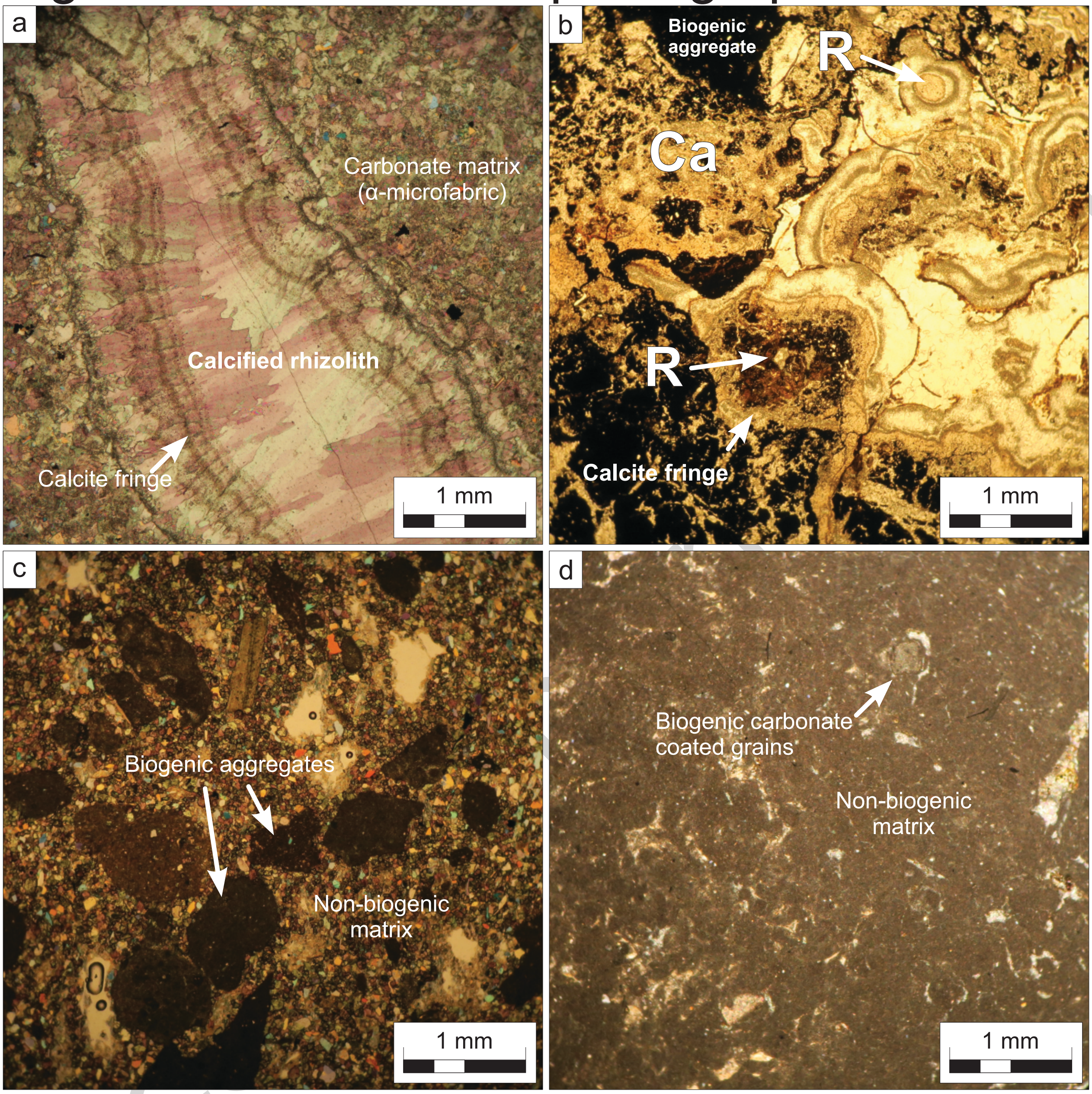

Figure 8: Regional Correlation (Left)

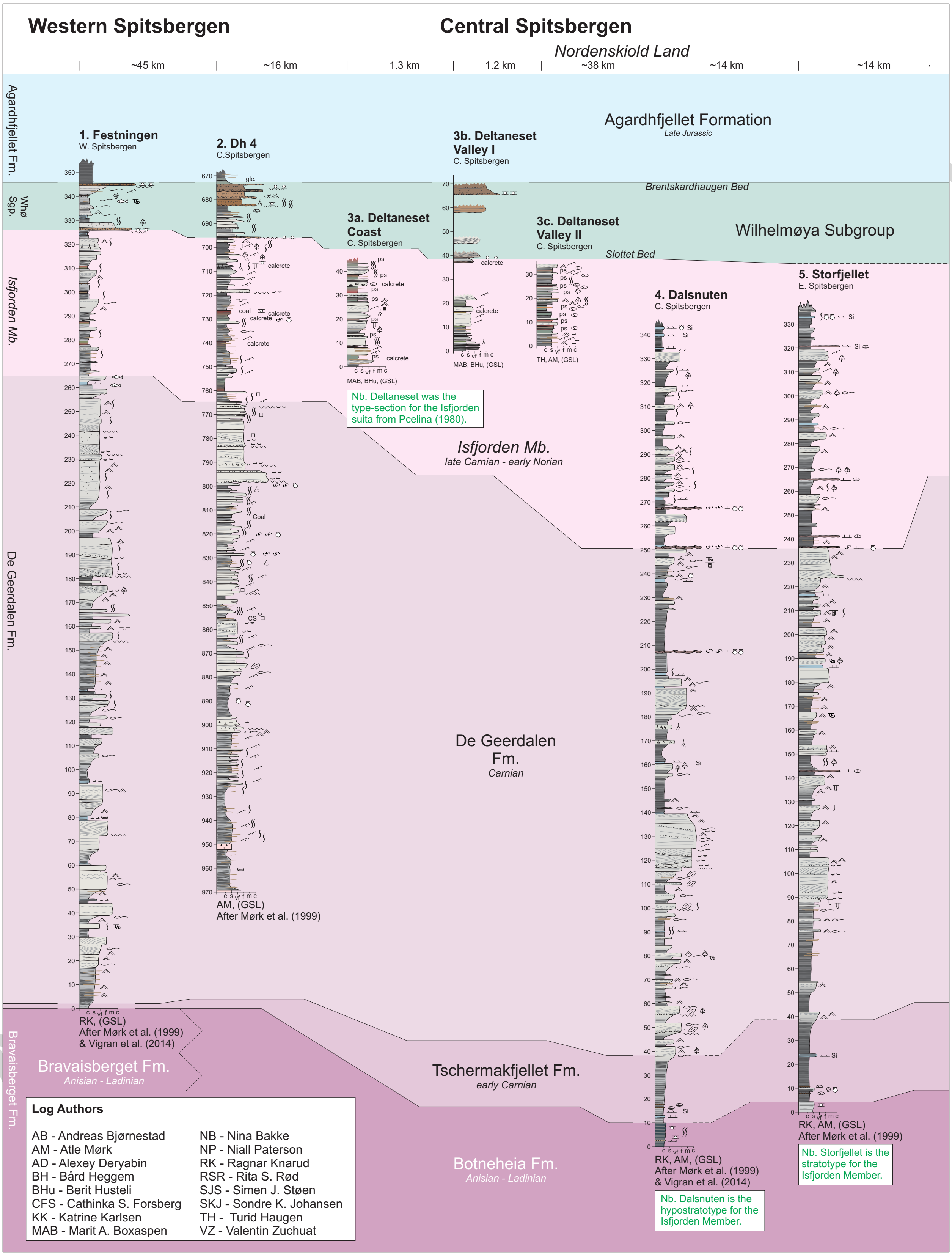

Figure 8: Regional Correlation (Right)

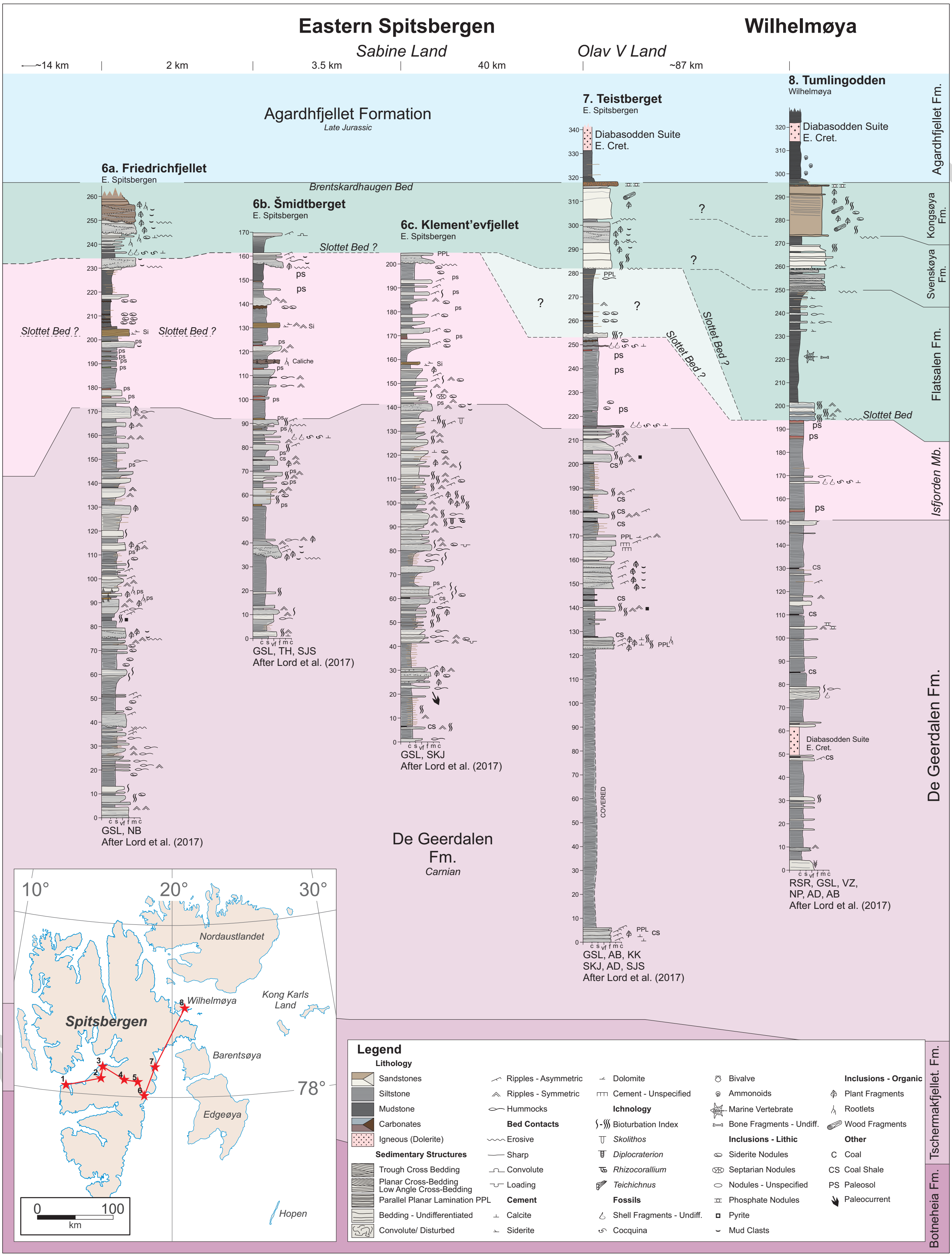

Figure 9: Overview photographs

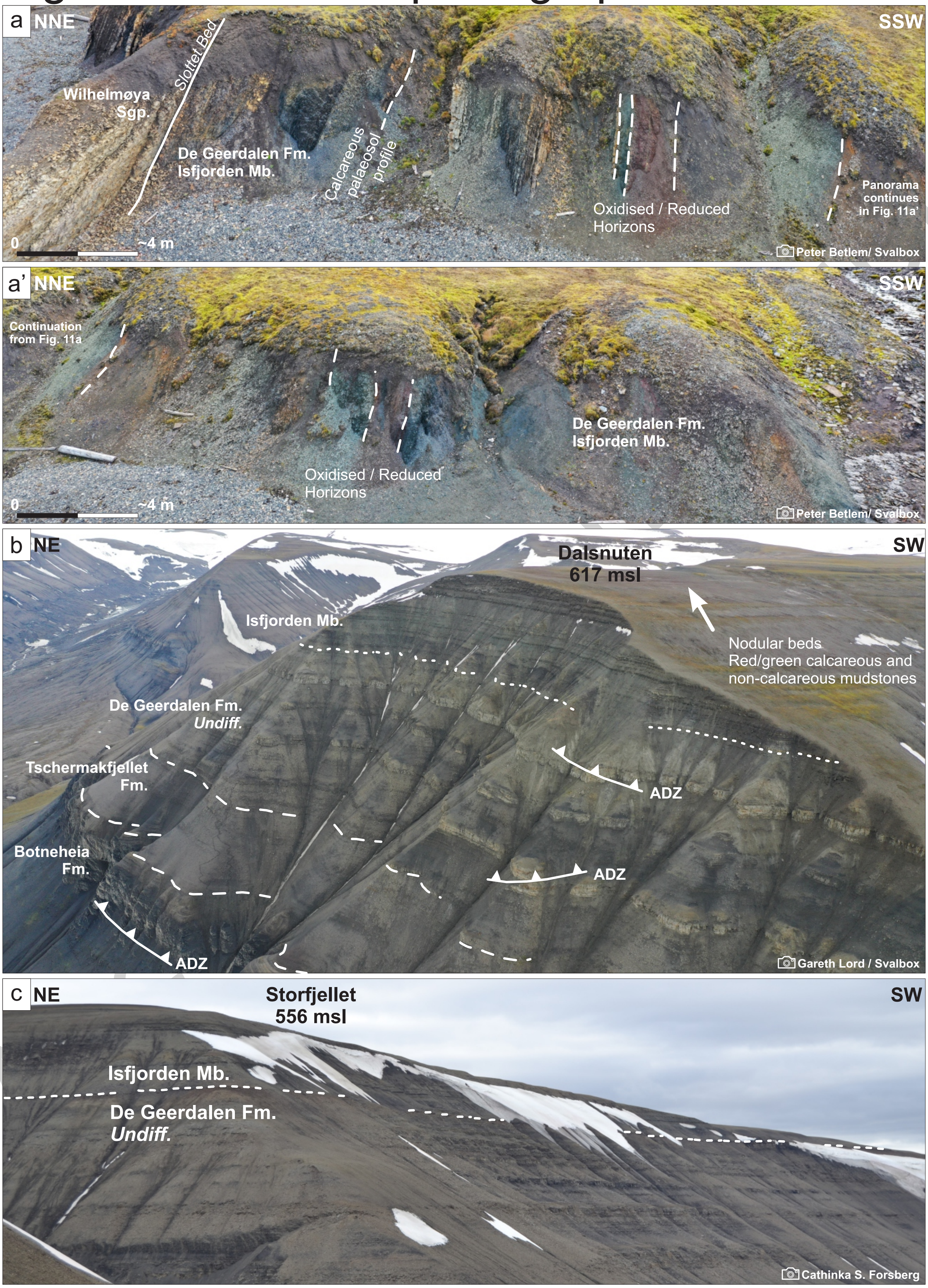

Figure 10: Stratotype Comparison

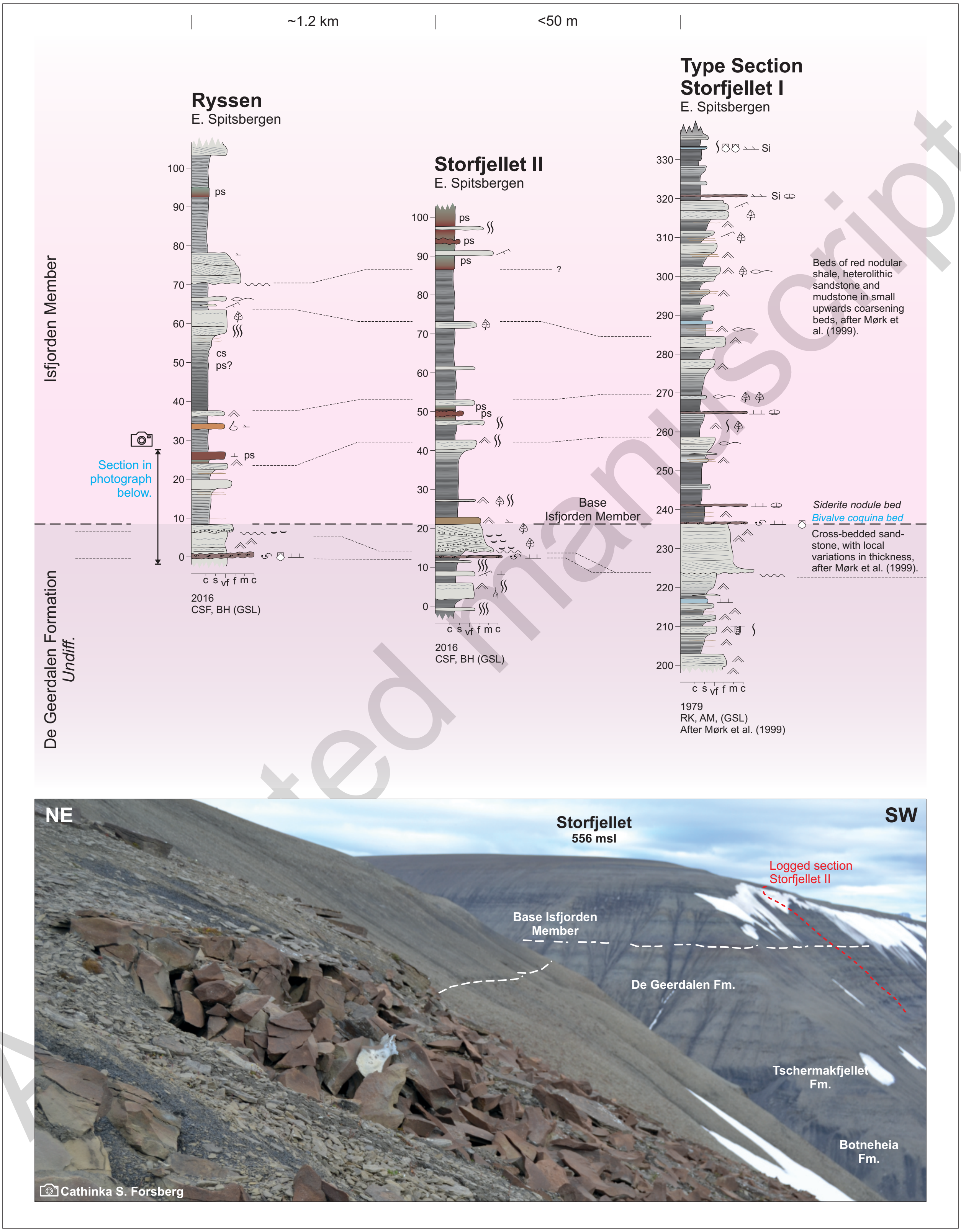

Table 1

Palaeosol classification	Colour	Appearance	Maturity	Occurrence	Thickness (cm)	Description	Interpretation
Vertisol	Dark brown to yellow	Homogeneous	Immature	Lower and middle part of De Geerdalen Formation	20 - 110 cm	Homogeneous, dark coloured beds with high organic content. No obvious horizonation is present, a blocky soil structure is common and mottles may be evident. Occurs in association with thin beds of coal shale or coal.	Homogeneous appearance likely results from pedoturbation, a key feature of vertisols. Suggested to be related to shrinking and swelling of clay minerals as a reaction to water saturation or later diagenesis. Coal/ coal shale indicates preservation of an organic horizon.
Argillisol	Various depending on horizon, typically dark grey to white or yellow	Horizonated	Mature	Typically constrained to the Isfjorden Member	40 -100 cm	Horizonated beds with at >3 soil horizons present. A prominent clay rich horizon is observed and is seen to be leached. Roots, mottles and wood fragments are common.	Well-developed palaeosols that are relatively mature due to the presence of roots, wood fragments and mottles. Horizonation indicates leaching of minerals and organic matter from the upper horizons to deeper levels in the soil profile. The most mature palaeosol type found in this study.
Protosol	Yellow, greyish or brown	Mottled	Immature	Throughout the De Geerdalen Formation	10 - 70 cm	No distinctive pedogenic features are evident in these beds. In outcrop these beds feature a tacky texture. Mottling may be present and these palaeosols often occur in association to thin organic rich beds of coal shale	These palaeosols are indicative of immature and poorly developed soils profiles and are thus defined as protosols. The coal shale likely occurs as a preserved organic horizon.
Non-calcareous mudstone (oxidised / reduced)	Grey-green weathering to bright red or green	Fissile or nodular mudstone	Mature	Constrained to the Isfjorden Member	30 - 200 cm (Occasionally thicker)	Red or green weathering beds composed of fissile mudstone with dark grey internal colour. Often form alternating beds. May also appear in association with thin caliche profiles and nodular rhizoliths or gleyed calcareous mudstones. These beds do not react with HCl acid.	These are defined as non-calcareous mudstones due to the lack of reaction with acid, dominating kaolinite and goethite composition. In the classification scheme of Mack et al. (1993) this type of palaeosols may be defined as a gleyed soil due to charachteristic patterning.
Calcareous mudstone / Calcrete / Caliche	Grey-green weathering to bright red or green / Dark grey weathered dark red to yellow	Fissile or nodular mudstone / Homogeneous blcoky or nodular calcareous beds	Mature	Constrained to the Isfjorden Member	30 - 200 cm (Occasionally thicker)	Red or green coloured beds of fissile mudstone. Often forming as alternating beds and commonly found in association with thin caliche profiles, rhizoliths and nodules. React with HCl acid. Calcretes and caliche are often blocky, dark grey beds or nodular beds consisting almost entirely of carbonate. Weathers dark grey to red in outcrop (sometimes yellow) and very resistant to erosion.	Red and green beds are interpreted as representing a gleyed calcareous mudstone and may indicate the presence of an immature or poorly developed caliche profile due to the high content of carbonate. Carbonaceous beds within delta plain deposits are interpreted as representing calcrete / caliche profiles. Calcretes are also found as rhizoliths formed around root structures.
Coal shale	Very dark brown to black	Fissile shale	Mature	Lower De Geerdalen Formation	5 - 20 cm	Fissile organic-rich black shale. Noticeably darker than surrounding shale or siltstone. Commonly found as thin beds atop palaeosols but may also be found as isolated beds within heterolithic delta plain facies. Features brown streak.	Interpreted to represent an organic horizon when seen in association with palaeosols. Individual coal shale beds not associated with palaeosol horizons may represent organic accumulations on the delta plain, forming a peat or poorly developed coal.
Coal (Histosol)	Black	Blocky	Mature	Lower De Geerdalen Formation	5 - 30 cm	Blocky, vitrinous coal beds with a vitreous/glassy lustre, often found capping parasequences. Pure coal beds are rare but are reported in eastern Svalbard and offshore to the NE. Root traces may also be common in well exposed sections.	Coal is indicative of dense humic build-up in a stable anoxic environment on the delta plain.

Table 2

Region	Log	Base of Isfjorden Member	Top of Isfjorden Member	Logged Thickness	Base Type	Top Type	Description of Base and Top	Comments
Western Spitsbergen	1. Festningen	256 m	326 m	70 m	Conformable	Erosional	Base defined at top of last prominent sanstone bed in the De Geerdalen Fm. at a conformable transition from shallow marine deposits, to fluvial, lagoonal and paralic delta plain deposits. Top of unit marked by erosional unconformity at Slottet Bed (phosphate nodule conglomnerate) at base Wilhelmøya Sgp.	The Isfjorden Mb. is condensed at the Festningen locality, as is the Wilhelmøya Sgp.
Central Spitsbergen	2. Dh-4 Borehole (Adventdalen)	764 mMD	696 mMD	68 m	Conformable	Erosional	Base of Isfjorden Mb. defined at top of last major sandstone interval at ~765 mMD representing a conformable transition to lagoonal and delta plain facies. Top defined at phosphate nodule conglomerate (Slottet Bed) at base Wilhelmøya Sgp.	Isfjorden Mb. is considered condensed in the Dh-4 well.
	3a. Deltaneset Coast	Not present	Not present	≥45 m	Not present	Not present	NA	Deltaneset was the original type section for the definition of the Isfjorden "suita" by Pčelina (1980) .
	3b. Deltaneset Valley I	Not present	39 m	≥39 m	Not present	Erosional	The base of the Isfjorden Mb. is not observed in this logged section. The top is however marked by a phosphate nodule bed that marks the base of the Wilhelmøya Sgp. in this area.	NA
	3c. Deltaneset Valley II	Not present	Not present	≥ 35 m	Not present	Not present	NA	NA
	4. Dalsnuten	251 m	Not Present (top of mountain)	~120 m (estimated) ≥94 m	Conformable	Removed by Quarternary erosion	Base Isfjorden Mb. at Dalsnuten interpreted at second coquina bed observed above the last sandstone interval. Base of the member is considered transitional at this locality and in nearby sections coquina bed may be missing. Top of member/ Slottet Bed not been identified at this locality. Summit features red and green scree with calcrete nodules indicating that the Isfjorden Mb. also present at top of mountain.	Phosphate nodules near the summit of Dalsnuten may represent Slottet Bed, suggesting presence of Wilhelmøya Sgp. Due to flat topography this has not been visualised in logged sections.
Eastern Spitsbergen	5. Storfjellet	237 m	Not Present (top of mountain)	~120 m (estimated) ≥87 m	Conformable	Removed by Quarternary erosion (?)	Original type section for the Isfjorden Mb. Base of the unit at second coquina bed observed in the section by Knarud (1980) occuring above a thick cross-bedded sandstone bed in De Geerdalen Fm. Top of member is considered indeterminate, see comment.	NB. Type section profile in Mørk et al. (1999) indicates Wilhelmøya Sgp. at top of the section with Isfjorden Mb. being 87 m thick. This is considered indeterminate based on recent understanding of the Wilhelmøya Sgp. in Spitsbergen (e.g. Rishmyr et al. 2018) and the potential for palaeosol horizons in scree at summit.
	6a. Friedrichfjellet	172.5 m	235 m	63.5 m	Conformable	Erosional	Base Isfjorden Mb. identified at top of last major sandstone in the De Geerdalen Fm., prior to siltier interval with nodular palaeosols and darker shale with siderite nodules. Top of member at the top of a cross-bedded sandstone bed with erosive base (after Klausen et al., 2022), base of Wilhelmøya Sgp. poorly constrained due to differential erosion at this boundary.	NB. Logged section on Friedrichfjellet correlates well to the section recorded at Klement'evfjellet by R. Knarud and presented in Vigran et al. (2014). Here Wilhelmøya Sgp. has been identified from presence of L.lundbladii palynomorphs. It is unclear how this succession relates to Friedrichfjellet accross the Lomfjorden Fault Zone.
	6b. Šmidtberget	92 m	162 m	70 m	Conformable	Erosional	Base Isfjorden Mb. identified at top of cross-bedded sandstone capped by a palaeosol at last major sandstone bed in the De Geerdalen Fm., prior to finer grained succession with nodular palaeosol horizons and siderite beds. A caliche horizon with rhoizoliths is present in this part of the succession. Top of the member is inferred at the top of a cross-bedded sandstone with erosive contact. Interval interpreted as representing a transition to the Wilhelmøya Sgp. which likely includes erosion of the Isfjorden Mb.	NB. Boundary to Wilhelmøya Sgp. is tentative based on lateral correlation to the sections at Klement'evfjellet and Friedrichfjellet following the resent understanding of the stratigraphic development of the Wilhelmøya Sgp. in the Agardhbukta area, interpreted by Klausen et al. (2022) and Rismyhr et at. (2018). The uppermost part of the Isfjorden Mb. is considered to be eroded in eastern Spitsbergen and is likely re-worked into the Wilhelmøya Sgp.
	6c. Klement'evfjell et	141 m	205 m	59 m	Conformable	Erosional	Base Isfjorden Mb. identified atop last major sandstone bed with palaeosol in the section, prior to a siltier interval featuring siderite nodules in addition to nodular palaeosols. Top of unit is marked above a cross-bedded sandstone with an erosional base. Transition to the Wilhelmøya Sgp. is not clear and erosion of the Isfjorden Mb. is interpreted in this area.	NB. Boundary to the Wilhelmøya Sgp. indicated as tentative based on lateral correlations to sections at Šmidtberget and Friedrichfjellet following understanding of the stratigraphic development in the Agardhbukta area by Klausen et al. (2022) and Rismyhr et at. (2018). The uppermost part of the Isfjorden Mb. is considered eroded in eastern Spitsbergen and likely re-worked into the Wilhelmøya Sgp.
	7. Teistberget	215 m	282 m	67 m	Conformable	Erosional	Base Isfjorden Mb. has been placed at a coquina bed atop the last prominent sandstone bed in the De Geerdalen Fm. (as with locations in central Spitsbergen) the boundary is considered conformable. No coal shales or immature palaeosols are observed. Top of member marked at a poorly exposed, erosional boundary to the Wilhelmøya Sgp.	NB. Extent of Wilhelmøya Sgp. on Teistberget not well constrained and may feature a well-developed Slottet Bed and Flatsalen Fm. In this study we favour a similar development in the Isfjorden Mb. to that of Rismyhr et al. (2018), Hounslow et al. (2022) and Klausen et al. (2022). This may be questionable when considering dating in this region by Vigran et al. (2014).
Wilhelmøya	8. Tumlingodd en	130 m	194 m	64 m	Conformable	Erosional	Base Isfjorden Mb. defined a conformable boundary at last coal shale bed in floodplain deposits in De Geerdalen Fm. where palaeosol horizons and coquina beds are observed. Top of the unit marked by a significant erosional surface and likely hiatus where the Slottet Bed scours into a palaeosoil profile.	A hiatus at the Slottet Bed is interpreted on Wilhelmøya with erosion of the Isfjorden Mb., based on new findings by Hounslow et al. (2022) and Klausen et al. (2022).